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FrancoAngeli

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ECONOMICS AND POLICY OF ENERGY AND THE ENVIRONMENT

Number 1 - 2026

CONTENTS

Articles

Special issue
The circular economy as a lever for decarbonization

Impact of wind energy on the European interconnections: Congestions, loop-flows and zonal pricing

Jacques Percebois[*], *Stanislas Pommeret*[**]

Abstract

This paper investigates the implications of the substantial expansion of renewable energy sources, particularly wind power, on cross-border electricity trade in Europe. Employing Germany – a market with a high penetration of renewables – as a case study, the analysis demonstrates that during periods of high wind generation, Germany functions as a net exporter to all neighboring jurisdictions. Conversely, during periods of negligible wind injection, Germany reverts to a net importer position. This volatility is attributable, in part, to internal congestion within the German transmission system. In the absence of adequate infrastructure, this bottleneck results in the emergence of loop flows, which compromise network management in adjacent countries. Consequently, it is imperative to invest in domestic grid infrastructure within countries generating these loop flows, while simultaneously incentivizing renewable energy storage. This may be achieved through the reform of transmission and distribution network access tariffs. An alternative market design involves the implementation of zonal pricing (market splitting), as observed in the Nord Pool (e.g., Norway and Sweden), which would internalize congestion constraints. While the implementation of locational marginal pricing is often politically resisted in favor of uniform national pricing to ensure regional equity, the consequent socialization of congestion costs may induce spatial distortions and market inefficiencies.

Keywords: electricity, energy markets, energy policy.

JEL classification: Q4, Q410, Q480

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Highlights

The substantial integration of intermittent renewable electricity sources significantly exacerbates price volatility within wholesale electricity markets.

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This heightened volatility can induce negative externalities on the transmission networks of interconnected, neighboring countries (e.g., the observed impact of German wind power on adjacent grids).

Furthermore, congestion on specific national electricity transmission networks often triggers the phenomenon of "loop flows" across the transmission infrastructure of adjacent nations.

Two primary policy and investment solutions exist to mitigate these issues:

1. Strategic investment in the transmission network of the originating country (where the loop flows primarily emerge).
2. The implementation of a zonal wholesale electricity price system, segmenting the market into distinct price zones.

1. Introduction

The interconnection of electricity networks is a key component in the development of a single electricity market in Europe (CRE, 2024). By 2030, all EU Member States are expected to establish cross-border interconnection capacities equivalent to 15% of their national electricity generation capacity. Additionally, by 2026, 70% of these interconnection capacities must be allocated to cross-border commercial exchanges, in accordance with Regulation (EU) 2019/943. The liberalization of the electricity industry in Europe aims to foster convergence in wholesale electricity prices across EU Member States and, ultimately, to establish a single electricity market in which wholesale prices are broadly harmonized. This objective is pursued despite the existence of heterogeneous generation mixes with differing production costs. The primary instrument to achieve this integration is the development of cross-border interconnection infrastructure.

Electricity interconnections facilitate commercial exchanges of electricity between European Union member states and provide mutual support in the event of grid failures. However, these interconnections can also create challenges when the policy decisions of one country constrain the energy strategies of its neighbors. Germany exemplifies this dynamic, having prioritized the large-scale deployment of intermittent renewable energy – particularly wind power which reaches 28% of electricity production in 2024. At times, Germany exports surplus electricity to neighboring grids, while at other times it is compelled to import significant volumes of hydroelectric or nuclear power from these countries to balance its own system.

Furthermore, transmission constraints within Germany – especially between the north and the south – result in loop flows, whereby wind-generated electricity from northern Germany is routed through the grids of neighboring countries to reach consumers in the south. We take Germany as a significant example because the share of renewables, particularly wind power, is higher than the European average. In addition, Germany has many neighboring countries to which it can export its surplus electricity and from which it can import electricity when there is no wind. The approach begins by outlining the methodology employed to track hourly physical electricity flows among key European countries during 2024. It subsequently examines the findings, which demonstrate the significant influence of German wind power generation on neighboring countries' grid systems.

2. Methodology

It is necessary to separate commercial flows from physical electricity flows because the paths are not the same. Physical flows are subject to Kirchhoff's laws and must be taken into account when analyzing congestion on the grid. In the following, the term *physical flow* (PF) refers to the hourly flows defined by the ENTSO-E Transparency Platform (Entso-e, 2024) and available on the ENTSO-E website. The time series consist of 8,784 data points for the year 2024. To distinguish physical flows between different European bidding zones, the resulting physical flow between zone A and zone B is denoted as PF_A^B. If $PF_A^B > 0$, the electrical flow moves from zone A to zone B (A exports to B); if $PF_A^B < 0$, the electrical flow moves from zone B to zone A (A imports from B). The physical flow from zone A to zone B at a given time *t* is denoted as$PF_A^B(t)$.

The *physical balance* from zone A to zone B is defined as the sum of the physical flows from zone A to zone B:

$$\boldsymbol{PB_A^B} = \sum_{\boldsymbol{Year}} \boldsymbol{PF_A^B(t)} \qquad \text{Equation 1}$$

The ENTSO-E website also allows downloading data related to electricity generation. We have downloaded the hourly data for Germany and summed the onshore and offshore wind power generation data. The time series representing the wind power component of German electricity generation is denoted as $P_{Germany}^{Wind}(t)$.

The time series $PF_A^B(t)$ can be decomposed into two components:

1. Projection onto a reference series $P_{Germany}^{Wind}(t)$: This component represents the part of $PF_A^B(t)$ that is aligned with $P_{Germany}^{Wind}(t)$. It is obtained by computing the orthogonal projection of $PF_A^B(t)$ onto $P_{Germany}^{Wind}(t)$: ${}_{Germany}^{\|Wind}PF_A^B(t)$.

$$\boldsymbol{{}_{Germany}^{\|Wind}PF_A^B(t)} = \frac{\boldsymbol{Cov\left(P_{Germany}^{Wind}, PF_A^B\right)}}{\boldsymbol{Var(PF_A^B)}} \boldsymbol{P_{Germany}^{Wind}(t)} \qquad \text{Equation 2}$$

where Cov denotes the covariance and Var the variance.

2. Orthogonal component ${}_{Germany}^{\perp Wind}PF_A^B(t)$:

$$\boldsymbol{{}_{Germany}^{\perp Wind}PF_A^B(t)} = \boldsymbol{PF_A^B(t)} - \boldsymbol{{}_{Germany}^{\|Wind}PF_A^B(t)} \qquad \text{Equation 3}$$

From Equation 2 and 3, it is easy to verify that ${}_{\mathrm{German}}^{\|\mathrm{Wind}}\mathrm{PF}_{\mathrm{A}}^{\mathrm{B}}(t)$ and ${}_{\mathrm{German}}^{\perp\mathrm{Wind}}\mathrm{PF}_{\mathrm{A}}^{\mathrm{B}}(t)$ are orthogonal since their covariance is null.

This decomposition (Equations 2 and 3), which separates the total physical flow into two orthogonal components, carries essential economic and physical meaning. The component parallel to German wind generation ${}_{Germany}^{\|Wind}PF_A^B(t)$ represents the portion of the electricity flow directly proportional to fluctuations in German wind output. It reflects the direct export of wind surpluses or import when wind power is low. Conversely, the orthogonal component ${}^{\perp Wind}_{Germany}PF_A^B(t)$ captures flows that are statistically independent of German wind variations, reflecting structural trade or imbalances stemming from other energy sources. Economically, the presence of strong orthogonal flows implies the need for complementary generation and storage capacity outside wind-intensive regions, while parallel flows indicate direct export of wind surpluses. These dynamics have implications for infrastructure planning, grid reinforcement, and market integration efforts within the EU and with its key non-member partners.

The parallel and perpendicular components of the *physical flows* between zone A and B may be integrated over a year to obtain the parallel and perpendicular *physical balance*:

$${}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PB}_{\boldsymbol{A}}^{\boldsymbol{B}} = \sum_{\boldsymbol{Year}} {}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PF}_{\boldsymbol{A}}^{\boldsymbol{B}}(\boldsymbol{t}) \tag{Equation 4}$$

$${}^{\perp Wind}_{Germany}PB_A^B = \sum_{Year} {}^{\perp Wind}_{Germany}PF_A^B(t) \tag{Equation 5}$$

For each EU27 member plus Norway, Switzerland, and the United Kingdom, one can calculate the *country balance* of a country A: CB_A . If the country is a single bidding zone then:

$$\begin{cases} \boldsymbol{CB_A} = \sum_{\boldsymbol{B}} \boldsymbol{PF_A^B} \\ {}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{CB_A} = \sum_{\boldsymbol{B}} {}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PF_A^B} \\ {}^{\perp \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{CB_A} = \sum_{\boldsymbol{B}} {}^{\perp \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PF_A^B} \end{cases} \tag{Equation 6}$$

If the country A is decomposed in multiple bidding zones A_i, then:

$$\begin{cases} \boldsymbol{CB_A} = \sum_{\boldsymbol{A_i}}\left(\sum_{\boldsymbol{B}\notin\{\boldsymbol{A_i}\}} \boldsymbol{PF_{A_i}^B}\right) \\ {}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{CB_A} = \sum_{\boldsymbol{A_i}}\left(\sum_{\boldsymbol{B}\notin\{\boldsymbol{A_i}\}} {}^{\parallel \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PF_{A_i}^B}\right) \\ {}^{\perp \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{CB_A} = \left(\sum_{\boldsymbol{B}\notin\{\boldsymbol{A_i}\}} {}^{\perp \boldsymbol{Wind}}_{\boldsymbol{Germany}}\boldsymbol{PF_{A_i}^B}\right) \end{cases} \tag{Equation 7}$$

The data have been analyzed and the figures have been realized with the help of the r language (R Core Team, 2021; Wickham, 2016). The base maps were obtained via the *rnaturalearth* library (Massicotte and South, 2025).

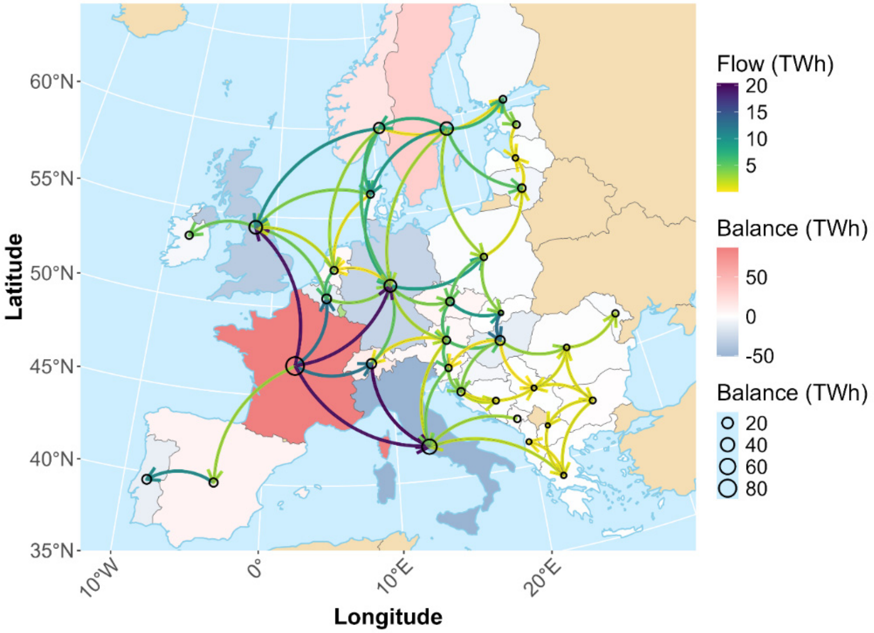
3. Results

3.1. Physical balance in 2024

In this analysis, we consider all physical electricity exchange flows between European countries for the year 2024, regardless of their origin. These figures represent net physical flows rather than commercial transactions. France appears as a net exporter to all of its neighboring countries. Export flows are particularly significant with Italy, the United Kingdom, and Germany. They are somewhat lower with Switzerland, Belgium, and also Spain. Given the substantial volume of Swiss electricity exports to Italy, it can be assumed that part of France's electricity exports transit through Switzerland. It should also be noted that Italy imports electricity from Austria. Italy is by far the largest net importer of electricity in Europe (net imports of 50.68 TWh), followed by the United Kingdom (35.02 TWh), Germany (28.84 TWh), Belgium (10.78 TWh), and Portugal (10.49 TWh) (see Figure 1 and Table 1).

France's status as a net electricity exporter is primarily attributable to its extensive nuclear generation capacity, which is characterized by very low marginal costs and facilitates substantial contractual exports, notably to Italy and Germany. Consequently, France serves as a stabilizing supplier for its interconnected neighbors. However, it is crucial to recognize that during periods of significant nuclear fleet unavailability, France's position can rapidly shift, transforming the country into a strong net importer. This volatility is exacerbated because its generation mix contains insufficient flexible conventional capacity to effectively compensate for peak demand or system outages.

Figure 1 – Physical Flows in Europe in 2024. The color of the arrow represents the total observed flow for the year 2024, while its direction indicates the flow direction. The color of the countries varies as follows: blue for net electricity-importing countries, red for net electricity-exporting countries, and light green for countries not considered for their exchanges with the EU27 zone. Only three non-EU countries – Norway, Switzerland, and the United Kingdom – are fully taken into account, while for other non-EU27 countries, only their electricity exchanges with an EU27 member state are considered



Data: ENTSO-E(2024)

Germany occupies a central position in European electricity exchanges, both along the north-south and east-west axes, due to its geographical location. It is a net exporter to the Czech Republic and Poland, but a net importer from France and the Nordic countries – namely Norway, Sweden, and Denmark. Overall, Germany is a substantial net importer of electricity.

Sweden is a net exporter to Denmark, Germany, Poland, Finland, Norway, and the Baltic States. Norway is a net exporter to Germany, the United Kingdom, and the Netherlands. Both Sweden and Norway possess significant hydroelectric generation capacity, which also enables them to serve as inter-seasonal storage hubs for part of the European electricity grid ("copperplate"). In addition, Sweden has a substantial nuclear power fleet.

To further deepen the data analysis, we chose to decompose commercial electricity exchanges into two orthogonal (uncorrelated) time series: one parallel (i.e., proportional) to German wind power generation, and one perpendicular to it (see methodology section). The decision to focus on German wind generation stems from the fact that Germany has the largest wind power capacity in the European Union and occupies a central geographical position within the continental grid. Furthermore, previous studies have shown that wind regimes in the United Kingdom, France, and Germany – more broadly, across the northern part of the European grid – are highly correlated (Percebois and Pommeret, 2018).

3.2. Impact of German wind power on cross-border physical flows

Table 1, Figures 2 and 3 present a detailed breakdown of cross-border (CB) electricity balances for European countries in 2024, distinguishing between total net physical electricity flows and their components aligned (∥) and orthogonal (⊥) to wind power generation in Germany. The data are expressed in terawatt-hours (TWh), with positive values indicating net exports and negative values net imports.

From an economic perspective, this decomposition provides insight into the spatial and temporal dynamics of electricity trade in relation to Germany's wind generation patterns – a key factor in Europe's renewable energy transition. As Germany is a major hub for wind energy, fluctuations in its wind output influence the cross-border flow structure across the continent.

Germany itself is a significant net importer in aggregate (−28.84 TWh), yet it exhibits a strong surplus (56.61 TWh) in flows aligned with its wind production and a large deficit (−85.45 TWh) in the orthogonal component. This suggests that during periods of high wind generation, Germany exports a substantial share of this surplus to its neighbors, while in low-wind or demand-peaking periods, it relies heavily on imports as showed in Table 1.

Table 1 – Electrical data for 2024[1] *(positive: net exporting country; negative: net importing country).* $CB_{Country}$ *is the balance for the physical flow,* ${}^{\parallel Wind}_{Germany}CB_{Country}$ *is the balance for the physical flow parallel to the wind production in Germany and* ${}^{\perp Wind}_{Germany}CB_{Country}$ *is the balance for the physical flow perpendicular to the wind production in Germany. Only three non-EU countries – Norway, Switzerland, and the United Kingdom – are fully taken into account, while for other non-EU27 countries, only their electricity exchanges with an EU27 member state are considered*

Country	$\boldsymbol{CB_{Country}}$ (TWh)	$\boldsymbol{{}^{\parallel Wind}_{Germany}CB_{Country}}$ (TWh)	$\boldsymbol{{}^{\perp Wind}_{Germany}CB_{Country}}$ (TWh)
Austria	4,75	-5,25	10,00
Belgium	-10,78	1,67	-12,44
Bulgaria	1,49	-2,04	3,52
Croatia	-5,06	0,79	-5,85
Czech Republic	6,39	-3,73	10,12
Denmark	-3,80	7,92	-11,72
Estonia	-3,17	-1,05	-2,12
Finland	-3,18	-1,91	-1,28
France	87,29	-8,39	95,68
Germany	-28,84	56,61	-85,45
Greece	0,66	-2,12	2,78
Hungary	-11,56	-2,21	-9,34
Ireland	-4,42	0,00	0,00
Italy	-50,68	-8,77	-41,91
Latvia	-0,92	0,38	-1,30
Lithuania	-5,73	0,15	-5,87
Netherlands	4,18	-2,52	6,70
Norway	17,89	-16,48	34,37
Poland	-2,30	1,72	-4,02
Portugal	-10,49	2,70	-13,19
Romania	-1,03	2,62	-3,65
Slovakia	0,12	-0,09	0,20
Slovenia	2,42	-1,25	3,66
Spain	7,54	-3,56	11,10
Sweeden	33,54	-0,92	34,46
Switzerland	12,46	-14,44	26,90
United Kingdom	-35,02	-1,33	-33,69

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[1] Malta and Cyprus are not taken into account in the present study. Luxemburg is in the bidding zone (Germany-Luxemburg).

Several countries exhibit contrasting behavior in the parallel and orthogonal flow components. France, for example, stands out as a major net exporter (87.29 TWh) overall. Its orthogonal surplus (95.68 TWh) far exceeds its parallel deficit (−8.39 TWh), indicating that its exports primarily support neighboring countries when Germany's wind production is low. This positioning reinforces France's role as a stabilizing supplier, likely driven by its large nuclear fleet.

The Nordic region shows a mixed picture. Sweden and Norway are notable net exporters (33.54 TWh and 17.89 TWh, respectively), with Sweden's orthogonal component (34.46 TWh) closely matching its total, indicating steady exports regardless of German wind patterns. Norway, however, shows a large orthogonal surplus (34.37 TWh) and a negative parallel balance (−16.48 TWh), suggesting its flexible hydro capacity is deployed counter-cyclically to Germany's wind output.

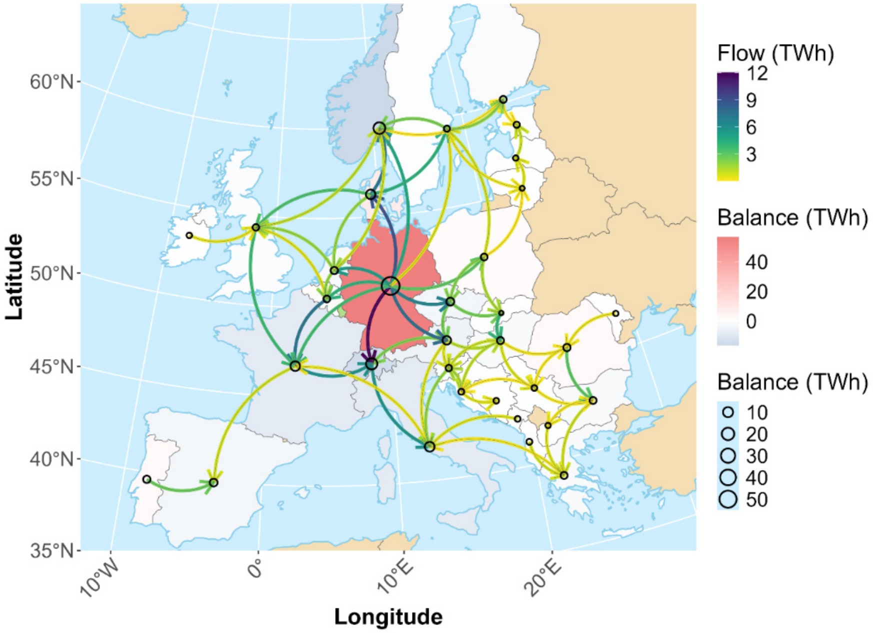
In contrast, southern countries such as Italy (−50.68 TWh) and the United Kingdom (−35.02 TWh) remain structurally dependent on imports, particularly in the orthogonal dimension, suggesting limited responsiveness to German wind generation and perhaps constrained domestic flexibility or interconnection.

Some Central and Eastern European countries (e.g., Czech Republic, Austria) demonstrate a pattern of counterbalancing Germany's wind output – Austria has a strong orthogonal surplus (10.00 TWh) and a negative parallel balance (−5.25 TWh), indicating adaptive export behavior when German wind is low. The Czech Republic displays complementary dynamics, potentially playing a buffer role in regional balancing.

Overall, this decomposition sheds light on how cross-border electricity trade responds not just to net imbalances but to intra-annual variability in renewable generation. Economically, the presence of strong orthogonal flows implies the need for complementary generation and storage capacity outside wind-intensive regions, while parallel flows indicate direct export of wind surpluses. These dynamics have implications for infrastructure planning, grid reinforcement, and market integration efforts within the EU and with its key non-member partners.

Since the data represent net physical flows, it is difficult to determine whether some of the wind electricity produced in northern Germany – where offshore wind farms are located in the Baltic Sea – is subsequently redirected to southern Germany (e.g., Bavaria). If that is the case, it would suggest the presence of loop flows caused by congestion in the north-south transmission corridors within the German grid.

Figure 2 – German wind parallel component of the Physical Flows in Europe in 2024. The color of the arrow represents the total observed flow for the year 2024, while its direction indicates the flow direction. The color of the countries varies as follows: blue for net electricity-importing countries, red for net electricity-exporting countries, and light green for countries not considered for their exchanges with the EU27 zone. Only three non-EU countries – Norway, Switzerland, and the United Kingdom – are fully taken into account, while for other non-EU27 countries, only their electricity exchanges with an EU27 member state are considered

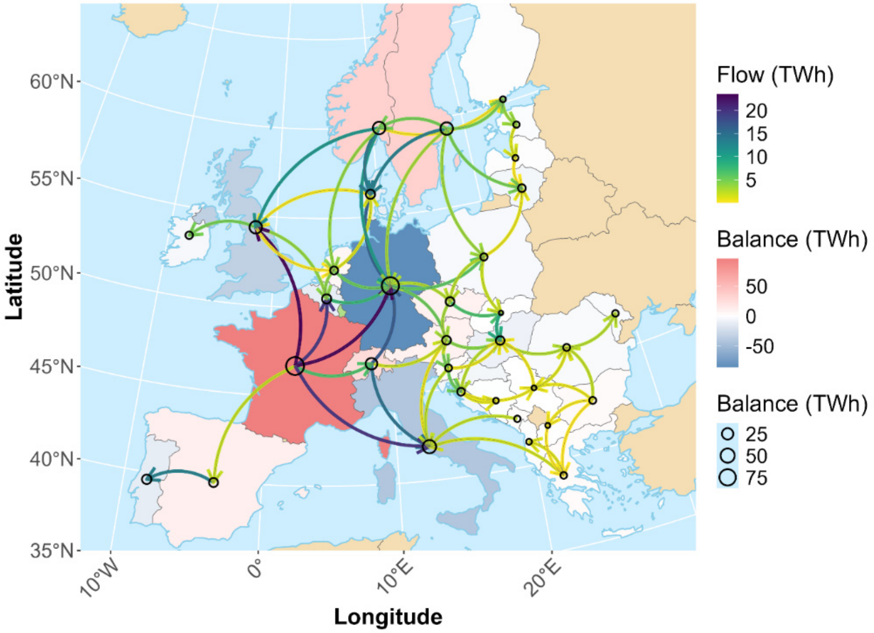


Data: ENTSO-E(2024)

Table 2 – Physical balance of Germany with the neighboring countries (positive: export; negative: import)

Country	$PB_{Germany}^{Country}$ (TWh)	${}_{Germany}^{\parallel Wind}PB_{Germany}^{Country}$ (TWh)	${}_{Germany}^{\perp Wind}PB_{Germany}^{Country}$ (TWh)
Austria	2.41	7.68	-5.27
Belgium	-3.51	4.22	-7.73
Czech republic	3.88	6.55	-2.68
Denmark	-7.41	8.88	-16.29
France	-19.77	3.63	-23.40
Netherlands	0.03	5.34	-5.31
Norway	-5.78	4.73	-10.51
Poland	8.81	2.97	5.84
Sweeden	-5.78	4.73	-10.51
Switzerland	-4.88	12.03	-16.91

Figure 3 – German wind perpendicular components of the Physical Flows in Europe in 2024. The color of the arrow represents the total observed flow for the year 2024, while its direction indicates the flow direction. The color of the countries varies as follows: blue for net electricity-importing countries, red for net electricity-exporting countries, and light green for countries not considered for their exchanges with the EU27 zone. Only three non-EU countries – Norway, Switzerland, and the United Kingdom – are fully taken into account, while for other non-EU27 countries, only their electricity exchanges with an EU27 member state are considered



Data: ENTSO-E(2024)

Overall, the data illustrate how variable renewable energy generation in a major hub like Germany generates significant cross-border spillovers, with wind output not only affecting German net exports but also reshaping flows between third countries. The Tables 1 and 2 and the Figures 2 to 3 provide strong evidence of the growing interdependence among European electricity systems and underscore the importance of coordinated grid operation and market design that can accommodate such variability – potentially through flexible infrastructure investments, dynamic pricing zones, or capacity-sharing mechanisms.

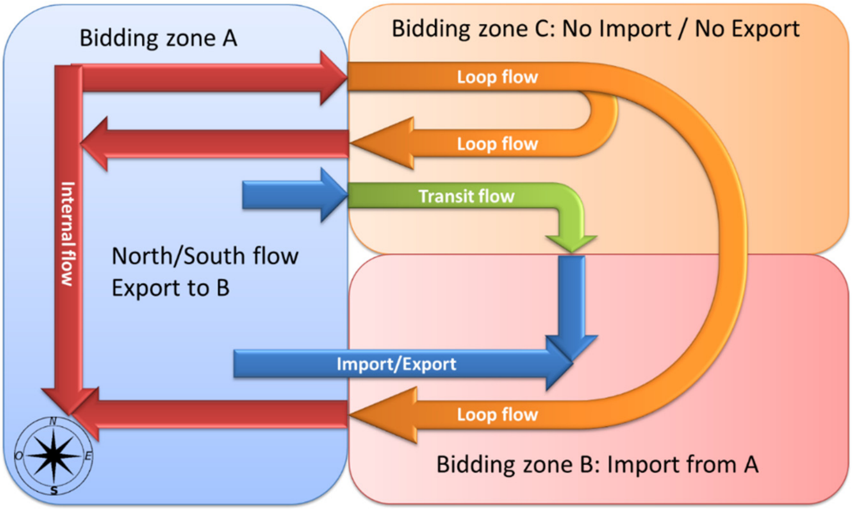
4. Loop-flows

Three types of cross-border electricity flows can be distinguished and are illustrated in Figure 4 (Entso-e, 2018; Lauer, 2021; Riou, 2024):

1. **Scheduled Commercial Flows:** These refer to the market-based exchange where a producer in Zone A sells electricity to a consumer in Zone B. This transaction results in a nominated commercial schedule representing the contractual obligation to transfer energy across the border from A to B.
2. **Unscheduled Physical Transit Flows:** Due to Kirchhoff's laws regarding voltage and impedance, the actual physical path of electricity does not strictly follow commercial paths. Consequently, a portion of the energy traded between A and B may physically flow through the grid of a third country (Zone C), which is not a party to the transaction. These are technically classified as transit flows.
3. **Loop Flows:** These represent unscheduled physical power flows driven by network impedance differences rather than commercial contracts. The figure illustrates two distinct manifestations of this phenomenon:
   a. **Intrazonal Loop Flows** ($A \rightarrow C \rightarrow A$): Electricity generated in Zone A exits to Zone C due to internal congestion (e.g., a North-South bottleneck in A) and subsequently returns to Zone A. The flow merely uses the neighbor's grid as a bypass for domestic transport.
   b. **Interzonal Loop Flows** ($A \rightarrow C \rightarrow B \rightarrow$ ...): These are complex unscheduled flows where electricity – intended for domestic use in A – traverses multiple neighboring zones (C, B, etc.) in a circular or parallel manner before reaching its final sink. Crucially, like the intrazonal variant, this flow is primarily attributed to structural congestion and the inability of the direct interconnections to absorb the entirety of the nominated physical flow.

In all cases, these unscheduled physical flows create a negative externality by consuming cross-zonal transmission capacity in transit zones (C) and importing zones (B) without a corresponding market-based payment, thereby degrading the overall efficiency and security of the interconnected system.

Figure 4 – Diagram illustrating the distinction between loop flows, transit flows, import/export flows, and internal flows in an electricity network



Electricity interconnections facilitate commercial exchanges of electricity between European Union member states and provide mutual support in the event of grid failures. However, these interconnections can also create challenges when the policy decisions of one country constrain the energy strategies of its neighbors. Germany exemplifies this dynamic, having prioritized the large-scale deployment of intermittent renewable energy – particularly wind power. At times, Germany exports surplus electricity to neighboring grids, while at other times it is compelled to import significant volumes of hydroelectric or nuclear power from these countries to balance its own system.

Furthermore, transmission constraints within Germany – especially between the north and the south – probably result in loop flows, whereby wind-generated electricity from northern Germany is routed through the grids of neighboring countries to reach consumers in the south. These negative externalities have prompted some stakeholders to propose reforms to the current European grid design, including the introduction of multiple wholesale price zones within countries. Such measures could partially alleviate internal congestion and better align market signals with physical grid constraints.

It is crucial to note that, within the scope of this analysis, physical power flows are aggregated exclusively at the bidding zone level. Consequently, the 'loop flows' referenced here are conventional numerical representations that capture the macroscopic phenomenon of unscheduled power transfers resulting from internal grid congestion, rather than the precise physical flows calculable via a detailed nodal network simulation. While this aggregation simplification is a conventional methodology employed by organizations such as ENTSO-E for cross-border analysis, it remains relevant for illustrating the external systemic impact of internal constraints -such as those observed within the German transmission system- on adjacent synchronous grids.

The issue of loop flows has been addressed in the literature in connection with problems encountered on interconnected networks, mainly in Central Europe. Here again, Germany appears to have played a role in the impact that these loop flows have had on its neighboring countries (Singh et al., 2016).

It is known that in the event of a massive injection of wind-generated electricity, wholesale electricity prices on the German market are low, or even zero or negative. This phenomenon impacts the wholesale prices of neighboring countries, which often complain about it, such as Sweden. Conversely, in the absence of wind, German wholesale prices surge, forcing Germany to import large quantities of electricity from its neighboring countries. This is explained by the significant share of wind power in Germany's energy mix. The volatility of wholesale prices in Germany's neighboring countries is partly due to the variability of German wind power production, raising concerns about the unintended consequences of cross-border interconnections. Electricity companies in Sweden and Norway have reduced investment activity in response to persistently low electricity prices, a phenomenon largely attributable to significant imports of wind-generated electricity from Germany.

This dynamic can constrain future system flexibility, particularly when wholesale prices experience upward shocks. Conversely, when wind generation in Germany is insufficient, exports of low-cost hydroelectricity from Sweden or Norway to Germany can exert upward pressure on wholesale prices within the Nordic region, a development frequently criticized by local industrial consumers. Nevertheless, it should be emphasized that such cross-border electricity flows displace more expensive and carbon-intensive fossil-based generation in Germany, thereby exerting a downward influence on European wholesale prices and contributing to CO_2 emissions reductions (Percebois and Pommeret, 2021). As a result, the intermittency inherent to renewable energy sources is emerging as a shared operational and economic constraint across Northern Europe, intensifying the interdependence of regional electricity markets.

5. Discussion and solutions

Although this analysis does not directly quantify the magnitude of physical loop flows, the data presented in Table 2 and Figure 2 offer indirect evidence of the negative externality generated by German internal grid congestion. Germany's substantial parallel balance (closely correlated with wind generation), projected at 56.61 TWh for 2024, indicates a massive export of its wind surplus. Given the existing north-south transmission constraints within Germany's internal transmission system, a significant portion of this northern wind power surplus is highly likely rerouted through the transmission networks of adjacent countries to serve southern German demand. This physical displacement effectively reduces the available transmission capacity (ATC) of these third countries for mutually beneficial commercial power exchange.

The European Commission actively advocates for increased investment in cross-border electricity interconnections to optimize the allocation and flow of electricity across member states. However, these enhanced interconnections can generate unintended systemic effects: when a country faces either surplus or deficit in intermittent renewable generation, it can destabilize the electricity balance in adjacent grids. Neighboring systems are then compelled to either absorb excess electricity or compensate for deficits, and, in some instances, facilitate the transit of surplus power due to congestion within the originating country's transmission network (Amundsen and Bergman, 2006).

With the growing frequency of network congestion, the reliance on costly redispatch measures is increasing, as highlighted by Neuhoff (Neuhoff et al., 2025, 2013). If internal grid bottlenecks become too pronounced, the delineation of national wholesale price zones ceases to be efficient, undermining market signals and welfare optimization. This challenge is fundamentally rooted in the non-storable nature of electricity, which necessitates real-time balancing between supply and demand.

Several policy and technical measures can mitigate the unintended externalities of cross-border electricity flows:

- First, countries generating surplus intermittent power could be mandated to curtail wind generation during oversupply periods and prioritize grid expansion to internalize congestion costs, notwithstanding high capital expenditures and potential community opposition to infrastructure projects. Moreover, the inability to feed part of the renewable electricity into the grid due to congestion or at the request of the grid operator can be collectively costly if the producer receives public support.
- Second, physical flow control mechanisms – such as Poland's deployment of phase-shifting transformers at interconnection points – can selectively block uncontrolled transit, though these risks contravening EU market integration principles.
- Third, adjusting transmission tariff structures to reflect marginal congestion costs could economically incentivize optimal flow patterns and reduce loop flows.

- Fourth, the Agency for the Cooperation of Energy Regulators (ACER) proposes subdividing national wholesale price zones in countries with pronounced internal congestion, thereby aligning market prices more closely with localized grid conditions and mitigating overflow externalities (ACER, 2022).

These measures collectively aim to address the spatial and temporal mismatches inherent in renewable energy systems while balancing economic efficiency, grid stability, and regulatory coherence.

A fundamental principle in European electricity market design is that, in the absence of internal congestion, a single wholesale price should be maintained within each country, reflecting uniform market conditions. In the event of congestion, and when grid expansion is not a viable option, the market adopts a zonal pricing system, segmenting into multiple price zones that correspond to the physical limitations of the grid. In cases of persistent internal bottlenecks, regulatory guidelines recommend redrawing zones to align market boundaries with actual physical limitations, thereby improving price signal accuracy and congestion management (Glachant and Pignon, 2005).

European electricity markets currently rely predominantly on zonal pricing, a model in which each bidding zone is assigned a single wholesale price. While this framework effectively supports cross-border market integration and liquidity, it increasingly fails to accurately reflect physical grid realities as the penetration of intermittent renewable generation expands and internal transmission congestion intensifies. Consequently, policymakers across the European Union are actively debating reforms to existing bidding zone configurations and considering the potential long-term transition towards more granular locational pricing schemes.

Wholesale prices vary across zones: they tend to be lower where electricity production exceeds demand and higher where demand surpasses supply. This price divergence incentivizes industrial consumers to relocate to lower-cost zones and encourages electricity producers to invest in higher-price zones, although the magnitude of price differentials may sometimes be insufficient to motivate significant relocation. It is important to recognize that industry location decisions are influenced by multiple factors beyond energy costs, such as infrastructure quality and labor availability.

Zonal pricing structures already exist in several European electricity markets, including five zones in Norway, four in Sweden, two in Denmark, and as many as seven in Italy (Amundsen and Bergman, 2007). In these systems, each zone establishes its own spot price when inter-zonal transmission constraints emerge, thereby reflecting the local supply-demand equilibrium and the available transfer capacity. The delineation of zones is based on actual physical congestion points in the transmission network, rather than on administrative or national boundaries. The Agency for the Cooperation of Energy Regulators (ACER) and the European Commission are currently evaluating the potential for a broader implementation of zonal pricing across the EU, including in France – where the transmission grid is highly meshed and internal congestion remains limited. ACER's objective is to move away from a price zone configuration that largely mirrors national borders and instead adopt one grounded in economic and physical grid realities (Montel, 2025).

The adoption of a multi-zonal wholesale pricing mechanism can yield efficiency gains by reducing network management costs, mitigating congestion, and providing locational price signals that guide investment and operational decisions. Nonetheless, such a system introduces significant complexity, particularly with respect to the accurate definition of zone boundaries and the potential for reduced market liquidity, which may exacerbate price volatility in less interconnected zones (Glachant and Pignon, 2005).

An alternative market design approach involves the establishment of transnational wholesale electricity price zones. For instance, low-price areas in northern Norway and Sweden could be aggregated into a single combined zone, while their respective high-price southern regions could constitute a separate zone. This strategy aims to align bidding zone configurations with the physical characteristics of the transmission network rather than being constrained by national political boundaries. Expanding the geographical size of zones generally enhances market liquidity and contributes to dampening price volatility by enabling more robust trading volumes and improved price discovery mechanisms within each enlarged zone. However, the efficacy of zonal splits is subject to intense policy debate. For example, the Swedish subsidiary of the German utility E.ON advocated in 2025 for the reunification of the country's electricity market into a single bidding zone in order to mitigate domestic price volatility. The Swedish market had been deliberately segmented into four auction zones in 2011 with the express goal of providing better locational investment signals for both new generation and consumption capacity. As this measure is largely assessed to have failed to attract the anticipated investment, the utility argued for its repeal. Conversely, in the Norwegian context, while the current five price zones are generally performing effectively, the potential subdivision of zone NO4 (Northern Norway) is under consideration. This proposed split is motivated by the aim to:

- facilitate a more optimal utilization of hydro-electric resources,
- reduce transmission congestion,
- narrow internal price discrepancies within the region.

The primary factor driving this consideration, as explained by Statnett (the Transmission System Operator), is the anticipated increase in industrial consumption within Northern Norway. The operational parameters of the Norwegian electricity transmission network are fundamentally constrained by geography (a highly mountainous topography). Furthermore, nearly all electricity generation is hydro-electric, with reservoirs and power stations dispersed widely across the country. Consequently, the existing auction zones are instrumental in allowing the Norwegian hydro-electric system to preserve the economic value of water by accurately reflecting the actual geographical and network constraints inherent to the system.

Most empirical and theoretical analyses converge on the conclusion that "multi-regional zonal pricing improves static market efficiency relative to uniform national pricing, albeit without reaching the allocative precision of full nodal pricing" (Neuhoff et al., 2013). While nodal pricing remains the theoretically first-best solution for achieving static economic efficiency, its significant implementation complexity, demanding data requirements, and critical institutional and political hurdles have rendered zonal pricing the most practical and preferred intermediate step in European market integration efforts (Borowski, 2020; Knörr et al., 2025). Internalizing transmission congestion within electricity prices (even through multinational zonal configurations) is the fundamental mechanism required to provide locational investment signals and enable market forces to rebalance the system through both generation and consumption investment. This approach is crucial because it minimizes network upgrade costs and incentivizes large electricity consumers to locate their activities in areas where system prices are lowest. However, it is pertinent to note that the cost of electricity is typically not the sole determinant in this locational decision-making process. Other critical factors, particularly political considerations such as tax incentives, subsidies, and labor costs, significantly influence the ultimate choice of industrial siting.

The reform of electricity bidding zone configurations is inextricably linked to the broader context of the energy transition toward renewable sources. Optimally configured zones have the potential to better monetize local renewable generation and enhance overall system flexibility. However, the frequency of such zonal configuration changes is a critical consideration. Excessive reconfiguration frequency introduces regulatory uncertainty for capital investment (Lété et al., 2022; Sarfati and Holmberg, 2020). Furthermore, reconfiguring zones entails tangible operational costs and may lead to potentially negative short-term market effects. A key concern raised by several market operators is that the shift to smaller zones could compromise market liquidity and increase local price volatility.

The massive development of storage facilities, particularly batteries, should also prevent these congestions and loop flows. One way to encourage producers to use storage as a flexibility solution is to introduce incentive pricing for access to electricity transmission and distribution networks. France has such a project. In France, for example, the regulatory commission in charge of access tariff will introduce a new tariff option, the injection-withdrawal tariff, reserved for standalone storage, which will come into effect on August 1, 2026 (CRE, 2025). The principle takes into account congestion zones linked to renewables.

Approximately 13% of the network's areas are constrained in terms of "photovoltaic and wind injection" – that is, in these areas, the network tends to be saturated on the production side during peak solar hours (summer, 12 p.m. to 4 p.m., ~125 consecutive days). In these areas, the injection-withdrawal tariff remunerates storage for withdrawing during these peaks. Approximately 50% of the grid's zones are subject to withdrawal constraints – the grid tends to be saturated on the consumption side during peak hours (winter tariffs). In these zones, the feed-in/withdrawal tariff remunerates storage for injecting during peaks. Thus, the toll can be negative: this tariff remunerates storage for its countercyclical activity.

Unlike the price zones proposed by the European regulator (ACER), which would create several wholesale price zones, the tariff zones planned by the French regulator are zones of differentiation in network access tariffs, with the aim of promoting on-site storage of renewables and thus limiting wholesale price volatility. The aim is to encourage storage facilities to adopt behavior that reduces local network peaks, whether these are local injection or withdrawal peaks. This tariff component therefore distinguishes between two types of network pockets based on their size: 1) in pockets sized for withdrawal, the tariff signal encourages a reduction in the withdrawal peak, i.e., injection during periods when withdrawal peaks are significant. To this end, the tariff component selected introduces an additional cost if the user withdraws during a local withdrawal peak, and a cost reduction if the user injects during a local withdrawal peak; 2) in so-called injection zones, the tariff signal selected encourages storage facilities to reduce injection peaks, i.e. to withdraw during injection peaks. To achieve this, the tariff component selected imposes an additional cost if the user injects during a local injection peak, and a cost reduction if the user withdraws during a local injection peak.

6. Conclusion

National energy policy decisions can impose externalities on neighboring electricity systems, either by exporting surplus electricity during periods of oversupply or by drawing heavily on cross-border imports during domestic shortages. Additionally, internal transmission bottlenecks within one country can induce unintended power flows – so-called loop flows – across the networks of neighboring countries, thereby compromising their operational stability and increasing congestion costs at the regional level.

This analysis highlights the necessity of reinforcing internal transmission infrastructure, or, where such investments are insufficient or delayed, the alternative of establishing zonal markets. Introducing transnational price zones is another potential measure to reduce redispatching and congestion management costs. Ultimately, a trade-off arises between expanding physical transmission capacity and implementing market-based spatial segmentation – a choice that has significant implications for the goal of achieving wholesale price convergence across the European interconnected grid.

Furthermore, the implementation of zonal or transnational locational pricing mechanisms introduces a significant policy trade-off. On one hand, these mechanisms provide the necessary locational signals for long-term generation and consumption investments, thereby restoring economic efficiency over time. On the other hand, the design of these mechanisms must be carefully balanced against national policy objectives. These objectives include the territorial harmonization of retail electricity tariffs and industrial strategies designed to steer the regional siting of energy-intensive sectors. Moreover, the existence of different zonal pricing structures raises fundamental concerns regarding the European Union's long-term goal of establishing a fully integrated wholesale electricity market primarily facilitated through cross-border interconnectors.

The growing development of renewable energies will increasingly require the storage and release of intermittent renewable electricity, which will necessitate the development of battery installations. Appropriate pricing for access to transmission and distribution networks can encourage the development of such storage facilities.

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Effects of institutional quality, agriculture, and industry on CO_2 emissions in Tunisia: Evidence from an ARDL approach

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Abstract

This paper investigates the impact of institutional quality, the agricultural and industrial sectors, as well as renewable and non-renewable energy consumption on CO_2 emissions in Tunisia, while accounting for institutional challenges and the energy transition. Using the Autoregressive Distributed Lag (ARDL) bounds testing approach for the period 1996-2023, the analysis explores the linear relationships between these variables and CO_2 emissions, incorporating the evolution of the country's economic and energy policies. The results show that, in the long term, non-renewable energy consumption and industrial added value significantly contribute to the increase in CO_2 emissions, whereas institutional quality plays a moderating role by influencing the trajectory of emissions. This suggests that improvements in governance and institutional frameworks could be instrumental in reducing CO_2 emissions. In the short term, non-renewable energy consumption, industrial added value, and agriculture emerge as key drivers of rising emissions, although institutional quality acts as a stabilizer, mitigating fluctuations and facilitating adjustments to past imbalances. This study highlights the complex interactions among institutional, economic, and energy policies and their effects on the environment, emphasizing the importance of strengthening institutions to support a sustainable energy transition.

Keywords: agriculture, ARDL model, CO_2 emissions, institutional quality, nonrenewable energy, renewable energy, sustainable development.

JEL classification: B15, C22, P18, Q01, Q1, Q2, Q28

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1. Introduction

Combating CO_2 emissions constitutes a major global challenge, necessitating robust institutional quality to effectively frame and implement environmental policies. Institutions play a pivotal role in the implementation of sustainable measures. Nonetheless, divergences persist regarding the approaches adopted. Developed countries primarily rely on technological innovation, whereas developing nations favour immediate solutions. sometimes to the detriment of long-term environmental objectives. These issues are further exacerbated by economic inequalities, geopolitical tensions, and resistance to change all of which undermine the effectiveness of climate policies and underscore the need for profound institutional reforms.

In Tunisia, the quality of environmental institutions has undergone significant development since the 1980s. The establishment of the Ministry of the Environment in 1989, the adoption of the Environmental Code in 1991, and the creation of the National Agency for Environmental Protection (ANPE) laid the groundwork for a structured institutional framework. Tunisia's international commitment to environmental issues was further strengthened by its participation in the Rio Earth Summit in 1992, followed by the launch of the National Environmental Action Plan in 1995. More recently, ambitious initiatives such as the National Strategy for Sustainable Development (SNDD 2016-2030) and the National Climate Change Strategy (PNCC) reflect the country's determination to pursue a sustainable development trajectory.

Despite this progress, numerous challenges remain; institutional shortcomings, budgetary constraints, and limited coordination between public and private actors. These limitations hinder the effectiveness of environmental policies, despite the efforts undertaken. In 2023, CO_2 emissions reached 32.79 million tons, compared to 9.50 million in 1980, an average annual growth rate of 2.92%. Per capita emissions also rose to a record level of 2.7 tons, reflecting the expansion of industrialisation, the predominance of fossil fuels, and intensive agricultural practices. This trend is largely driven by the dependence of the industrial and agricultural sectors on non-renewable energy sources, despite efforts towards energy diversification.

At present, Tunisia's environmental priorities include the energy transition, waste management, and climate change adaptation. However, the success of these transitions will depend to a large extent on a significant improvement in environmental governance. It is within this context that the present study is situated. Employing an Autoregressive Distributed Lag (ARDL) model, this research examines the impact of institutional quality, as well as the agricultural, industrial, and energy sectors, on CO_2 emissions in Tunisia. The objective is to provide robust empirical evidence to advise the formulation of targeted and sustainable environmental policies.

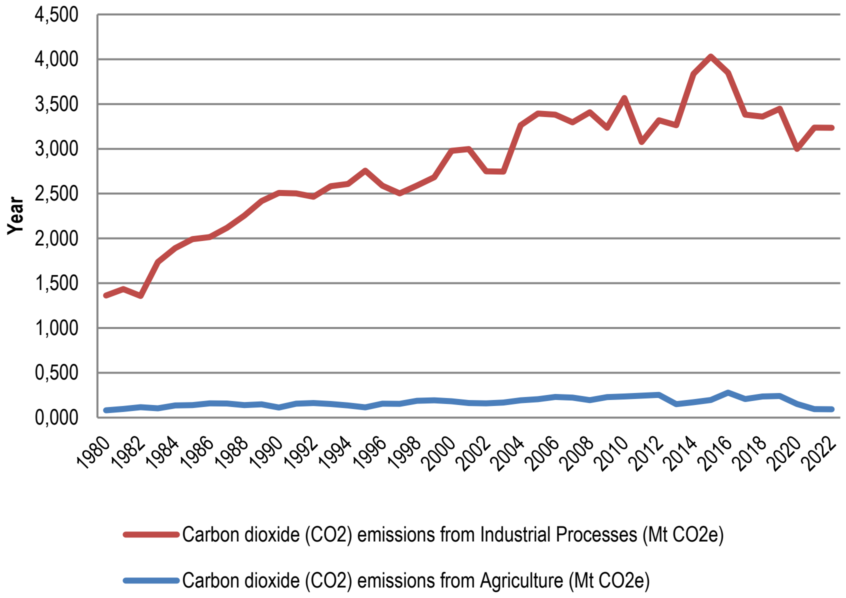
2. Tunisia's environmental challenges: Institutional quality and the agricultural and industrial sectors

A growing debate highlights the key role of institutional quality in the energy transition towards renewable sources and the improvement of environmental quality. This debate particularly handles energy-intensive sectors such as industry and agriculture, which remain largely dependent on fossil fuels. The New Institutional Economics (NIE) emphasises the importance of effective institutions and rigorous governance to ensure the success of reforms and sustainable growth (Chtourou, 2004).

Since the 1980s, Tunisia has made renewable energy a strategic priority, placing it at the core of its energy efficiency policy. The country strengthened its legal and institutional framework with the establishment of the Ministry of the Environment in 1989, the creation of the National Agency for Environmental Protection (ANPE) in 1988, and the adoption of the Environmental Code in 1991. On the international stage, Tunisia committed itself at the 1992 Earth Summit in Rio and launched a National Environmental Action Plan in 1995. More recently, environmental policy has been reinforced by the framework law No. 2020-72 on waste management, the National Climate Change Strategy (PNCC, 2021), and a target of 30% renewable energy in the national energy mix by 2030. Reforestation campaigns were also carried out in 2023.

The agricultural and industrial sectors accounted for 32.98% of Tunisia's GDP in 2023, with agriculture representing 9.47% and industry 23.51%. These sectors present significant environmental challenges, including intensive agricultural practices, high energy consumption, and polluting industrial emissions. According to Figure 1, agricultural CO_2 emissions increased until 2016 before beginning to decline, while industrial emissions rose in parallel with national energy consumption until 2019.

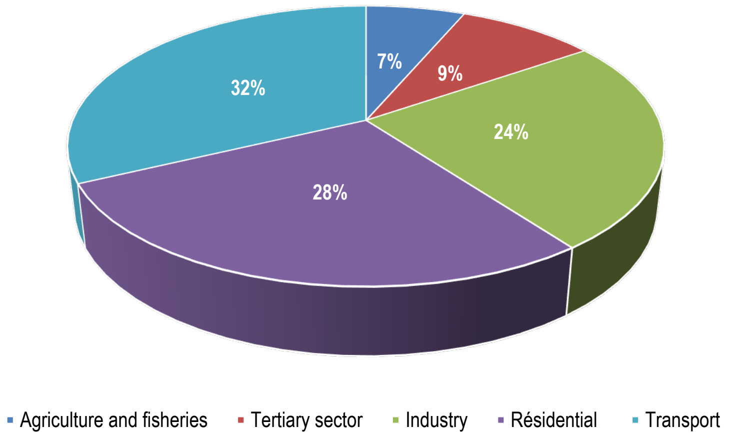
Figure 1 – Evolution of CO_2 emissions in the agricultural and industrial sectors



Source: WDI

In 2023, the combined energy consumption of the agricultural and industrial sectors accounted for 30.8% of the country's final energy demand (see Figure 2).

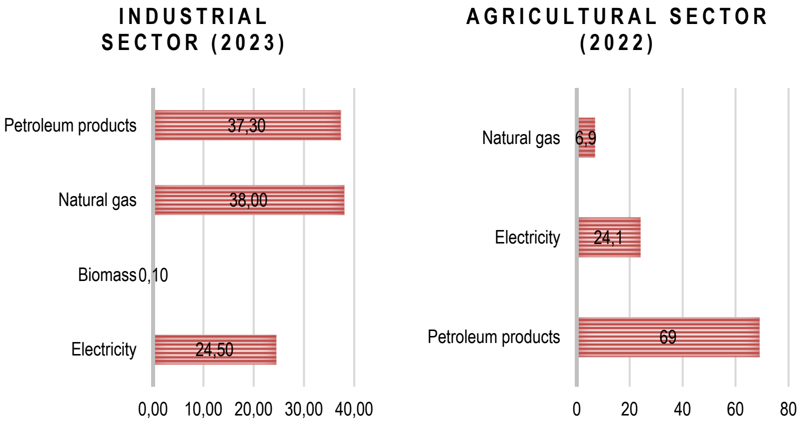
Figure 2 – Structure of final consumption by sector in 2023



Source: ANME[1]

The industrial sector, which is particularly energy-intensive, relies mainly on natural gas (38%), petroleum products (37.3%), and electricity (24%) (Figure 3). Agriculture primarily consumes petroleum products (69%) and electricity (24%), with a growing share of photovoltaic energy used for water pumping.

Figure 3 – Structure of final consumption in agriculture and industry by energy type



Source: ANME

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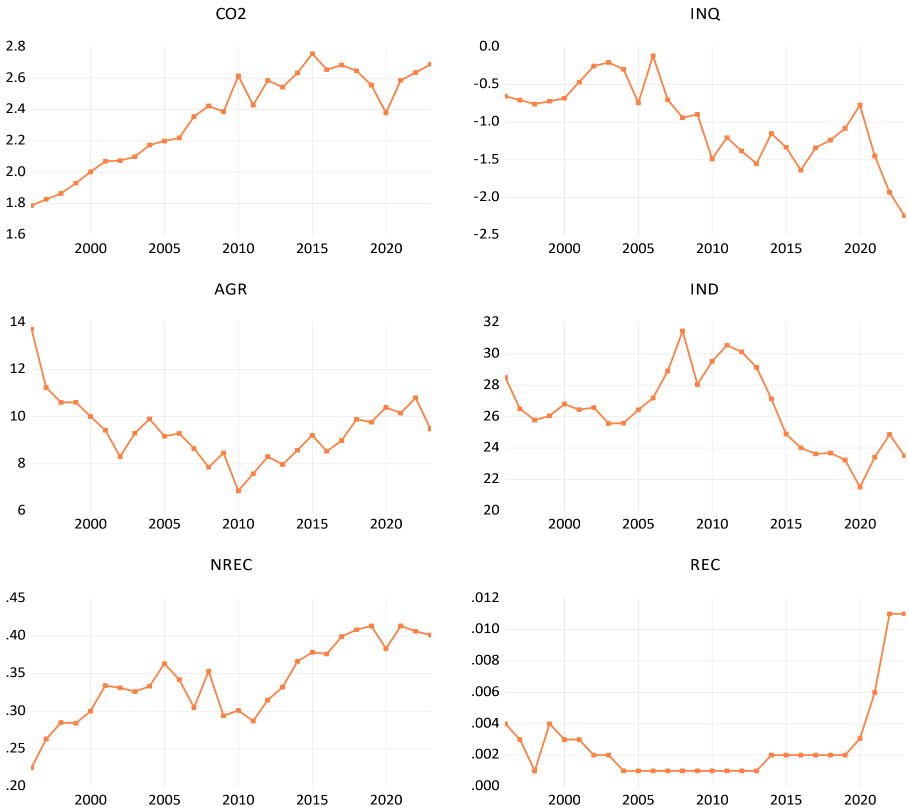
[1] ANME: The National Agency for Energy Management.

The share of renewable energy remains marginal (0.8% in 2022), reflecting structural constraints in investment and regulation. Figure 4 highlights a decline in institutional quality since 2010, which has hindered the effective implementation of environmental policies. In conclusion, Tunisia must strengthen its governance and improve coordination between public and private players in order to successfully achieve the energy transition, fully integrating the agricultural and industrial sectors into this process.

The Tunisian industrial sector, which accounts for nearly 24% of final energy demand, is one of the country's main energy consumers, particularly in the cement, chemical, metallurgy, and agri-food industries. This sector relies primarily on natural gas (38%), petroleum products (37.3%), and electricity (24%). To address energy and environmental challenges, Tunisia has implemented several policies aimed at modernising industrial processes, improving energy efficiency, and integrating renewable energy sources.

Figure 4 – Evolution of variables from 1996 to 2023



Source: Author's calculation (2025)

However, the decline in institutional quality since 2010 has undermined the effectiveness of these policies. Graphical data reveal a correlation between CO_2 emissions, the energy structure of the industrial sector, and the country's environmental governance.

3. Literature review

The effects of institutional quality, the agricultural and industrial sectors, as well as the energy sector, on CO_2 emissions in Tunisia have been extensively examined through recent studies employing advanced econometric approaches. For instance, Gharbi et al. (2025) apply the ARDL model to the period 1988-2021 and demonstrate that tourism and industrialisation exacerbate CO_2 emissions, while renewable energy and capital formation contribute to their reduction. Comparative studies confirm these dynamics. Amin and Rahman (2024) highlight that industrialisation increases emissions in developing countries, whereas the agricultural sector tends to mitigate them. A similar trend is observed in Vietnam, where Raihan (2023) finds that economic growth and rising energy consumption drive emissions upwards, while agricultural added value helps reduce them.

Other studies stress the role of renewable energy and sustainable agricultural practices in reducing CO_2 emissions, although results vary across national contexts (Chaouali et al., 2023; Waheed et al., 2022). In Tunisia, several studies identify specific policy levers. Talbi et al. (2022) emphasise the importance of energy efficiency in the industrial sector. Similarly, Ben Jebli and Ben Youssef (2019), as well as Farhani (2014), underline the need to promote renewable energy and implement sustainable energy policies. An analysis of Tunisian data over the period 2000-2022 reveals a general increase in CO_2 emissions, with a slight decline after 2010 followed by a recent rebound, correlated with the growing consumption of non-renewable energy. In this context, Saadaoui and Chtourou (2022) employ an ARDL model to investigate the links between institutional quality, financial development, and renewable energy consumption, highlighting the importance of sustainable financial mechanisms.

Finally, several studies confirm the central role of institutional quality in reducing CO_2 emissions (Saboori et al., 2019; Azam, 2020; Salman et al., 2019). Khan et al. (2023) examine the combined effect of urbanisation and institutional quality, stressing the moderating role of government effectiveness. Overall, these studies illustrate the complex interactions between economic development, industrialisation, agriculture, and energy consumption, and advocate the implementation of integrated policies that promote renewable energy, energy efficiency, and sustainable agricultural practices in order to reduce Tunisia's carbon footprint.

4. Materials and methods

4.1. Data description

This study investigates the influence of socio-economic variables on CO_2 emissions in Tunisia, based on an annual time series covering the period from 1996 to 2023.

The variables considered in this study include per capita CO_2 emissions and institutional quality (INQ). Institutional quality consists of six indicators, namely: corruption control, government effectiveness, political stability and absence of violence or terrorism, regulatory quality, law rules, and voice and accountability. These indicators are combined using principal component analysis (PCA) to build a complex index (INQ). Other key variables incorporated into the analysis are agricultural value added (AGR), industrial value added (IND), non-renewable energy consumption (NREC), and renewable energy consumption (REC). To facilitate the interpretation of the results, all variables are expressed in natural logarithms. This transformation allows the interpretation of coefficients in percentage terms i.e., elasticities thus offering a clearer understanding of the relative impact of each variable on CO_2 emissions. The data are obtained from two primary sources, namely the World Development Indicators (WDI) and the U.S. Energy Information Administration (EIA). All simulations were conducted using the EViews 12 software package. Table 1 presents the definitions of the variables, data sources, and the units of measurement used in the analysis. In addition, Table 2 provides descriptive statistics for the variables, including the mean, standard deviation, and minimum and maximum observed values.

Table 1 – Description of the variables used

Variables	Abbreviations	Unit of Measurement	Source
CO_2 emissions	CO_2	(Tonnes per capita)	WDI[2]
Value added of agriculture (agriculture, forestry and fisheries)	AGR	(% of GDP)	
Value added of industry (industry including construction)	IND		
Institutional quality	INQ	Index	
Renewable energy consumption	REC	(QBTU)[3]	EIA[4]
Non-renewable energy consumption	NREC		

The descriptive statistics reveal significant variability among the variables under study. Per capita CO_2 emissions (LogCO2) have a mean of 0.846 with a standard deviation of 0.132, ranging from a minimum of 0.581 to a maximum of 1.013. Agricultural added value (Log AGR) shows a mean of -2.375 and a standard deviation of 0.139, with extreme values ranging from -2.681 to -1.987. Industrial added value (LogIND) has a mean of -1.336, a standard deviation of 0.094, a minimum value of -1.537, and a maximum of -1.157. Institutional quality (LogINQ) displays greater variability, with a mean of 0.653, a standard deviation of 0.302, and values ranging from -0.280 to 1.058.

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[2] WDI: World Development Indicators.

[3] QBTU: quadrillion de British Thermal Units.

[4] EIA: The U.S Energy Information Administration

Table 2 – Descriptive statistics

Variables	LogCO2	Log AGR	Log IND	Log INQ	Log NREC	Log REC
Mean	0.846	-2.375	-1.336	0.653	-1.090	-6.217
Median	0.877	-2.376	-1.330	0.732	-1.098	-6.214
Maximum	1.013	-1.986	-1.156	1.058	-0.884	-4.509
Minimum	0.581	-2.681	-1.536	-0.280	-1.491	-6.907
Std. Dev.	0.132	0.139	0.094	0.302	0.153	0.718
Skewness	-0.580	0.344	-0.004	-1.157	-0.524	0.878
Kurtosis	2.046	3.869	2.361	4.548	2.844	3.108
Jarque-Bera	2.633	1.435	0.476	9.047	1.313	3.618
Probability	0.267	0.487	0.788	0.010	0.518	0.163
Sum	23.693	-66.501	-37.418	18.301	-30.528	-174.096
Sum Sq. Dev.	0.473	0.523	0.239	2.476	0.637	13.940

Source: Author's calculation (2025)

Non-renewable energy consumption (LogNREC) has a mean of -1.090, with a standard deviation of 0.153, and values ranging from -1.492 to -0.884. Finally, renewable energy consumption (LogREC) exhibits the greatest variability, with a mean of -6.218, a standard deviation of 0.718, a minimum of -6.908, and a maximum of -4.510. These results highlight notable differences in the distribution and magnitude of variations across the different variables.

5. Modelling and methodological framework

This study aims to analyse the relationship between CO_2 emissions ($LogCO_2$), institutional quality (LogINQ), the added value of the agricultural sector (LogAGR), the added value of the industrial sector (LogIND), renewable energy consumption (LogREC), and non-renewable energy consumption (LogNREC), based on data for Tunisia covering the period 1996–2023. Drawing on the methodologies proposed in previous studies (Çobanoğulları 2024; Saadaoui and Chtourou 2022; Rauf et al. 2018; Apergis et al. 2018; Zaidi and Saidi 2018; Cherni and Essaber-Jouini 2017) and taking into account the specific characteristics of our dataset, the most appropriate approach selected is the Autoregressive Distributed Lag (ARDL) model with bounds testing for cointegration, as introduced by Shin and Pesaran (1999) and formalised by Pesaran et al. (2001).This model allows a rigorous assessment of both short- and long-term dynamics between CO_2 emissions, institutional quality, the performance of the agricultural and industrial sectors, and the various forms of energy consumption in Tunisia. The adopted ARDL model is presented in equations (1) and (2).

$$\text{Log CO2} = f(\text{Log INQ}, \text{Log AGR}, \text{Log IND}, \text{Log NREC}, \text{Log REC}) \quad (1)$$

$$\begin{aligned}\text{Log CO2}_t = {} & \alpha + \beta_1 \text{Log INQ}_t + \beta_2 \text{Log AGR}_t + \beta_3 \text{Log IND}_t \\ & + \beta_4 \text{Log NREC}_t + \beta_5 \text{Log REC}_t + \varepsilon_t \end{aligned} \quad (2)$$

In equation (2), where t represents the years from 1993 to 2023, LogCO2 denotes the logarithm of carbon dioxide emissions, LogINQ the logarithm of institutional quality, LogAGR the logarithm of agricultural value added, LogIND the logarithm of industrial added value, LogNREC the logarithm of non-renewable energy consumption, and LogREC the logarithm of renewable energy consumption. The coefficients are denoted by β, α represents the constant term, and ε_t denotes the error term.

Table 3 – Findings of the ADF and PP tests

Variables	**ADF**				**PP**			
	(Level)		**(First Difference)**		**(Level)**		**(First Difference)**	
	t-stat	**p-val**	**t-stat**	**p-val**	**t-stat**	**p-val**	**t-stat**	**p-val**
Log CO2	1,648	0,972	-7,648 ***	0,000	2,075	0,988	-7,189 ***	0,000
Log AGR	-3,332 **	0,023	-6,297 ***	0,000	-3,332 **	0,023	-6,393 ***	0,000
Log IND	-3,332 **	0,023	-4,651 ***	0,005	0,618	0,843	-4,716 ***	0,000
Log INQ	-1,124	0,230	-4,885 ***	0,003	-1,120	0,230	-4,598 ***	0,001
Log REC	-0,522	0,480	-6,895 ***	0,000	-0,522	0,480	-6,759 ***	0,000
Log NREC	-1,795 *	0,069	-6,608 ***	0,000	-1,795 *	0,069	-5,969 ***	0,000
Critical values	(1%)	-2,656	(1%)	-3,711	(1%)	-2,656	(1%)	-3,711
	(5%)	-1,954	(5%)	-2,981	(5%)	-1,954	(5%)	-2,981
	(10%)	-1,609	(10%)	-2,629	(10%)	-1,609	(10%)	-2,629

Note: ***, ** and * indicate statistical significance at 1 %, 5 % and 10 % respectively.

Source: Author’s calculation (2025)

An ARDL model can be employed because the variables are either I (0) or I (1), which constitutes a fundamental condition for the application of the ARDL approach. However, it is necessary to verify the presence of cointegration among the variables in order to confirm the existence of a long-term relationship prior to estimating the model. If cointegration is detected, the ARDL model will prove to be an appropriate tool for analysing both the short- and long-term dynamics among the variables.

6. The ARDL approach and bounds test

The Autoregressive Distributed Lag (ARDL) model, introduced by Shin and Pesaran (1999) and further developed by Pesaran et al. (2001), enables the analysis of simple cointegration relationships. One of its main advantages lies in its flexibility:

it allows a combination of variables that are stationary at level [I(0)] and at first difference [I(1)], without requiring that all variables be integrated of the same order. Due to this methodological flexibility, the ARDL approach is widely employed in empirical studies, including the present research. It constitutes an effective method for examining long-term relationships between variables. Consequently, equation (2) can be reformulated as an ARDL model with a constant term, as presented in equation (3) below:

$$\begin{aligned}\Delta \mathrm{Log\,CO2}_t = \beta_0 &+ \sum_{i=1}^{P} \beta_1 \Delta \mathrm{LogCO2}_{t-i} + \sum_{i=0}^{q} \beta_2 \Delta \mathrm{LogINQ}_{t-i} \\ &+ \sum_{i=0}^{q} \beta_3 \Delta \mathrm{LogAGR}_{t-i} + \sum_{i=0}^{q} \beta_4 \Delta \mathrm{LogIND}_{t-i} \\ &+ \sum_{i=0}^{q} \beta_5 \Delta \mathrm{LogNREC}_{t-i} + \sum_{i=0}^{q} \beta_6 \Delta \mathrm{LogREC}_{t-i} \\ &+ \beta_7 \mathrm{LogCO2}_{t-i} + \beta_8 \mathrm{LogINQ}_{t-1} + \beta_9 \mathrm{LogAGR}_{t-1} \\ &+ \beta_{10} \mathrm{LogIND}_{t-1} + \beta_{11} \mathrm{Log\,NREC}_{t-1} \\ &+ \beta_{12} \mathrm{Log\,REC}_{t-1} + \varepsilon_t \end{aligned} \qquad (3)$$

The Bounds test is used to determine whether a long-run relationship exists between the variables. The alternative hypothesis ($\beta_7 \neq \beta_8 \neq \beta_9 \neq \beta_{10} \neq \beta_{11} \neq \beta_{12}$)contradicts the null hypothesis ($\beta_7 = \beta_8 = \beta_9 = \beta_{10} = \beta_{11} = \beta_{12}$), which implies no cointegration. The null hypothesis is rejected if the estimated F-statistic exceeds the upper bound critical value I(1) for the number of explanatory variables (k), as provided by Pesaran et al. Conversely, the null hypothesis cannot be rejected if the F-statistic falls below the lower bound critical value I(0). The F-statistic indicates inconclusive evidence of cointegration if it lies between the I(0) and I(1) bounds. Alternative critical values for I(0) and I(1), better suited to small sample sizes, have been proposed by Narayan (2005).

The optimal lag lengths p and q in equations (3) and (4) are determined using model selection criteria, such as the Akaike Information Criterion (AIC) or the Schwarz Information Criterion (SIC). The optimal values of p and q correspond to the minimum information criterion value, whether AIC or SIC. Additionally, the model residuals should not exhibit serial correlation. The model with the highest R^2 value or the lowest information criterion is considered to provide the best estimation. Finally, the following equation estimates the short-run dynamics of the ARDL model, also referred to as the error correction model:

$$
\begin{aligned}
\Delta \mathrm{LogCO2}_t = \beta_0 &+ \sum_{i=1}^{P} \beta_1 \Delta \mathrm{Log\ CO2}_{t-i} + \sum_{i=0}^{q} \beta_2 \Delta \mathrm{Log\ INQ}_{t-i} \\
&+ \sum_{i=0}^{q} \beta_3 \Delta \mathrm{LogAGR}_{t-i} + \sum_{i=0}^{q} \beta_4 \Delta \mathrm{LogIND}_{t-i} \\
&+ \sum_{i=0}^{q} \beta_5 \Delta \mathrm{LogNREC}_{t-i} + \sum_{i=0}^{q} \beta_6 \Delta \mathrm{Log\ REC}_{t-i} \\
&+ \beta_7 \mathrm{Log\ CO2}_{t-1} + \beta_8 \mathrm{Log\ INQ}_{t-1} + \beta_9 \mathrm{LogAGR}_{t-1} \\
&+ \beta_{10} \mathrm{Log\ IND}_{t-1} + \beta_{11} \mathrm{Log\ NREC}_{t-1} \\
&+ \beta_{12} \mathrm{Log\ REC}_{t-1} + \lambda \mathrm{ECT}_{t-1} + \varepsilon_t
\end{aligned} \tag{4}
$$

The speed of adjustment parameter, also known as the error correction term coefficient ($\mathrm{ECT}_{(t-1)}$) λ in equation (4), determines how quickly the series return to long-run equilibrium. The model is subjected to diagnostic tests to assess its validity, including tests for serial correlation, normality, functional form, and heteroscedasticity. Brown et al. employed stability tests such as the Cumulative Sum (CUSUM) and the Cumulative Sum of Squares (CUSUMSQ) to examine whether the coefficients in the graphical representations remain stable over time.

7. Empirical results

The main objective of this study is to provide empirical evidence on the impact of institutional quality (Log INQ), agricultural added value (Log AGR), industrial value added (Log IND), non-renewable energy consumption (Log NREC), and renewable energy consumption (Log REC) on carbon dioxide emissions (Log CO_2). The analysis follows several methodological steps: first, the application of the bounds testing approach to cointegration to examine the relationships among the variables across the full dataset; second, the presentation of both long-run and short-run estimation results; and finally, the assessment of model stability using the Cumulative Sum (CUSUM) and the Cumulative Sum of Squares (CUSUMSQ) tests.

The results of the bounds test for cointegration, presented in Table 5, show that the null hypothesis of no cointegration is strongly rejected. Indeed, the F-statistic, which reaches a value of 7.465, significantly exceeds the upper critical bounds (I (1)) at all conventional significance levels, thus confirming the existence of a long-run relationship among the variables under study. This cointegration relationship indicates that the variables are linked in the long term. Consequently, the use of an error correction model (ECM) is justified to analyse both the short-run dynamics and the long-run equilibrium relationships among these variables.

Table 5 – Results of the bounds testing approach to cointegration

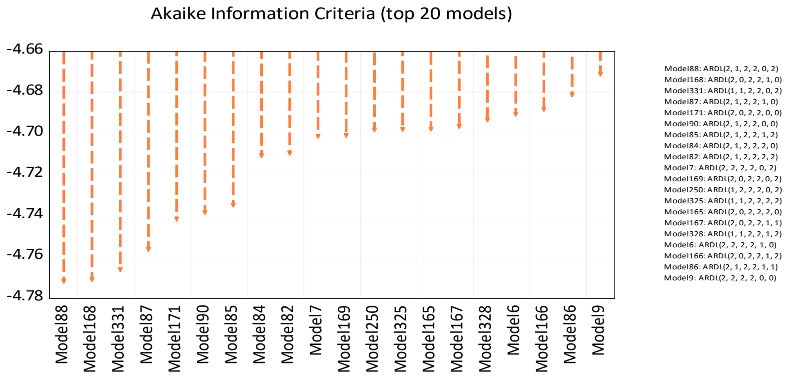
F-Bounds Test				
F-Bounds Test	Null Hypothesis: No levels relationship			
Test Statistic	Value	Signif.	I(0)	I(1)
Asymptotic: n=1000				
F-statistic	7.465	10%	2.08	3
K	5	5%	2.39	3.38
		2.50%	2.7	3.73
		1%	3.06***	4.15***
ActualSample Size	27	Finite Sample: n=35		
		10%	2.331	3.417
		5%	2.804	4.013
		1%	3.9***	5.419***
		FiniteSample: n=30		
		10%	2.407	3.517
		5%	2.91	4.193
		1%	4.134***	5.761***

Note: ***, ** and * indicate statistical significance at 1 %, 5 % and 10 % respectively.

Source: Author's calculation (2025)

The analysis reveals that, in Tunisia, there exists a significant long-run relationship between CO_2 emissions and institutional quality (INQ), agricultural added value (AGR), industrial added value (IND), non-renewable energy consumption (NREC), and renewable energy consumption (REC). Table 6 presents the long-run and short-run estimation results of the ARDL model (2,1,2,2,0,2), which was selected as the optimal model due to its lowest Akaike Information Criterion (AIC) value, as shown in Figure 5.

Figure 5 – Selection of optimal lag



Source: Author's calculation (2025)

In this analysis, CO_2 emissions serve as the dependent variable, explained by the following proxy variables: institutional quality (INQ), agricultural value added (AGR), industrial value added (IND), non-renewable energy consumption (NREC), and renewable energy consumption (REC).

Table 6 – Long-run and Short-run ARDL estimates

Long-run estimates				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob**
Log INQ	-0.234***	0.052	-4.510	0.000
Log AGR	0.116	0.215	0.539	0.600
Log IND	1.241**	0.468	2.652	0.022
Log NREC	0.892***	0.152	5.848	0.000
Log REC	0.007	0.022	0.343	0.737
C	3.987**	1.326	3.005	0.012

Short-run estimates				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
D (Log CO2 (-1))	-0.171	0.105	-1.615	0.134
D (Log AGR)	0.195***	0.051	3.794	0.003
D (Log IND)	0.574***	0.092	6.211	0.000
D (Log IND (-1))	-0.528***	0.095	-5.517	0.000
D (Log NREC)	0.198***	0.045	4.346	0.001
D (Log NREC (-1))	-0.184**	0.065	-2.824	0.016
D (Log INQ_)	-0.097***	0.019	-5.021	0.000
D (Log INQ (-1))	0.063**	0.022	2.863	0.015
ECT (-1)	-0.630***	0.070	-8.986	0.000

Note: ***, ** and * indicate statistical significance at 1 %, 5 % and 10 % respectively.

Source: Author's calculation (2025)

Institutional quality (Log INQ) exhibits a negative and statistically significant relationship with carbon dioxide emissions in both the long and short run. In the long run, a 1% improvement in the institutional quality index leads to a reduction of about 0.234% in carbon dioxide emissions, whereas in the short run, an equivalent improvement reduces emissions by around 0.097%. These findings, conform with the studies of Sekrafi and Sghaier (2025), Wang et al. (2022), Hamrouni et al. (2025), and Abbas et al. (2025), and can be attributed to strengthened regulations, enhanced institutional mechanisms, and more effective governance.

These elements limit the use of highly carbon-intensive inputs in favour of less polluting alternatives in Tunisia. They illustrate the positive impact of improved governance on environmental protection: more effective anti-corruption measures, greater government efficiency, increased political stability, stricter regulations. Besides, enhanced adherence to the rule of law contribute to reducing polluting practices, enforcing environmental standards rigorously, and overseeing high carbon dioxide-emitting sectors more efficiently, particularly energy-intensive industries and fossil fuel-dependent activities. The negative effect of institutional quality on carbon dioxide emissions in Tunisia, observed both in the short and long term, is confirmed by Sekrafi and Sghaier (2025), who highlight a significant relationship between corruption control and environmental quality. This pattern is also clear in other emerging economies in Africa, North Africa, and the MENA region. It indicates that the beneficial impact of institutions on emissions reduction extends beyond the national context and reflects a regional dynamic in which institutional reforms support environmental transition.

However, these positive effects are contingent upon the robustness of institutional frameworks e.g. economic liberalisation since when they are absent they may exacerbate environmental degradation. Surveys in ten emerging economies (Brazil, China, India, Russia, South Africa, Turkey, Mexico, Thailand, Egypt, and South Korea) confirm that institutional quality directly reduces carbon dioxide emissions (Hamrouni et al., 2025), as do Wang et al. (2022) for a panel of twenty-four African countries. For the MENA region, Abbas et al. (2025) show that institutional improvement across 21 countries, including Egypt, Morocco, and Tunisia, is associated with a decline in emissions in both the short and long term, while Saboori et al. (2025) specify that the majority of institutional indices, except for political stability and absence of violence, also contribute to this reduction. These findings are reinforced by Haldar and Seth (2020) for thirty-nine developing countries, including Tunisia, and by Obobisa (2022) for twenty-five African countries, demonstrating that institutional consolidation promotes both emissions reduction and sustainable development. On the other side, Obobisa et al. (2022) observe that, in certain countries such as Morocco, Egypt, and South Africa, some institutions may raise emissions by favouring energy-intensive growth policies with limited environmental constraints.

Non-renewable energy consumption (Log NREC) exhibits a positive and statistically significant relationship with carbon dioxide emissions, both in the long and short run. In the long run, a 1% increase in non-renewable energy consumption leads to an increase of approximately 0.892% in carbon dioxide emissions. In the short run, an equivalent increase results in a rise of around 0.198% in emissions. This finding is in conformity with the results of Ben Jebli and Ben Youssef (2016), Aguir Bargaoui, S. & Amri Amamou, S. (2020), and Shahbaz et al. (2014). In Tunisia, oil and natural gas remain the primary energy sources, and their direct use contributes significantly to the high levels of air pollution.

Similarly, the industrial sector elasticity is positive, high, and statistically significant in both the long and short run. In the long run, a 1% increase in industrial added value leads to an increase of almost 1.241% in carbon dioxide emissions, while in the short run, an equivalent rise results in an increase of around 0.574%. This finding confirms the energy-intensive and carbon-heavy nature of Tunisia's industrial sector, notably including the construction industry, which remains largely dependent on fossil fuels. These observations conform to the conclusions of Dallali and Ben Jebli (2025) and Ghazouani (2019), who emphasise the significant impact of industrialisation on environmental degradation in Tunisia. Moreover, the energy structure of the industrial sector, dominated by natural gas (38%) and petroleum products (37%), reflects a persistent reliance on high-carbon sources. Thereby it explains the sector's substantial contribution to national carbon dioxide emissions.

In contrast, while agricultural added value is positive (0.116), it is not statistically significant in the long run, suggesting that the sector does not have a structural influence on carbon dioxide emissions in Tunisia, given its limited energy contribution. However, in the short run, a 1% increase in agricultural added value leads to a 0.195% rise in emissions. This reflects the immediate impact of intensive farming practices, such as the use of machinery and energy-intensive inputs. Consequently, agriculture appears to have a transitory effect on emissions, in line with its modest share of national energy consumption (6.4% in 2023). This observation aligns with the short-run findings of Ben Jebli and Ben Youssef (2016), though it diverges in the long run.

Renewable energy consumption (Log REC) has a positive, and yet very limited and statistically non-significant effect, on carbon dioxide emissions in Tunisia. This suggests that, despite efforts to develop solar, wind, and hydro capacities, their contribution to total energy consumption remains low (11.4% of final consumption) and is not enough to reduce emissions in the long run significantly. This situation reflects the country's economic context, where renewable energies have yet to constitute a substantial alternative to fossil fuels. These findings are in conformity with the studies of Chaouali et al. (2023), Ben Jebli and Belloumi (2017), Apergis et al. (2010), and Nguyen and Kakinaka (2019), which demonstrate that the impact of renewable energy consumption on environmental degradation depends on a country's level of economic development. While, it can effectively reduce carbon dioxide emissions in high-income countries; it may conversely contribute to environmental degradation in low-income countries. In the short run, renewable energy consumption (Log REC) does not appear to be a significant determinant of carbon dioxide emissions, reflecting its minimal immediate effect, as it has a lag of zero in the selected specification (2,1,2,2,0,2). Consequently, its impact on carbon dioxide emissions is immediate and is not captured in the short-run dynamics of the explanatory variables.

Finally, the coefficient of the error correction term (-0.63) reveals a rapid convergence towards the long-run equilibrium, highlighting the economy's capacity to adjust quickly to shocks. These findings suggest that, in the absence of structural policies aimed at greener industrialisation and an accelerated energy transition, Tunisia will remain vulnerable to the environmental pressures linked to its development model. Diagnostic tests applied to the ARDL model are essential for assessing the validity, reliability, and robustness of the empirical estimates. The results, presented in Table 7, confirm that the model does not suffer from major econometric issues.

Table 7 – Diagnostic test results

Test	F-Statistic	P-Value
Breusch-Godfrey Serial Correlation LM Test	0.366	0.703
Jarque-Bera Test	1.354	0.508
Breusch-Pagan-Godfrey-test	0.417	0.936
Arch-test	2.002	0.170
Ramsey rese-test	0.669	0.432
Chow break point-test	0.762	0.588

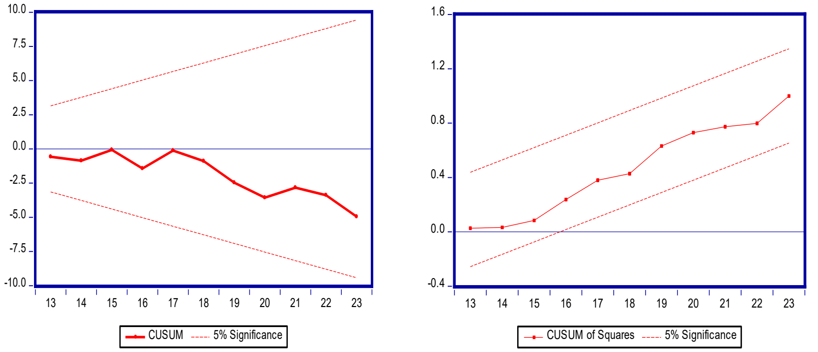
Note: ***, ** and * indicate statistical significance at 1 %, 5 % and 10 % respectively.

Source: Author's calculation (2025)

The Breusch-Godfrey test for residual autocorrelation yields an F-statistic of 0.366 with a p-value of 0.703, indicating no autocorrelation. The ARCH test produces a statistic of 2.002 (p = 0.170), showing no evidence of conditional heteroskedasticity. Furthermore, the Breusch-Pagan-Godfrey test yields a high p-value (0.936), confirming the homoscedasticity of the residuals. Residual normality is verified by the Jarque-Bera test, whose statistic of 1.354 with a p-value of 0.508 suggests that the errors follow a normal distribution. The Ramsey RESET test, with an F-statistic of 0.669 and a p-value of 0.432, confirms that the model is correctly specified. Finally, the Chow structural break test (F = 0.762; p = 0.588) reveals no structural instability in the model's coefficients. Taken together, these results indicate the robustness and reliability of the ARDL model employed.

The CUSUM and CUSUMSQ tests were conducted to determine whether any structural breaks exist in the time series, as illustrated in Figure 6. According to the results, the CUSUM (Cumulative Sum of Recursive Residuals) and CUSUMSQ (Cumulative Sum of Squared Recursive Residuals) statistics lie within the critical bounds at the 5% significance level, indicating that no significant structural break was detected during the study period.

Figure 6 – Stability assessment using the CUSUM and CUSUM of Squares tests



Note: ***, ** and * indicate statistical significance at 1 %, 5 % and 10 % respectively.

Source: Author's calculation (2025)

The CUSUM and CUSUM of Squares stability tests confirm the robustness of the model by showing that both its coefficients and the variance of its residuals remain stable over the analysed period. The CUSUM test, which assesses the stability of the estimated coefficients, indicates no major structural changes, as the curve remains within the 5% significance bounds. Similarly, the CUSUM of Squares test, used to detect possible variations in the variance of the residuals, reveals no significant instability. These results indicate that the model maintains a coherent and reliable structure over time, thereby reinforcing the validity of the estimates obtained and their relevance to the analysis conducted. Consequently, the absence of structural instability ensures that the relationships identified by the model remain robust and interpretable throughout the entire study period.

8. Conclusion and policy implications

The empirical analysis in this study has highlighted the impact of institutional quality, agricultural and industrial added value, as well as energy consumption (both renewable and non-renewable) on CO_2 emissions in Tunisia, both in the short and long term. The findings of this study indicate that institutional quality alone exhibits a negative relationship with CO_2 emissions, contributing to their reduction in both the short and long term. In contrast, the main factors drivers of increased CO_2 emissions over both periods are industrialisation and non-renewable energy consumption. However, the contribution of agriculture to CO_2 emissions is only short-term, reflecting the immediate effects of intensive farming practices, such as the use of machinery and energy-intensive inputs. This is due to the relatively low share of fossil fuel use in comparison to sectors such as industry and transport. The impact of renewable energy consumption remains negligible, largely due to the current insufficiency of renewable sources as a viable alternative to fossil fuels, as their share in total energy consumption remains too limited to achieve a substantial reduction in CO_2 emissions.

The results of this study indicate that institutional reforms in Tunisia can play a pivotal role in reducing carbon dioxide emissions. Indeed, corruption control ensures the efficient use of resources allocated to environmental protection and helps limit polluting practices. Government effectiveness facilitates the swift and coherent implementation of environmental policies, while political stability and the absence of violence or terrorism create a conducive environment for investment in clean technologies and low-carbon infrastructure. Regulatory quality establishes strict environmental standards and promotes sustainable economic practices. Moreover, the fact of adhering to the law rules ensures their effective enforcement and the sanctioning of perpetrators. Finally, citizen participation and democratic accountability (voice and accountability) encourage individuals and businesses to adopt environmentally responsible behaviours. Together, these institutional dimensions strengthen environmental regulations and enhance energy efficiency. Additionally, they promote the adoption of clean energy sources, and contribute to the sustainable reduction of carbon dioxide emissions.

These study findings have significant policy implications for Tunisia, and highlight the need to strengthen governance and institutional quality in order to achieve low-carbon sustainable development objectives. Priority recommendations include promoting environmentally-friendly agricultural and industrial practices, investing in modern energy infrastructures particularly solar energy, given the country's substantial solar potential as well as developing renewable energy sources and biomass. It is essential to ensure the strict implementation of environment standards, empower democratic institutions and the law rules, and preserve natural resources through rigorous anti-corruption measures. It is also vital to diversify energy sources, and improve national energy efficiency.

Policymakers should also boost Tunisian enterprises to adopt concrete measures so as to reduce pollution, rehabilitate and upgrade existing pollution-control facilities, and adopt clean technologies financed according to the value of environment investments. Awareness-raising among producers, firms, and citizens regarding the use of renewable energy and the reduction of polluting practices represents an additional lever for action. The Tunisian state must also issue and enforce regulatory directives effectively. For instance, emission quotas and mandatory filtration systems for the most polluting installation are supported by the Tunisian Pollution Control Fund (FODEP, 1995). Implementing these measures will contribute to reducing carbon dioxide emissions, expanding renewable energy use, and strengthening Tunisia's environment resilience. Future research could build on these findings by examining, in a more disaggregated manner, the various indicators of institutional quality and their effects on carbon dioxide emissions. Meanwhile, they might also incorporate further relevant variables such as transport, services, and tourism in the Tunisian context or in other developing countries.

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The impact of carbon and fossil fuel prices on renewable energy companies' stock prices: New evidence from piece-wise approach

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Abstract

This study aims to elucidate the relation between oil, gas, coal, carbon prices and the clean market index. We adopt a piece-wise linear approach and assume that each piece represents a unique structural mechanism. We utilize an optimization model that endogenously finds cut-off dates on non-stationary data along with the model coefficients for each period. Our findings highlight that the clean market index is positively related to stock market performance and negatively related to carbon and oil prices. The direction of the effects of gas and coal, on the other hand, are found to be alternating among the break periods. Moreover, predictor importance of the factors also changes through the timeline. Empirical evidence indicates that splitting the time series data into pieces according to their distinct structural characteristics improves the prediction performance and it is imperative to better understand the behavior of the renewable energy market. By doing so, we aim to provide insights for policy makers on how to utilize the leverage effect of financial markets to empower renewable energy companies.

Keywords: renewable energy companies, financial markets, carbon prices, fuel prices, structural break, piece-wise linear regression.

JEL classification: G11, G15, G17

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1. Introduction

Incidents such as wildfires, abrupt hailstorms, and the occurrence of the hottest days in July vividly manifested the severe ramifications of global warming. UN Secretary-General António Guterres has characterized this epoch as the termination of the global warming era and the commencement of a 'global boiling' era (the Guardian, 2023). The sixth assessment report released by the Intergovernmental Panel on Climate Change (IPCC) in 2021 asserts that climatic changes are irreversible, yet concerted endeavors to mitigate global warming can shape the future and avert more adverse consequences. Greenhouse gases, particularly carbon dioxide, constitute the primary

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catalyst for global warming, underscoring the imperative of decarbonizing the economy as a pivotal measure in combating climate change. A low-carbon economy is defined as an economic system that minimizes the emission of greenhouse gases, specifically carbon dioxide. The key sector in facilitating the transition to a low-carbon economy is the energy sector. The International Energy Agency (IEA) report of 2022 states that the energy sector surpasses the industry, transportation, and building sectors in global carbon dioxide emissions. According to the report, notably, the energy sector exhibited the most significant increase in emissions, registering a 1.8% upsurge to an all-time high in 2022, compared to previous years primarily attributed to emissions emanating from electricity and heat production. Clean energy enterprises, utilizing renewable resources such as solar, wind, hydropower, and biofuel, represent the exclusive alternative to fossil fuel-based energy production and are integral to the shift towards sustainable energy systems. The transition to renewable energy assumes heightened significance for the European Union (EU), particularly considering geopolitical events, such as Russia's invasion of Ukraine, which underscored vulnerabilities associated with dependence on Russian natural resources. According to the IEA's 2022 report, renewable energy production has attained record levels, constituting 90% of the growth in global total electricity generation. Consequently, numerous studies in literature have examined the role of clean energy companies in the energy market, scrutinizing their financial performance and the factors influencing their stock performance. Despite this, there remains a notable gap in the literature concerning the insufficient exploration of carbon prices as a determinant of clean energy companies' performance, especially within the European market. Notably, the European Union stands out as the world's most ambitious region in terms of emission reduction and combating climate crises, further underscored by the European Emissions Trading System's status as the largest carbon market globally.

The Emission Trading System (ETS) stands out as a pivotal market-oriented mechanism for mitigating carbon emissions. The inception of the European Union Emission Trading System (EU ETS) in 2005 marked a concerted effort to impose a cost on carbon emissions for energy companies throughout its four sequential phases. Across each phase, the European Commission, drawing from insights gained in preceding periods, introduces innovations designed to enhance market efficiency and further curtail emission volumes. The fourth and concluding phase witnessed the implementation of the Market Stability Reserve (MSR) mechanism, strategically devised to prevent entities, particularly those within the energy sector with elevated carbon emissions, from accumulating excess carbon permits. Through this mechanism, the European Commission aims to enhance market stringency, precluding pronounced declines in carbon prices by mitigating emission allowance surpluses. Consequently, carbon permits, constituting a significant cost for energy enterprises, are anticipated to wield substantial influence over the energy market by the year 2030. A robust association is expected between the financial performance of clean energy firms, exempt from carbon permit expenses, and carbon prices, particularly within the European context.

This study seeks to investigate the influence of carbon prices, fossil fuel prices, and stock market index on European clean energy companies. We employ an optimization model based on dynamic programming that distinguishes the structural mechanism shifts through the timeline and offers cut-off dates of these shifts. The model uses a piece-wise linear regression approach and finds the cut-off dates of the structural breaks by minimizing the total squared errors. Although dynamic programming approaches are computationally challenging and not time efficient, we utilize a heuristic approach that is grounded on column generation, so that the model approach is even applicable to very long time series data. The contribution of this study is three-fold. First, it determines the cut-off dates of structural shifts endogenously with a rigorous modelling study within reasonable time limits. Second, the model coefficients of piecewise linear regression provide interpretability as opposed to the most machine learning algorithms that offer a black box representation. Third, we study the results further with predictor importance graphs for different numbers of structural breaks (i.e. 3 and 4), where the relative importance of the factors is presented. This enables policy makers to unveil the behavioral change in stock market index on European clean energy companies as a function of carbon and fossil fuel prices on a timeline. Moreover, the modelling approach we offer is versatile such that the users can impose different numbers of structural breaks that are defined according to the granularity level they prefer. Therefore, they can evaluate the effectiveness of the interventions that have been applied at a particular time frame or in a short period of time.

The subsequent structure of the study is outlined as follows: In the second section, existing studies examining the factors influencing the stock performance of renewable energy companies are summarized, and the gaps in the literature are identified. The third section elucidates the data utilized in the study, providing an explanation of the data and sharing summary statistics. The fourth section details the statistical background of the methodology employed in the study. The fifth section presents empirical findings and discusses the implications of the results. The final section summarizes the findings and presents policy recommendations.

2. Literature review

There are only few studies on the relation between clean energy companies and carbon prices. The existing literature mainly focuses on the impact of fossil fuel prices on the clean energy companies globally by using WilderHill Clean Energy Index (ECO) and there is no agreement on how the fossil fuel market and clean energy market is related. The pioneer study in the literature by Henriques & Sadorsky (2008) examines the clean energy market and its relationship with technology and oil market. This study documents that interest rates, oil prices and stock market performance of technology firms have impact over clean energy stocks although the effect of oil prices is not that strong as expected. Maghyereh et al. (2019) employ MGARCH model to analyze the return and risk transmission between oil prices, clean energy and clean energy technology markets. While they find strong relations between renewable energy and clean energy technology markets, return transmission from oil to clean energy market exists in the long run. Inchauspe et al. (2015) apply the state-space model with time-varying coefficients and use monthly data for the period August 2001 to February 2014. They find that MSCI World index and technology stock index is more influential on the stock market performance of clean energy firms. The results reveal weak impact of oil prices on the stock returns of renewable energy companies, but they suggest that the influence of oil is more pronounced since 2007. Ferrer et al. (2018) analyze the frequency and time dynamics of connectedness among clean energy, conventional energy and technology stocks and oil prices along with some other financial indicators in the period from January 2003 to September 2017 in the USA. The results of the study suggest no significant impact of oil prices on the stock market performance of clean energy companies and that the clean energy market and technology market are connected. From January 2003 to June 2015, Bondia et al. (2016) apply non-linear cointegration tests to analyze the relation between clean energy stocks and technology stocks, oil prices and interest rates and they ascertain long run relation among the variables. They also find short run causality running from technology stocks, oil prices and interest rates to clean energy stocks but that no causality exists in the long run from the variables to clean energy stocks. Sadorsky (2012a) applies multivariate GARCH model using data ranging from January 2001 to December 2010. It is found that there is dynamic conditional correlation between clean energy companies and oil prices, but that technology market is more influential on the renewable energy. Nasreen et al. (2020) use FIGARCH-a-cDCC model and FIGARCH-DECO model over the period December 2000 to June 2018 and document the strong connection between technology and clean energy market and underline that oil is not a major driver of clean energy stock prices. Between November 2003 to March 2018, Elie et al. (2019) analyze if oil and gold are effective hedge for clean energy stocks with blended copulas approach and they find that these commodities are only weak hedges for the clean energy indices. About the riskiness of clean energy market, Sadorsky (2012b) find that increasing oil prices has positive effect on the systematic risk of renewable energy company stocks between the years 2001-2007.

There is a body of literature which is in line with the expectations and suggests that the oil price is an important factor explaining the financial risk of clean energy stocks. Dutta (2017) examines how the risk of clean energy stocks is affected by the oil price volatility between May 2007 and June 2016. The results demonstrate that the volatility of clean energy stock return is strongly related with the oil price volatility. Managi and Okimoto (2013) apply MSVAR considering structural changes and asymmetry for the period January 2001 to February 2010 and suggest that clean energy market is positively affected by both the technology stocks and oil prices. For the period May 2005 to April 2015, Ahmad (2017) finds that clean energy and technology stocks mostly move in the same direction, so they are not good hedge and that oil is better in hedging for clean energy stocks. Kocaarslan and Soytas (2019) consider the asymmetric impact of oil prices and apply NARDL approach between January 2004 to January 2018. They document that an increase in oil prices with speculative attacks positively affects the clean energy stocks in the short run but that the impact of rising oil prices is adverse in the long run. About the impact of natural gas prices and coal prices, there are limited number of studies. Fu et al. (2022) evaluate the impact of global financial stress, oil price, gold prices, and natural gas prices on the global renewable energy stocks by utilizing quantile autoregressive distribute lag approach between January 2008 and April 2021. They ascertain that, under bullish market conditions, oil prices exhibit an adverse effect on the performance of renewable energy stocks, while natural gas prices demonstrate a favorable impact on the clean energy stocks in bearish market conditions in the long run. Bibi et al. (2022) report positive impact of coal and oil prices and negative impact of natural gas prices on the global clean energy stocks both in the short run and long run by utilizing ARDL method between February 2011 and February 2020. Sun et al. (2019) analyze the impact of coal, oil and natural gas prices on the Chinese new energy companies and document weak impact of fossil fuels and no impact of carbon prices on the clean energy stocks. Gu et. a. (2020) reveal that there is bi-directional volatility transmission between coal prices and clean energy companies in China from January 2008 to February 2019. Song et al. (2019) show that the influence of oil is more conspicuous compared to the effects of coal and natural gas on the global clean energy stocks. They posit that the impact of coal has manifested only in recent times, while the impact of natural gas is weak on the clean energy stocks.

There are a few studies exploring the European renewable energy companies and the factors affecting their pricing. With multivariate quantile dependence approach, Reboredo and Ugolini (2018) examine how the oil, gas, coal and electricity prices affect the stock market performance of the European Renewable Energy index (ERIX) in the EU and ECO Clean Energy Index for the USA in the period 2009-2016. They find that energy prices affect the renewable energy companies' stock prices. They reveal that oil prices play an important role in the clean energy market in the USA while the stocks of clean energy companies are mainly affected by the electricity prices in the EU. Reboredo (2015) analyses the ERIX together with other clean energy indices and finds significant impact of oil prices on the renewable energy stock risk between 2005 and 2013. It is argued that the increasing oil prices spurred the interest of investors in the renewable energy market and that it encourages the development of the sector. Reboredo et al. (2017) use the ERIX with other renewable energy indices from January 2006 to March 2015 and examine the co-movement and causality between stock return of clean energy sector and oil prices for the period 2006-2015. They document a strong relation between oil prices and clean energy sector and that the interaction between oil and clean energy is growing strong in the long run. The impact of oil, gold prices and financial stress on clean energy prices in USA and in Europe are analyzed by He et al. (2021) in November 2003-January 2020 period with Quantile Autoregressive Distributed Lag approach. They find negative impact of gold prices and financial stress on the clean energy stocks while volatility of oil prices is found to be positively related with clean energy market in the long run. Xia et al. (2019) explore the effect of fossil fuels on ERIX with network approach from April 2008 to July 2019. They argue that clean energy market is the determinant in fossil energy market in Europe and that renewable energy market has the potential to reshape the energy systems in the world.

The interest in the interaction between carbon prices and clean energy gains momentum in the literature in the last decade. Kumar et al. (2012) estimate a VAR model for the period April 2005 to November 2008 and examine the relation between clean energy and technology stocks, oil prices and carbon prices. They conclude that high technology market and oil prices impact the clean energy market, but carbon prices have no effect on the stock market performance of clean energy firms. Ahmad et al. (2018) estimate the time varying hedge ratios between clean energy stocks and some financial variables like VIX, European carbon prices and oil prices for the period March 2008 to October 2017 and apply MGARCH models. They find that VIX (Volatility Index), OVX (Crude Oil Volatility Index) and oil are good hedges and interestingly they find no strong impact of carbon prices on the clean energy stocks. Dutta et al. (2018) use bivariate VAR-GARCH model to study the relation between

EUA, ECO and ERIX from July 2009 to December 2017. They find that clean energy prices and carbon prices are not strongly correlated, and the volatility of carbon prices and clean energy prices are only linked in Europe. Tiwari et al. (2022) analyze the connectedness and spillover between green bonds, carbon prices, solar and wind indices and global clean energy index between January 2015-September 2020 and find that clean energy market is the net transmitter of shocks.

The existing literature focuses on the relation between global clean energy companies and fossil fuel energy market while the studies focusing on the EU ETS and European renewable energy prices are limited. To the best of our knowledge, there is only one study that examines the impact of carbon prices along with Stoxx 600 Europe using TVP-VAR methodology (Qiu et al., 2023). They examined the impacts of Brexit, the launch of the European Green Deal and COVID-19 pandemic between 2014-2021. In this study, we analyze the impact of the EU carbon prices on the clean energy index considering the fourth phase of the EU ETS as a factor shaping the market. Besides carbon prices, this study also investigates the influence of fossil fuel prices and stock market indices on European clean energy market. The contribution of the study is two-fold: policy and methodology oriented. It elucidates the interplay between key determinant factors in the clean energy market, providing information for policy implications. On the other hand, the model used in this study accounts for structural shifts and, opposite to the literature, endogenously finds cut-off dates for a predetermined number of structural breaks. To the best of our knowledge, this study marks the inaugural implementation of Bai and Perron's well-established structural break estimation method (1998, 2003), specifically tailored to minimize estimation errors globally in the context of the clean energy market.

3. Data

The analysis covers the period from January 1, 2021, and July 31, 2023, with the specified dates aligned with the fourth phase of the European Emission Trading System. As a proxy for the European clean energy firms, we used the NASDAQ OMX Clean Energy Europe index as the independent variable in the model. The inaugural factor to be incorporated into the model is the stock market factor, deemed paramount in accordance with the recommendations posited by the Capital Asset Pricing Model (Sharpe, 1963). To represent the stock market index, we considered NASDAQ EURO 50 index. ICE Carbon Emission Futures contract is used to represent the carbon prices. For the oil price, we used the most extensively used Brent spot price. Dutch TTF Natural Gas Futures is considered to represent the natural gas price factor. Finally, Newcastle Coal Futures is included as the proxy for coal prices. To ensure all the series are traded in the same currency, the series denominated in USD (Newcastle Coal Futures, Brent Spot, NASDAQ OMX Clean Energy Europe) converted to Euro currency by daily Euro/USD exchange rate. All the data is compiled from investing.com.

The stationarity characteristic of the series is tested with Augmented Dicky Fuller Test for two models namely Intercept and Intercept & Trend and the results are shared in Table 1 Panel A. All the series have unit root at the level which suggest the existence of structural breaks. We share the descriptive statistics in Panel B. Finally, Panel C shows the correlation coefficients among the series.

Table 1 – Unit Root Test results and Summary Statistics

Panel A: Augmented–Dickey–Fuller test						
	Clean energy index	**Stock market Index**	**EUA**	**Oil price**	**Natural gas price**	**Coal price**
Intercept	-2.44 (0.1301)	-1.96 (0.3065)	-2.25 (0.1874)	-1.88 (0.3399)	-2.14 (0.2281)	-1.28 (0.6419)
Intercept and Trend	-2.770321 (0.2089)	-1.999136 (0.6002)	-2.999314 (0.1331)	-1.415186 (0.8560)	-1.998760 (0.6004)	-0.540537 (0.9815)
Panel B: Descriptive statistics						
Mean	1607.18	999.99	72.14	76.75	79.32	218.80
Std. Deviation	112.53	73.55	17.59	17.84	57.54	120.59
Skewness	-0.32	-0.39	-0.64	0.38	1.23	0.49
Kurtosis	2.66	1.97	2.21	2.25	4.43	1.74
Number of observations	672	672	672	672	672	672
Panel C: Correlation matrix						
Clean energy Index	1.00	0.57	-0.50	-0.73	-0.56	-0.79
Stock market Index	0.57	1.00	0.25	-0.41	-0.49	-0.56
EUA	-0.50	0.25	1.00	0.63	0.38	0.50
Oil price	-0.73	-0.41	0.63	1.00	0.72	0.87
Natural gas price	-0.56	-0.49	0.38	0.72	1.00	0.83
Coal price	-0.79	-0.56	0.50	0.87	0.83	1.00

4. Methodology

This study explores the potentially time-variant impact of carbon and fossil fuel prices and stock market index on the European clean energy market. To do so, we utilize the multiple structural change model approach introduced by Bai and Perron (1998, 2003). This approach estimates multiple structural changes in linear models. Our aim is to determine cut-off dates indicating when structural changes occur and estimate the corresponding linear model parameters for each regime. To better expose such a model, let us consider the following multiple linear regression model with m cut-off points corresponding to $m+1$ structural breaks (i.e. regimes).

$$y_t = c_k + \beta_k x_t + \epsilon_t \qquad t \in [l_k + 1, u_k] \tag{1}$$

where $k \in [1, m+1]$ and stands for the structural break period, y_t denotes the dependent variable (clean energy index) at time t, $x_t \in \mathbb{R}^6$ represents the vector of independent variables – namely time index, stock market index, carbon, oil, gas, and coal prices, β_k and c_k respectively refer to the coefficient vector and the constant for a structural break k, and ϵ_t denotes the error term at time t. Also, l_k and u_k respectively refer to lower and upper time bounds of regime k for $1 \leq k \leq m+1$. We use the convention that $l_1 = 0$ and $u_{m+1} = T$ simply referring that the first regime starts with the first observation, whereas the last regime ends with the last observation. Also, each regime must be disjoint, i.e. $u_i \leq l_j$ for $i \leq j$, and collectively exhaustive, that is, their union yields the entire set of observations, i.e. $u_i = l_{i+1}$.

Here, the bounds of regimes, i.e. $[l_k + 1, u_k]$, and associated regression parameters are unknown. Therefore, one aims to compute the cut-off points and corresponding estimation parameters. The computational approach developed by Bai and Perron (2003) is a dynamic programming model that eventually computes the optimal cut-off points along with the corresponding estimation parameters.

The dynamic programming model can be seen as a variant of the infamous shortest path problem in a directed acyclic graph that entails finding the shortest path having exactly m hops (edges) in a graph $\mathcal{G}(\mathcal{V}, E)$ where vertices represent time indices, i.e. $\mathcal{V} \in \{1, \dots, T\}$ and edges stand for each regime, i.e. $E \in \{(i,j) | i \in \mathcal{V}, j \in \mathcal{V},\ i < j\}$. Now, let $\mathcal{C}(i,j)$ denote the squared residuals of the multiple linear regression model computed in regime $(i,j]$ and $\mathcal{S}(r,j)$ represent the sum of squared residuals corresponding to the optimal partitioning of the time frame $[1,j]$ using r regimes. As such, the shortest path problem can be formulated as follows.

$$\mathcal{S}(r,j) = \min_{i|i<j}\{\mathcal{C}(i,j) + \mathcal{S}(r-1,i)\} \tag{2}$$

where

$$\mathcal{C}(i,j) = \sum_{t=i+1}^{j} (y_t - \hat{y}_t)^2 \tag{3}$$

and $\mathcal{S}(0,j) = 0$ for any $j \in \mathcal{V}$. Here, the optimal sum of squared residuals of having m regimes on the given dataset is found by computing $\mathcal{S}(m,T)$.

It is observable that the dynamic programming model given above requires solving a large number of least square equations, making it computationally inefficient. In fact, the complexity of the dynamic program has already been shown to be $O(n^2d^2 + n^2m)$ where n refers to the number of observations in the dataset and d denotes the number of independent variables (Acharya et al., 2016). These findings indicate that it may be unable to compute the parameters of interest for even small sized datasets. Due to the aforementioned computational issues, we opt for using the computationally efficient heuristic method introduced by Tunc and Genc (2021). This method relies on a mathematical programming heuristic known as the column generation, which enables smart filtering of options and solving only a small subset of least square equations. Specifically, there is no need to compute the least squares of every possible regime that could establish the partition. Instead, the method begins with a relatively small subset of potential regimes and then iteratively extends the subset as necessary. By doing so, it provides the user with the opportunity to work with large datasets. Both of those methods work with a predetermined number of break points. That is, the number of breaks, i.e. the number of regimes, are exogenous. Within a particular regime k, i.e. for $t \in [l_k + 1, u_k]$, the traditional least-squares approach is employed, and unknown values displayed in Equation 4 are found for each regime $k \in \{1,2,\dots,m+1\}$, where m denotes the number of cut-off points.

$$Clean\ index_t = c + \beta_{time\ index} t + \beta_{index} marketindex_t + \beta_{carbon} carbon_t + \beta_{oil} oil_t + \beta_{gas} gas_t + \beta_{coal} coal_t + \epsilon_t \tag{4}$$

Bai (1997) shows that the estimator minimizing the sum of squared residuals maximizes Wald-type statistics as well. As such, the aim of the method used in this study is to minimize the sum of squared residuals across all structural breaks.

5. Empirical findings

We have applied piece-wise linear regression method with different number of structural breaks, namely, 3 and 4. For the coherence of the results and comparison purposes, we also report the case where no breaks are considered. Clean energy index is taken as dependent variable, while stock market index, carbon, oil, gas and coal prices are taken as independent variables. We have also included time index increasing by 1 on each consecutive day. The estimation results of these models are displayed in Figure 1 within 4 equal time frames for a better visual representation. Note that the figure displays data on daily basis and no smoothing is done. As the figure shows, there are too many ripples in the data and linear regression approach is unable to mimic those ripples, especially when they are sharp in magnitude. However, when we apply structural breaks, an obvious improvement is observed. Increasing the number of breaks also improves the model performance. However, we keep our analysis restricted to 3 and 4 number of breaks, because we do not want to sacrifice the practicality for a higher granularity. Yet, one can still get the idea how number of breaks enhance the performance of the estimation model by comparing the results of 3 and 4 breaks.

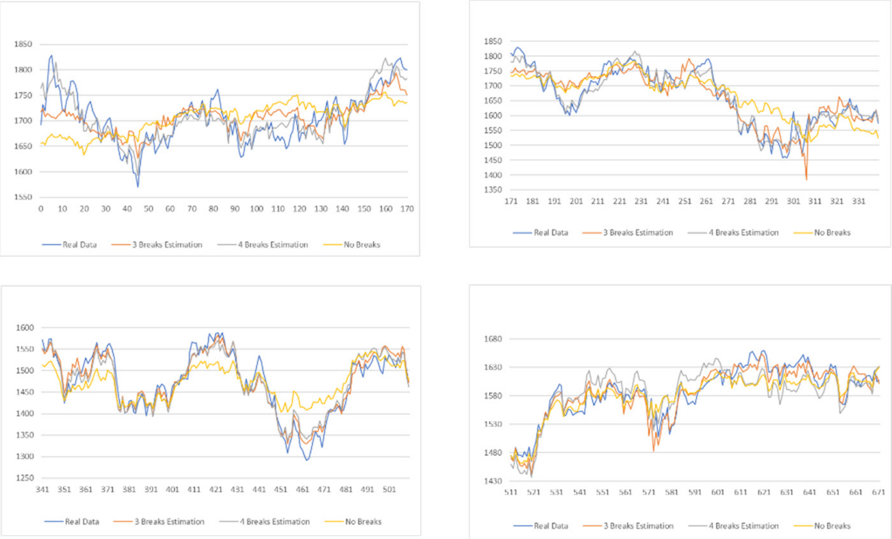
We summarize the error measures of those models in Table 2 together with R^2 values. These measures indicate that 'no break' case, namely multiple linear regression, is reported with the minimum error terms, nevertheless, with the smallest value for explanatory power, i.e. R^2=84%. As it is seen in Figure 1, it is the case that displays the worst performance in terms of catching up with the real data where sharp ripples are present. By minimizing total error terms, it can only comply with the general trend in the data, in other words, it can estimate the real data only when a smoothing is applied. When we elaborate on piece-wise linear regression models, we observe that total measures for residuals slightly increase, but it reveals better catch up with the ripples along with higher explanatory values. As it can be seen from Figure 1 and R^2 values reported in Table 2, estimation model with 4 breaks showcases a very high level of catch up with the real data, even displaying some overlaps in particular times.

Table 2 – Error and R^2 Measures

	MAD	**MAPE**	**MSE**	**RMSE**	**R^2**
NO BREAK	105,30	6.91%	17776	133.33	0.84
3 BREAKS	106.02	6.99%	18912	137.52	0.93
4 BREAKS	109.61	7.19%	19276	138.84	0.96

MAD: Mean absolute deviation; MAPE: Mean absolute percentage error; MSE: Mean square error; RMSE: Root mean square error

Figure 1 – Renewable energy companies stock index



Results of no break case is reported in Table 3. As we have discussed earlier, piece-wise linear regression model provides a high interpretability as opposed to black box models. We, hereby, present structural breaks/cut-off dates and coefficients of independent factors within each structural break in Table 4 and 5 for the models where the number of structural breaks is given as 3 and 4. Each cell in the table represents coefficient, [standard error] and (t-values) respectively for the constant and the independent factors. The significance levels of the factors are denoted by single, double and triple star sign at different α levels that are 10%, 5% and 1%.

In no break case, all factors except oil prices are found to be statistically significant in the estimation model of clean index. Index and gas have positive impact with coefficients 1.01641 and 0.3893 respectively, where time index, carbon and coal prices are negatively related to clean index with coefficients -0.2121, -1.8848 and -0.2294 respectively. Explanatory power of the model is also reported to be around 83%.

When the number of structural breaks is given as three, the cut off dates are determined as 08/03/2022 and 12/04/2023. The general trend with respect to time is found to be positive in the first break and negative in the last two breaks, with time index coefficients of 0.6929, -0.6505 and -1.0864. The relationship between clean index and stock market index is found to be statistically significant and positive in entire timeline with the coefficients 0.8760, 1.6069, 1.1382. Clean index, however, deviates inversely proportional to carbon price, such that it displays a negative relationship between dates 01/01/2021-08/03/2022 with coefficient -4.9870, but its effect on clean index is found to be insignificant between the dates 09/03/2022-12/04/2023 and 13/04/2023-31/07/2023. Similar to carbon prices, oil prices are also inversely proportional to clean index and it is found to be significant with coefficient values of -6.8967 and -3.9494 between dates 01/01/2021-08/03/2022 and 13/04/2023-31/07/2023. Gas prices, on the other hand, reveals an alternating effect on clean index and are found to be significant in all structural breaks with coefficients of 0.8618, 0.4607, -2.5001. When it comes to the effect of coal, we again observe a directional change in the behaviour, such that it is positive between 09/03/2022-12/04/2023 and changes to negative between the dates 13/04/2023-31/07/2023 with coefficients 0.0513 and -0.4901, where its impact is found to be insignificant in the first structural break until 08/03/2022. Also note that its positive effect in the second structural break is found to be significant, but at a significance level of 10% only.

Table 3 – Empirical Findings (No breaks)

Variable	Coefficient	[Standard Error]	(T-Value)
$\boldsymbol{c}$	830.3239***	[43.6379]	(19.0276)
$\boldsymbol{\beta_{time\ index}}$	-0.2121***	[0.0190]	(-11.1646)
$\boldsymbol{\beta_{index}}$	1.01641***	[0.0441]	(22,9993)
$\boldsymbol{\beta_{carbon}}$	-1.8848***	[0.2699]	(-6,9829)
$\boldsymbol{\beta_{oil}}$	-0.17046	[0.2395]	(-0,7116)
$\boldsymbol{\beta_{gas}}$	0.3893***	[0.0583]	(6,67203)
$\boldsymbol{\beta_{coal}}$	-0.2294***	[0.0441]	(-5,2007)
$\boldsymbol{R^2}$	0.8366		
$\boldsymbol{Adj.R^2}$	0.8351		

*, **, *** denote the significance at the level %10, %5 and %1 respectively

Table 4 – Empirical Findings (Number of breaks: 3)

	Cut-off Dates		
Variable	**01/01/2021-08/03/2022**	**09/03/2022-12/04/2023**	**13/04/2023-31/07/2023**
c	1379.0962*** [112.374] (12.272)	216.4980*** [55.042] (3.933)	1389.828*** [168.4131] (8.253)
$\beta_{time\ index}$	0.6929*** [0.227] (3.050)	-0.6505*** [0.028] (-23.371)	-1.0864*** [0.1909] (-5.6887)
β_{index}	0.8760*** [0.090] (9.733)	1.6069*** [0.040] (40.490)	1.1382*** [0.1745] (6.5228)
β_{carbon}	-4.9870*** [0.597] (-8.358)	0.0847 [0.200] (0.424)	1.2297 [0.7841] (1.5683)
β_{oil}	-6.8967*** [0.653] (-10.562)	-0.3294 [0.206] (-1.597)	-3.9494*** [0.7537] (-5.2396)
β_{gas}	0.8618*** [0.149] (5.794)	0.4607*** [0.030] (15.201)	-2.5001*** [0.5983] (-4.1787)
β_{coal}	0.0123 [0.140] (0.088)	0.0513* [0.027] (1.891)	-0.4901** [0.2178] (-2.2502)
R^2	0.725	0.939	0.558
$Adj.R^2$	0.720	0.938	0.52

*, **, *** denote the significance at the level %10, %5 and %1 respectively

When the number of structural breaks is forced to be 4, the cut-off dates are determined as 05/07/2021, 04/02/2022 and 07/04/2022. Time index is found to be negatively related to clean index at the first, and the last breaks (i.e. 01/01/2021-05/07/2021 and 08/04/2022-31/07/2023) with coefficients -1.8712 and -0.5734. It is effect on clean index is demonstrated to be insignificant during the period 06/07/2021-04/02/2022 and statistically significant and positive during 07/02/2022-07/04/2022 with a coefficient of 4.4487. Index has a positive effect all through the timeline with coefficients 1.9469, 2.0597, 0.7165, 1.6019 for each break respectively. Carbon price, on the other hand, has a negative impact all through the timeline except the period between 07/02/2022-07/04/2022, where it is found to be insignificant. The corresponding coefficients for those breaks that it is found to be significant have been reported as -5.5038, -1.4163, -1.0358. Oil price also displays a negative impact on clean index for the first two breaks with coefficients of -4.4269 and -7.3147 respectively, and it is found to be insignificant afterwards. Clean index is found to be directly proportional to gas price during 01/01/2021-05/07/2021 and 08/04/2022-31/07/2023 with coefficients 9.7644 and 0.5663. Lastly, the effect of coal price changes direction among breaks, such that, it is coefficient is found to be -1.2400 between 01/01/2021-05/07/2021, 0.5795 between 07/02/2022-07/04/2022 and -0.1964 between 08/04/2022-31/07/2023. Its impact is found to be insignificant between 06/07/2021-04/02/2022.

Table 5 – Empirical Findings (Number of breaks: 4)

	Cut-off Dates			
Variable	**01/01/2021-05/07/2021**	**06/07/2021-04/02/2022**	**07/02/2022-07/04/2022**	**08/04/2022-31/07/2023**
c	299.2693 [194.074] (1.542)	145.3533 [115.965] (1.253)	-459.5278 [452.963] (-1.014)	319.8922*** [69.1897] (4.623)
$\beta_{time\ index}$	-1.8712*** [0.444] (-4.210)	-0.0917 [0.197] (-0.466)	4.4487*** [0.644] (6.904)	-0.5734*** [0.040] (-14.252)
β_{index}	1.9469*** [0.195] (9.959)	2.0597*** [0.103] (19.923)	0.7165** [0.266] (2.689)	1.6019*** [0.049] (32.111)
β_{carbon}	-5.5038*** [1.596] (-3.449)	-1.4163*** [0.474] (-2.990)	-0.6170 [1.508] (-0.409)	-1.0358*** [0.256] (-4.045)
β_{oil}	-4.4269*** [1.115] (-3.971)	-7.3147*** [0.617] (-11.857)	-1.5685 [1.100] (-1.426)	0.0506 [0.252] (0.200)
β_{gas}	9.7644*** [1.431] (6.825)	0.1467 [0.105] (1.395)	-0.1107 [0.354] (-0.313)	0.5663*** [0.038] (14.703)
β_{coal}	-1.2400* [0.669] (-1.852)	-0.0523 [0.101] (-0.518)	0.5795*** [0.183] (3.167)	-0.1964*** [0.032] (-5.989)
R^2	0.695	0.898	0.762	0.957
$Adj. R^2$	0.680	0.894	0.723	0.916

*, **, *** denote the significance at the level %10, %5 and %1 respectively

After reporting the empirical findings, we further scrutinize the structural behaviour mechanism by predictor importance graphs that are plotted in SPSS Software package for each linear regression model of a particular break. At this stage, we also checked on the residuals and ensured that we comply with the principal assumptions that the errors are independently and normally distributed with mean 0 and standard deviation 1. Predictor importance graphs are utilized to visualize the relative impact of independent factors within each structural break. The importance measure is given within a continuum between [0,1]; 0 representing the least important and 1 representing the most important. Figure 2 showcases the predictor importance graph of the model where no structural break is imposed. In that model, although most independent variables are found to be statistically significant, they display a very low importance, but the main driver of estimation is found to be the conventional market performance. As expected, this simplistic approach of multiple linear regression does not provide much explanation about the relationship between the performance of renewable energy companies or energy related commodity prices.

Figure 2 – Predictor importance graph (No Break)

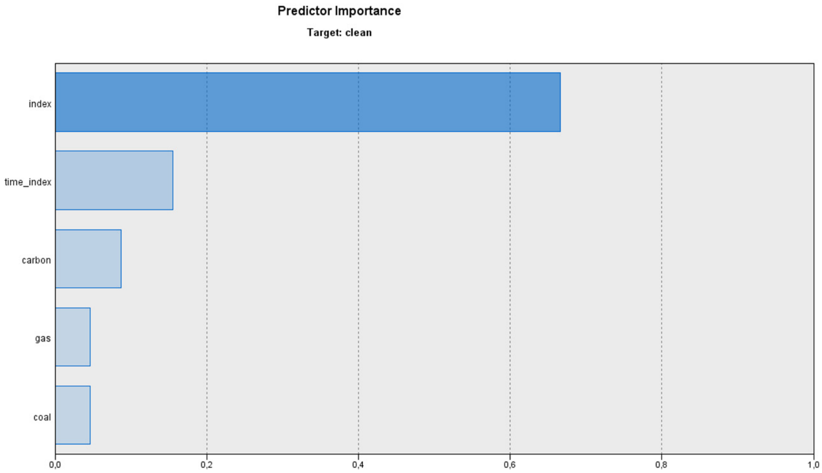


Figure 3 explores the predictor importance when the number of breaks is set to 3. In that case, index is still listed among the key influencing factors, however, we can also observe the effect of energy commodity prices, especially in the first break, oil being the key driver that is followed by carbon and gas. Moreover, the time index is also included in the bundle with relatively high importance in the second and third breaks. In the third break, the importance of index and time index recede, while the energy commodity prices gain an impact on the clean index estimation with a descending order of oil, gas, coal and carbon. Figure 4, on the other hand, reveals a different picture. In the first break driver force of estimation is found to be index followed by gas, oil, time index, carbon, coal with a descending order. In the second break the bundle of significant factors shrinks mainly to conventional market index and oil prices supported with slight impacts of carbon and gas. Clean index estimation function in the third break is dominated by time index, further enhanced by the contribution of coal, index and oil price. In the last break, the clean index is mainly derived by index, time index and gas.

These results assert that there does not appear to be a single bundle of factors that will fit into a one single recipe for clean index estimation. As expected, the relationships are dynamic, non-stationary and non-linear. Nevertheless, the outputs indicate that a piece-wise linear regression approach works well in terms of catching up the ripples in the real data along with the feature of interpretability and it provides some generalizable insights that we can list. Index is the robust estimator for clean index with positive influences in any circumstances. Carbon and oil prices, on the other hand, are the determinant factors that are found to be significant/insignificant depending on the time period that they are analysed. Those are the factors that explain the structural changes along with the alternating time trends during structural breaks. Furthermore, they demonstrate consistent behaviours as explanatory variables. Namely, they always display a negative impact in those cases that they are deemed to be statistically significant. On the contrary, gas and coal prices demonstrate a directional shift in the relationship with the clean index. Last but not the least, when energy commodity prices are not listed among the influencing factors or listed there with a relatively low importance, then the behaviour of the clean index is explained mainly by conventional market index and the time index only.

Figure 3 – Predictor importance graph (3 Breaks) (impact rate the more the darker)

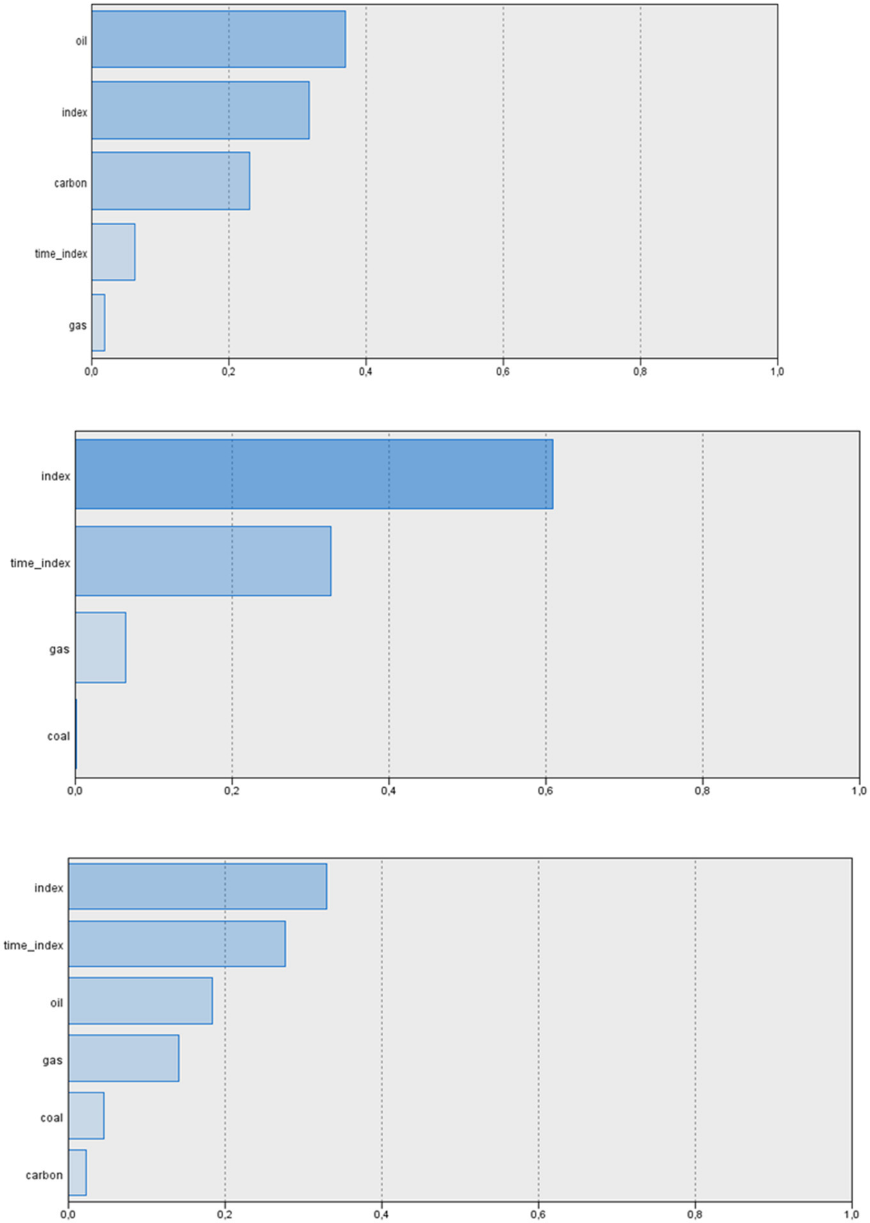
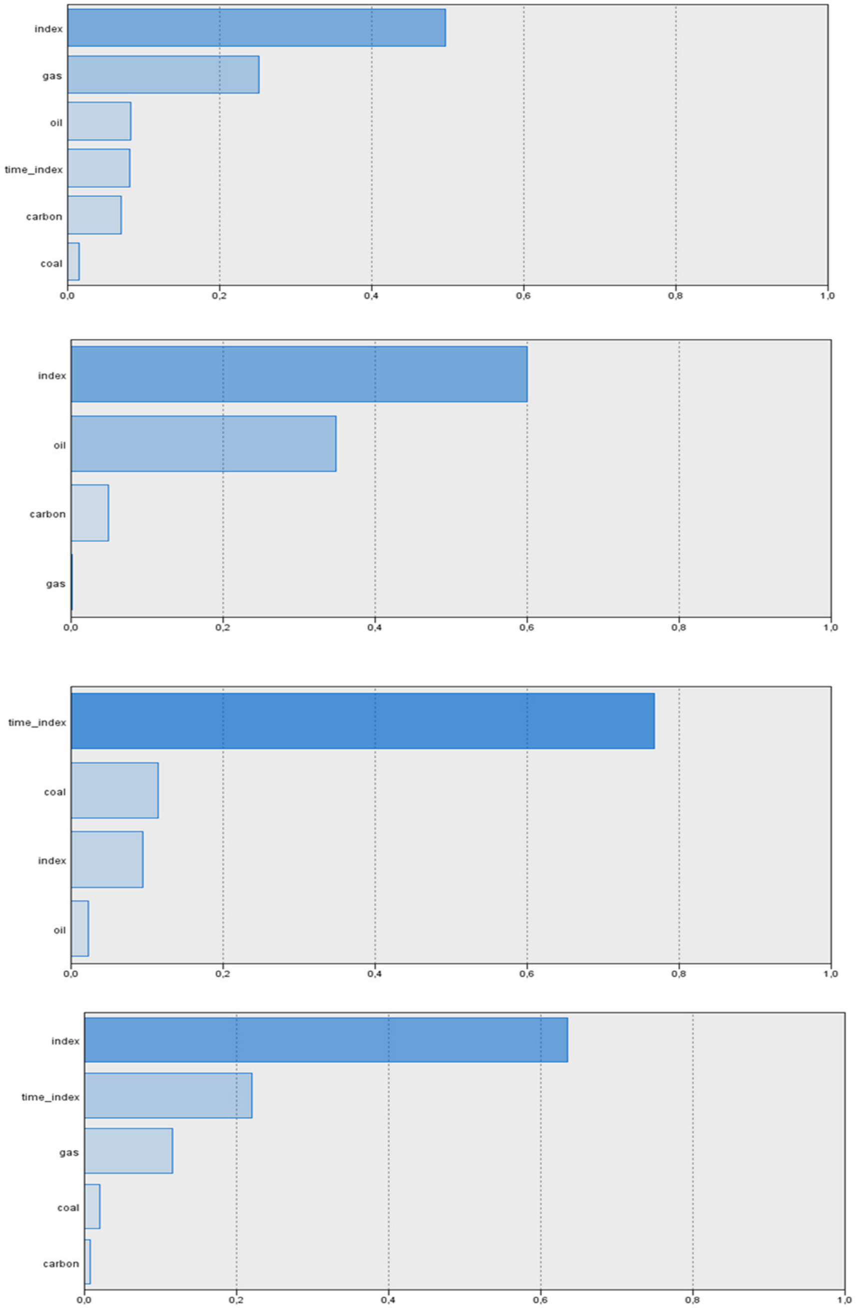


Figure 4 – Predictor importance graph (4 Breaks)



6. Discussion

The NASDAQ EURO 50 index has consistently exhibited positive trends during all identified structural break periods, serving as an indicative validation of the model's accuracy, given the anticipated positive impact of the NASDAQ EURO 50 on the NASDAQ OMX Clean Energy Europe index (Sharpe, 1963).

In instances denoted as structural break periods 3 within the model, a negative effect of carbon prices on the clean energy index was observed at the onset of the periods. Similarly, in situations designated as structural break periods 4, the negative impact of carbon prices was observed at both the conclusion and commencement of the periods. No discernible relationship between carbon prices and clean energy prices was identified between the dates of 09/03/2022-31/07/2023 in the first model and 07/02/2022-07/04/2022 in the second model. This finding aligns with the conclusions reached in studies conducted by Kumar et al. (2012), Ahmad et al. (2018), and Dutta et al. (2018). However, despite the general expectation that increasing carbon prices would positively influence clean energy stocks due to the lesser dependency of clean energy firms on carbon fuels and the absence of carbon allowance costs compared to traditional energy firms, the results contradict these expectations. Possible explanations for this phenomenon may include the potential inefficiency of the Market Stability Mechanism system and failed efforts for imposition of a substantial cost burden associated with carbon allowances on traditional energy firms. Due to the insufficient pressure of carbon costs on fossil energy firms, the anticipated relationship between carbon prices and clean energy stocks does not materialize. However, the anticipation of a recession in Europe due to the Russia-Ukraine tension has collectively impacted all markets, including clean energy firms, resulting in a depreciation of renewable energy stocks in the face of rising carbon prices. As a result, a negative relation is observed between carbon allowances and clean energy stocks.

The relationship between oil prices and the stocks of clean energy firms was modeled, and no statistically significant relationship was observed between 09/03/2022 and 12/04/2023 dates in the first model and between 07/02/2022 and 31/07/2023 in the second model, except for negative associations during other structural breaks. Regarding the negative relationship between clean energy stocks and oil prices, the results contradict with the studies conducted by Managi and Okimoto (2013), Bibi et al. (2022), Reboredo (2015) and confirms Fu et al. (2022) under bullish market conditions, and consistent with the findings of Kocaarslan and Soytas (2019) in the long term, as well as those reported by Ahmad (2017). The escalating impact of rising oil prices, resulting in negative effects on firms' production costs and household income levels, results in a negative economic outlook and thus oil prices adversely influences the stock performance of clean energy companies (Kocaarslan and Soytas, 2019). Examination of temporal characteristics is necessary to understand the observed negative relationship between oil prices and clean energy firm stocks, particularly during the fourth phase of the EU Emission Trading System (EU ETS). The period encompassing the onset of the COVID-19 pandemic witnessed record-low levels of oil prices, which subsequently exhibited a substantial surge during the normalization phase that commenced in 2021. However, economic recovery during the same period did not proceed at an equivalent pace, leading European economies to suddenly confront the looming threat of escalating inflation. Despite the fact that the increase in oil prices in response to growing demand (Kilian, 2009) have positive impact on the stock markets, the overall negative impact of the rising oil prices on the economy has been more pronounced. Additionally, due to inflationary pressures, clean energy stocks have not gained sufficient value in tandem with the general market outlook.

The impact of natural gas prices is found to be positive between 01/01/2021-12/04/2023 in the first model and between the dates 01/01/2021-05/07/2021 and 08/04/2022-31/07/2023 in the second model. Given that the general trend is positive, the results are in line with the study of Fu et al. (2022) in bearish market conditions. In general, rising natural gas prices have positive impact on the stock market performance of clean energy companies and this is in line with the expectations. Investors turn their eye to renewables in the EU when natural gas prices are rising. Especially after the invasion of Ukraine, both models (i.e. number of structural break 3 and 4) give the same result that the rise in natural gas prices affected the clean energy companies positively. The impact of coal prices is negative in the final period of both models and positive between 09/03/2022 and 12/04/2023 in the first model 07/02/2022 and 07/04/2022 and this is in line with the study of Bibi et al. (2022). Examination of the results suggests that the influence of coal has only begun to be discernible in recent years. As indicated by Sun et al. (2019), for a long time, clean energy firms were primarily associated with technology companies. In a manner akin to the findings of the study by Song et al. (2019), this investigation also indicates that in recent years, investors have commenced establishing connections between fossil fuels such as coal and clean energy firms, with the impact of coal becoming increasingly apparent.

7. Conclusion and policy implications

This study aims to investigate the effect of fossil fuels including oil, gas and coal; carbon prices as well as stock market index on the European clean energy market, using the time series data between 01/01/2021-31/07/2023 covering the 4th phase of EU ETS. Besides the practical contribution of the study, we have utilized a computationally efficient piece-wise linear regression approach. This methodology accounts for the structural shifts in a non-stationary data with a predetermined number of possible structural breaks. The timing of the shifts, nonetheless, is determined endogenously. The results highlight that stock market index has a positive effect and that is in line with expectations. On the other hand, gas has generally positive effect, where carbon and oil reveal a negative effect. We should remark that the effects of carbon, oil, gas, and coal alternate between significant and insignificant based on the structural shifts. Yet, only the effects of gas and coal change direction from positive to negative in some structural breaks.

The results of the study lead us for the discussion of policy implications in the field of renewable energy studies. The EU should employ the Market Stability Reserve more effectively to proactively address abrupt and significant declines in carbon prices. To achieve this objective, it must actively monitor the carbon market and restore market equilibrium and stability through the reacquisition of allowances. In doing so, sectors with a low carbon footprint, such as the renewable energy sector, should derive advantages from rising carbon prices, and the stocks of renewable energy companies should continue to appreciate in the face of increasing carbon prices.

Our study, in general, has elucidated the impact of market portfolio, carbon, oil, natural gas, and coal prices on the stock performance of renewable energy companies in Europe during the fourth phase of the EU Emissions Trading System (EU ETS). The findings have significant implications for understanding how EU will shape the EU carbon market and formulate policies in the energy market in the future.

Statements and declarations

Competing Interests: The authors declare that they have no known conflict of interest.

Data Availability Statement

All data is compiled from Investing.com. Below links provide each time series data

Investing.com (2023). NASDAQ OMX Clean Energy Europe (GRNFOCEUR). -- https://www.investing.com/indices/nasdaq-omx-clean-energy-europe.

Investing.com (2023). NASDAQ EURO 50 (NQEURO50). -- https://www.investing.com/indices/nq-euro-50.

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Investing.com (2023). XBR/USD – Brent Spot US Dollar. -- https://www.investing.com/currencies/xbr-usd.

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Exploring the food-energy inflation relationship through Fourier methods: Asymmetric and nonlinear causality

Havva Koç[*]

Abstract

This study investigates the long-run relationship and Granger-type predictive causality between food and energy inflation in Türkiye, with a particular focus on asymmetric transmission, price stickiness, and structural changes. Monthly data covering the period from January 2003 to February 2025 are employed. The analysis begins with linearity testing, followed by the application of Fourier-based unit root and cointegration tests to account for structural shifts. Long-run coefficients are estimated using Dynamic OLS, Fully Modified OLS, and Canonical Cointegration methods. In addition, Hatemi-J asymmetric causality tests are conducted within a Granger framework to examine the direction and nature of shocks. The findings reveal that a 1% increase in energy inflation leads to a 1.13% increase in food inflation in the long run. Bidirectional Granger-type causality is detected for positive shocks, whereas negative shocks exhibit weaker and asymmetric linkages. These results support the presence of price stickiness and nonlinear transmission mechanisms. Overall, the study provides a comprehensive framework for understanding energy-food inflation dynamics and highlights the importance of accounting for asymmetries in policy design.

Keywords: food inflation, energy inflation, Fourier cointegration test, asymmetric causality, price stickiness.

JEL classification: E31, C32, C58, Q11, Q43

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1. Introduction

In recent years, volatility in global energy markets has coincided with rising food prices. This development has raised concerns about macroeconomic stability. Changes in energy prices directly affect agricultural production and transportation costs. As a result, they influence food inflation. Understanding how energy and food prices move together over time has therefore become important for both researchers and policymakers.

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This study examines the long-term relationship between food and energy inflation. Rising food prices and energy market volatility have increased cost pressures in agriculture and logistics. Traditional linear models may not fully capture these dynamics. There is a growing need for approaches that allow for nonlinear behavior and asymmetric shock effects. To address this issue, this study combines Fourier-based structural break analysis with asymmetric causality tests.

Much of the existing literature analyzes the energy-food relationship under linear and symmetric assumptions. However, some evidence suggests that increases in energy prices may have stronger and more persistent effects on food prices than decreases. This pattern points to possible asymmetric adjustment dynamics. Therefore, methods that account for structural breaks and nonlinear behavior are needed.

For Türkiye, empirical studies on asymmetric causality between energy and food inflation remain limited. Research that jointly considers structural breaks and nonlinear dynamics using Fourier methods is also scarce. This study focuses on the time-varying and asymmetric features of the relationship between energy and food inflation. The objectives are:

i. To investigate the nonlinearity of the series,
ii. To analyze stationarity properties using the Fourier unit root test,
iii. To examine the long-term relationship through the Fourier cointegration test,
iv. To estimate long-term coefficients using FMOLS, DOLS, and CCR methods,
v. To assess shock-direction-based Granger-type causality using the Hatemi-J Asymmetric Causality Test.

This paper is organized into five main sections. Following the Introduction, the second section reviews the relevant literature and highlights the study's contributions. The third section details the methodology and data. The fourth section presents the empirical findings, and the fifth section discusses the results and concludes with policy implications.

1.1. Theoretical background: Price stickiness

Price stickiness is a central concept in macroeconomics. It refers to the idea that prices do not adjust immediately to changes in supply or demand. In classical theory, prices are assumed to be flexible and markets clear automatically. However, Monetarist, Keynesian, and New Keynesian approaches recognize that prices may be slow to adjust, especially in the short run. When prices do not respond quickly, imbalances such as unemployment or idle capacity can persist (Keynes, 1936; Phillips, 1958; Friedman, 1968; Phelps, 1967; Lucas, 1972; Sheshinski & Weiss, 1977; Taylor, 1979; Mankiw, 1985; Mankiw & Reis, 2002).

Keynes (1936) argued that downward rigidity in wages and prices may prevent the economy from returning quickly to full employment. Later, New Keynesian models formalized this idea. Mankiw (1985) introduced the concept of "small menu costs," suggesting that even minor costs of changing prices can lead firms to delay adjustments. Empirical studies by Blinder (1991) and Ball and Mankiw (1994) show that firms tend to respond more quickly to positive shocks than to negative ones. Price increases are often implemented faster than price reductions.

This framework helps explain the interaction between energy and food prices. Increases in energy prices quickly raise production and transport costs in agriculture. In contrast, energy price declines may pass through more slowly. Such patterns are consistent with price stickiness. Therefore, analyzing the energy–food inflation relationship requires attention not only to how much prices change, but also to the direction and speed of those changes.

2. Literature

Fluctuations in energy prices can significantly affect food production and distribution costs, making the interaction between food inflation and energy inflation a critical area of study. Below is a summary of the relevant literature covering both developed and developing countries.

Table 1 – Literature Review[1]

Author(s)	**Country & Time**	**Data Set**	**Method**	**Findings**
Bello & Sanusi (2019)	Nigeria (1995:Q1-2018:Q2)	Food Inflation, Core Inflation, Marginal Cost, Imported Inflation, Exchange Rate	STR, NKPC	Inflation occurs under low and high regimes; exchange rate becomes main driver in high regime.
El-Karimi & El-Ghini (2020)	Morocco (1998:Q1-2018:Q1)	Global Oil, Global Food Prices, Domestic Inflation	BC Causality Test	Food prices have a stronger short-term impact on inflation; asymmetry observed in shocks.
Ganioglu (2020)	EU-27 (2003:01-2018:07)	Inflation Expectations, Food & Energy Prices, Interest Rate, Unemployment	SADF, GSADF, Panel Regression	Food and energy prices show extreme deviations influencing expectations and macro indicators.
Odondo (2021)	Kenya (2017:01-2020:02)	Manufacturing Growth, Core, Food, and Energy Inflation	Johansen, VECM, Wald Test	Long-term link between manufacturing growth and inflation types; short-term causal effects detected.

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[1] STR: Smooth Transition Regression. NKPC: Nonlinear New Keynesian Phillips Curve. BC: Breitung and Candelon Causality Test. SADF: Supremum Augmented Dickey-Fuller Test. GSADF: Generalized Supremum Augmented Dickey-Fuller Test. VECM: Vector Error Correction Model. LP: Local Projection Method. SVAR: Structural Vector Autoregression. Panel SVAR: Panel Structural Vector Autoregression FSHIN: Fourier Shin Cointegration Test. FMOLS: Fully Modified Ordinary Least Squares. TY: Toda-Yamamoto Causality Test FTY: Fourier Toda-Yamamoto Causality Test. WC: Wavelet Coherence. QGC: Quantile Granger Causality. QQR: Quantile-on-Quantile Regression. QR: Quantile Regression. TVP-VAR: Time-Varying Parameter Vector Autoregression. GCQ: Granger Causality in Quantiles. RALS: Residual Augmented Least Squares. EG Cointegration: Engle-Granger Cointegration Test. SPE: Static Panel Estimator. DPE: Dynamic Panel Estimator. WEM: Within Effects Model. MIA: Multiplicative Interaction Approach. NARDL: Nonlinear Autoregressive Distributed Lag Model.

Author(s)	Country & Time	Data Set	Method	Findings
Kohlscheen (2022)	OECD (1990-2020)	Food Price Inflation, Current & Expected Inflation, Output Gap	LP Method	Weak link between domestic and global food prices after exchange rate adjustment.
Kose & Unal (2022)	Latin America (2003:01-2020:12)	Temperature, Oil Price, Exchange Rate, Agricultural Wages, Food Prices	SVAR, Panel Granger	Oil prices and temperature are significant; exchange rate less so long-term.
Ali et al. (2022)	Pakistan (2005:09-2020:10)	Food Inflation, Monetary Policy, Transportation Prices	QR, VAR, ARDL	Monetary policy and transport costs significantly affect food inflation across quantiles.
Arintoko et al. (2023)	Indonesia (2001:01-2022:12)	World Oil Prices, CPI, Exchange Rate	QR, DOLS	Asymmetric long-term impacts of oil price changes on CPI.
Škare et al. (2023)	44 Countries (2005:Q1-2021:Q1)	HCPI, ECPI	Panel SVAR	Energy shocks have significant but temporary effects; high sensitivity in emerging economies.
Ozayturk (2023)	Turkey (2016:02-2023:04)	Energy and Agricultural Inflation	FSHIN, FMOLS, TY, FTY	Positive co-integration and bidirectional causality between energy and agricultural inflation.
Kartal & Depren (2023)	Turkey (2004:01-2021:06)	Domestic Food Prices, Global and National Factors	WC, QGC, QQR, TY, QR	Food prices show asymmetric relations across time, frequency, and distribution dimensions.
Tasdoken & Kahyaoglu (2023)	Global (2003:03-2022:09)	Commodity Prices, Food Commodities, Crude Oil, Baltic Dry Index	TVP-VAR	Food prices highly interact with global inflation and shipping costs.
Derindag et al. (2023)	India (1999:01-2022:08)	Local Food Prices, Oil Prices, Exchange Rate, EPU Index	WC, QQR, GCQ, QR	Strong multi-frequency relations between food prices and external factors.
Demirtas, (2023)	Türkiye (2003:01-2022:09)	Oil Prices, Food Prices	RALS, DOLS, FMOLS, CCR	Negative long-term impact of oil prices on food prices; inflation main driver.
Borisov (2024)	Euro Area (2019-2024)	Food Inflation (HICP), Energy Prices (HICP Subgroup)	Regression, Granger	Energy price increases significantly impact food prices with six-month lag.
Arintoko et al. (2024)	Indonesia (2001:01-2023:02)	CPI, Global Energy and Food Prices, Exchange Rate, Money Supply	NARDL, QR	Energy price drops reduce inflation; exchange rate is the dominant factor.
Khan et al. (2024)	Pakistan (2019:01-2023:05)	Energy Price Index, Food Price Index	EG Cointegration, Granger	Energy prices have significant and long-term effects on food prices.
Ikue et al. (2024)	Nigeria (2016:Q1-2024:Q2)	Oil Product Prices, Exchange Rate, Headline and Food Inflation	SPE, DPE, WEM, MIA	Oil prices and exchange rate fluctuations strongly affect inflation.

Author(s)	Country & Time	Data Set	Method	Findings
Ikue (2024)	Nigeria (2010:Q1-2024:Q2)	Oil Prices, Headline and Food Inflation, Exchange Rate	NARDL	Positive shocks in energy prices have stronger and lasting inflationary effects.
Dash & Padhan (2024)	South & Southeast Asia (2012:05-2022:04)	Global Crude Oil Prices, Food Inflation	NARDL	Strong and asymmetric effect of oil prices on food inflation.
Borrallo et al. (2024)	Euro Area (Recent decades)	Food and Energy Commodity Prices, Food Consumer Prices	Extended Food Value-Chain Model, Asymmetry Analysis	Persistent and asymmetric effects of commodity price shocks on food prices; positive shocks have stronger effects than negative ones.

* The literature table was meticulously compiled by the author during the period from March 10 to April 20, 2025.

Core inflation excludes volatile items such as energy and food and helps identify underlying inflation trends. SVAR-based studies show that energy price shocks play a significant role in European inflation dynamics (Gartner & Wehinger, 1998; Wehinger, 2000). By separating core components, researchers can distinguish between temporary and persistent inflationary pressures.

Relative price variability also shapes inflation dynamics. In Europe, changes in logistics and market structures have affected how energy shocks transmit into prices. However, the relationship between relative price variability and inflation is not always positive. Market integration and fiscal frameworks may reduce the inflationary impact of energy shocks (Fielding & Mizen, 2000).

Inflation persistence in the Euro Area has also been linked to policy frameworks. Tighter institutional settings tend to weaken the transmission of cyclical shocks and reduce inflation persistence (Cournède et al., 2005). Energy crises and environmental constraints further introduce uncertainty, influencing agricultural production and global trade (Irwin & Penn, 1975).

Most existing studies have primarily focused on examining the effects of food and energy inflation on overall inflation using linear models. However, the possibility that price movements may exhibit asymmetric characteristics – particularly that upward shocks in food prices are more rapid and persistent while downward shocks are more limited and delayed – has not been sufficiently explored.

For Türkiye, studies investigating asymmetric causality between energy and food inflation are particularly scarce. Furthermore, comprehensive analyses that simultaneously account for structural breaks and nonlinear dynamics using Fourier transformation are rarely encountered in the literature.

This study offers a novel contribution by examining the relationship between energy and food prices in Türkiye through:

- The dimension of asymmetric causality;
- The impact of price stickiness;
- A detailed methodological framework based on the Fourier approach that incorporates structural breaks.

In doing so, it aims to fill an important gap in the existing literature concerning asymmetric transmission effects and price stickiness.

3. Methodology and data

In the first stage of the Fourier KSS test, equation (1) is estimated, similar to the first stage of the FADF test. In the estimation of this equation using the ordinary least squares method, it is crucial to determine the frequency number k. The value of k corresponding to the model with the minimum sum of squared residuals is selected as the appropriate frequency number. The model with the selected k value is considered the model to be evaluated in the first stage. The selected model is then estimated as described, and the residuals are obtained (Hepsag, 2022):

$$y_t = a + \gamma_1 \sin(\frac{2\pi kt}{T}) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \varepsilon_t \qquad (1)$$

In Equation (1), π represents pi (approximately 3.14), k is the frequency, t refers to the deterministic trend, and T is the number of observations. The sin and cos terms are trigonometric components included as deterministic elements. In the Fourier KSS test, the second stage differs from the FADF test: Christopoulos and Leon-Ledesma (2010) assume that the residuals follow an ESTAR process, allowing for a direct unit root test using a first-order Taylor expansion.

$$\Delta\hat{\varepsilon}_t = \delta\hat{\varepsilon}^3_{t-1} + \sum_{i=1}^{m} \Delta\,\hat{\varepsilon}_{t-i} + v_t \qquad (2)$$

After estimating the test regression in Equation (2) using the ordinary least squares (OLS) method, the null hypothesis indicating the presence of a unit root ($\delta = 0$) is tested against the alternative hypothesis indicating stationarity ($\delta < 0$). The test statistic, referred to as $F - t_{NL}$, is calculated as follows:

$$F - t_{NL} = \frac{\hat{\delta}}{SE(\hat{\delta})} \qquad (3)$$

$\hat{\delta}$ is the estimated value of the δ parameter in Equation (3), and SE($\hat{\delta}$) is its standard error. If the absolute value of the $F - t_{NL}$ statistic is smaller than the critical values by Christopoulos & Leon-Ledesma (2010), the null hypothesis of a unit root cannot be rejected; otherwise, it is rejected, indicating stationarity. If the series is stationary, it is necessary to test the significance of the sine and cosine coefficients (γ_1 and γ_2) in Equation (1), following Becker, Enders & Lee (2006). As Christopoulos & Leon-Ledesma's (2010) test considers only constant models, the $F_\mu(\hat{k})$ statistic is used for this purpose.

$$F_\mu(\hat{k}), F_t(\hat{k}) = \left(\frac{ESS_R - ESS_{UR}(k)/2}{ESS_{UR}\, k/(T-q)}\right) \tag{4}$$

In Equation (4), ESS_R and ESS_{UR} represent the sum of squared residuals for the restricted and unrestricted models, respectively; T is the number of observations, and q is the number of parameters in the unrestricted model. If the calculated $F_\mu(\hat{k})$ or $F_t(\hat{k})$ statistic exceeds the critical values by Becker, Enders & Lee (2006), the null hypothesis is rejected, confirming at least one significant trigonometric coefficient and the stationarity of the series (Christopoulos & Leon-Ledesma, 2010). Otherwise, the standard KSS unit root test is recommended (Hepsag, 2022). Shin (1994) introduced a cointegration test based on the KPSS unit root framework, which was later extended by Tsong et al. (2016) with trigonometric terms to account for structural breaks, resulting in the Fourier-Shin (FShin) cointegration test.

$$y_t = a + \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \theta x'_t + \sum_{i=-l}^{l} \psi_i \Delta x'_{t-i} + \varepsilon_t \tag{5}$$

$$y_t = a + \beta_t \gamma_1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma_2 \cos\left(\frac{2\pi kt}{T}\right) + \theta x'_t + \sum_{i=-l}^{l} \psi_i \Delta x'_{t-i} + \varepsilon_t \tag{6}$$

In Equations (5) and (6), k represents the frequency number, T denotes the number of observations, t refers to the deterministic trend, π is the mathematical constant approximately equal to 3.14, and *-l* and *l* indicate the lag lengths for past and future periods, respectively. The sin and cos functions represent the trigonometric terms, which are other deterministic components included in the regression.

The model with the appropriate frequency number k determined in the first stage is considered the baseline model for estimation. In the second stage of the test, the residuals obtained from the model where the appropriate k has been selected are subjected to the Shin (1994) cointegration test. The null hypothesis ($\sigma_u^2 = 0$) indicating the existence of cointegration is tested against the alternative hypothesis ($\sigma_u^2 > 0$), which suggests the absence of cointegration. The test statistic to be calculated for this purpose is as follows:

$$CI_f^0, CI_f^1 = \frac{1}{T^2} \frac{\sum_{t=1}^{T} S_t(k)^2}{\sigma^2} \tag{7}$$

In Equation (7), CI_f^0 and CI_f^1 represent the test statistics for models with only a constant term and with both a constant and a trend, respectively. $S_t(k)$ denotes the cumulative sum of residuals from the model estimated with the appropriate frequency k, T is the number of observations, and σ^2 is the long-run variance. If CI_f^0 or CI_f^1 is smaller than the critical values (Tsong et al., 2016), the null hypothesis of cointegration cannot be rejected; otherwise, it is rejected in favor of no cointegration.

After establishing cointegration, the significance of the sine and cosine coefficients (γ_1 and γ_2) in Equations (5) and (6) is tested using the restriction-based $F^m(k^*)$ statistic.

$$F^m(k^*) = (\frac{ESS_R - ESS_{UR}(k)/2}{ESS_{UR}\ k/(T-q)}) \qquad (8)$$

In Equation (8), ESS_R denotes the sum of squared residuals from the restricted model, ESS_{UR} represents the sum from the unrestricted model, T is the number of observations, and q is the number of parameters in the unrestricted model. If the $F^m(k^*)$ statistic exceeds the critical values by Tsong et al. (2016), the null hypothesis ($\gamma_1 = \gamma_2 = 0$) is rejected, indicating that at least one trigonometric coefficient is significant ($\gamma_1 \neq \gamma_2 \neq 0$). If the $F^m(k^*)$ statistic falls below the critical values, the null hypothesis cannot be rejected, implying insignificance. In this case, the Shin (1994) cointegration test is recommended (Hepsag, 2022).

For the asymmetric causality analysis, the integrated series y_1t and y_2t are defined by random walk processes as shown in Equations (9) and (10) (Hatemi-J, 2012: 449).

$$y_{1t} = y_{1t-1} + \varepsilon_{1t} = y_{10} + \sum_{i=1}^{t} \varepsilon_{1t} \qquad (9)$$

$$y_{2t} = y_{2t-1} + \varepsilon_{2t} = y_{20} + \sum_{i=1}^{t} \varepsilon_{2t} \qquad (10)$$

In Equations (9) and (10), t=1,2,.,T. y_{10} and y_{20} represent the initial values. ε_{1t} and ε_{2t} are white noise error terms. The positive and negative shocks of the variables are defined as follows (Hatemi-J, 2012):

$$\begin{aligned} &\varepsilon_{1t}^{+} = \max(\varepsilon_{1t}, 0), \\ &\qquad \varepsilon_{2t}^{+} \\ &\qquad = \max(\varepsilon_{2t}, 0), \quad \varepsilon_{1t}^{-} = \min(\varepsilon_{1t}, 0), \\ &\qquad \varepsilon_{2t}^{-} = \min(\varepsilon_{2t}, 0) \end{aligned} \qquad (11)$$

$$\varepsilon_{1t} = \varepsilon_{1t}^{+} + \varepsilon_{1t}^{-} \ and\ \varepsilon_{2t} = \varepsilon_{2t}^{+} + \varepsilon_{2t}^{-}$$

As shown in Equation (11), the variables can be expressed through positive and negative shocks as follows.

$$y_{1t} = y_{1t-1} + \varepsilon_{1t} = y_{10} + \sum_{i=1}^{t} \varepsilon_{1t}^{+} + \sum_{i=1}^{t} \varepsilon_{1t}^{-} \qquad (12)$$

$$y_{2t} = y_{2t-1} + \varepsilon_{2t} = y_{20} + \sum_{i=1}^{t} \varepsilon_{2t}^{+} + \sum_{i=1}^{t} \varepsilon_{2t}^{-} \tag{13}$$

The cumulative positive and negative shocks of each series are expressed as shown in Equation (14).

$$y_{1t}^{+} = \sum_{i=1}^{t} \varepsilon_{1t}^{+}, y_{1t}^{-} = \sum_{i=1}^{t} \varepsilon_{1t}^{-}, and\ y_{2t}^{+} = \sum_{i=1}^{t} \varepsilon_{2t}^{+}, y_{2t}^{-} = \sum_{i=1}^{t} \varepsilon_{2t}^{-} \tag{14}$$

The causality relationship between the components of the variables in terms of cumulative positive shocks is represented as shown in Equation (15).

$$y_{t}^{+} = v + A_1 y_{t-1}^{+} + \cdots + A_p y_{t-1}^{+} + u_{t}^{+} \tag{15}$$

Causality testing can be conducted using a VAR(p) model of order p. Here, y_t^{+} represents a (2x1) vector of variables, v is a (2x1) vector of intercept terms, u_t^{+} is a (2x1) vector of error terms, and A_r (for r=1,2,...,p) are (2x2) matrices representing the lag orders. In the Hatemi-J (2012) approach, the null hypothesis (H_0) states that the element at the k-th column and w-th row of the A_r matrix is zero. This hypothesis is tested for lag orders r=1,2,...,p. Hatemi-J emphasizes that traditional tests may be inadequate, especially when variables are not normally distributed and ARCH effects are present. Therefore, he suggests that it is more reliable to use critical values obtained through bootstrap simulations. Accordingly, in this study, the causality relationship between the variables was first investigated using the Hacker and Hatemi-J (2006) Bootstrap Causality Test. Subsequently, the Hatemi-J Asymmetric Causality Test was applied to reveal asymmetric relationships based on positive and negative shocks.

It should be noted that the causality results are conditional on the selected VAR specification, lag length, and the maximum integration degree (dmax). Although bootstrap critical values reduce size distortions under non-normal errors and potential ARCH effects, the findings remain sensitive to model specification and the chosen information criterion. Therefore, the results should be interpreted within the limits of the econometric framework.

3.1. Data set

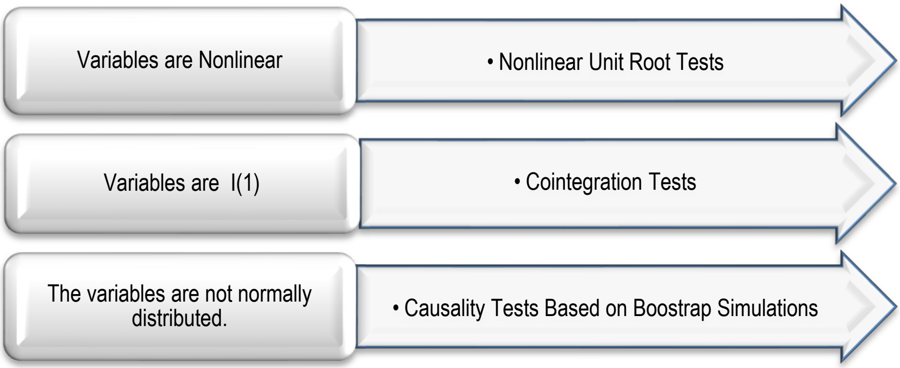
In this study, monthly data covering the period from January 2003 to February 2025 were used to examine the food and energy inflation indicators of the Turkish economy. The data (Food Price Index and Energy Price Index) were obtained from EVDS (Electronic Data Delivery System) in their level values. Natural logarithm transformation is frequently employed in statistical analyses for data transformation and modeling purposes. The natural logarithm of the series obtained in level form was taken using the formula $ln(x) = log_e(x)$. Logarithmic transformation reduces the impact of large values and softens the influence of outliers, resulting in a more balanced modeling process.

Table 2 – Variables and Their Descriptions

Variable	Description	Data Range
LNFPI	Logarithmic of Food Price Index	2003:01-2025:02
LNEPI	Logarithmic of Energy Price Index	2003:01-2025:02

Table 2 summarizes the names and data ranges of the variables used in the analysis. The selection scheme of the tests to be applied in the analysis is shown below in Figure 1.

Figure 1 – Decision Diagram



Nonlinear unit root tests were preferred for variables identified as nonlinear. Variables confirmed as I(1) were subjected to cointegration analysis. Additionally for variables not normally distributed, asymmetric causality tests developed by Hacker & Hatemi-J (2006) and Hatemi-J (2012), employing bootstrap simulations, were conducted.

4. Findings

Descriptive statistics, covariance and correlation coefficients for the variables LNFPI and LNEPI are presented in Table 3.

Table 3 – Descriptive Statistics, Covariance and Correlation Analyses

Descriptive Statistics	**LNFPI**	**LNEPI**
Mean	5.751598	5.681614
Median	5.539222	5.591248
Maximum	8.322623	7.865061
Minimum	4.539030	4.589244
Std. Dev.	0.960416	0.813334
Skewness	1.055694	0.941132
Kurtosis	3.374312	3.303932
Jarque-Bera	50.96196	40.29118
Probability	0.000000	0.000000
Sum	1529.925	1511.309
Sum Sq. Dev.	244.4355	175.3009
Observations	266	266
Covariance Analysis	LNFPI	LNEPI
LNFPI	0.918930	
LNEPI	0.773394	0.659026
Correlation Analysis	LNFPI	LNEPI
LNFPI	1.000000	
LNEPI	0.993821	1.000000

Table 3 presents descriptive statistics for LNFPI and LNEPI. Mean and median values are close, indicating a balanced distribution. LNFPI shows greater volatility (standard deviation: 0.96) than LNEPI (0.81). Skewness, kurtosis, and Jarque-Bera test results ($p < 0.01$) confirm that neither variable follows a normal distribution. Covariance and correlation analyses reveal a strong positive relationship, with a correlation coefficient of 0.9938, indicating that the two variables move closely together. However, since both variables are non-stationary at levels, this high correlation may reflect a common stochastic trend. Therefore, cointegration analysis is required to determine whether the relationship represents a stable long-run equilibrium rather than a spurious association.

Table 4 – Linearity Test Results

Variables	**Harvey et al. (2008)**
LNFPI	4.64*
LNEPI	12.88***

Note: Critical values for Harvey et al. (2008) test at 1%, 5%, and 10% are 9.21, 5.99, and 4.60 respectively. *, **, and *** denote rejection of the null hypothesis of linearity at the 10%, 5%, and 1% significance levels, respectively.

The linearity test results presented in Table 4 indicate that the LNFPI variable is nonlinear at the 10% significance level according to the Harvey et al. (2008) test. The LNEPI variable is nonlinear at the 1% significance level based on the same test.

The results of the FKSS unit root tests for the LNFPI and LNEPI series are presented in Tables 5 and 6. The test results have been evaluated separately for models with intercept and models with intercept and trend.

Table 5 – FKSS Unit Root Test for LNFPI

LNFPI	**k**	$\boldsymbol{F - t_{NL}}$	$\boldsymbol{F_\mu(\hat{k})}$	**optimallag**	**MinSSR**
Constant	1	1.92354	81.85614**	1	150.65545
	k	$F - t_{NL}$	$F_t(\hat{k})$	optimallag	MinSSR
C&T	1	-1.85523	400.39865**	1	7.53467
	k	$F - t_{NL}$	$F_\mu(\hat{k})$	optimallag	MinSSR
ΔConstant	1	-4.02993**	15.11483**	1	0.15168
	k	$F - t_{NL}$	$F_t(\hat{k})$	optimallag	MinSSR
Δ C&T	1	-4.07950**	10.45863**	1	0.13714

Note: * and ** denote significance at the 10% and 5% levels, respectively. Δ denotes the first difference of the series.

Table 5 presents the optimal frequency number k for both Constant and C&T models, the $F - t_{NL}$, $F_\mu(\hat{k})$, and $F_t(\hat{k})$ statistics, optimal lag lengths (AIC-based), and MinSSR values. For the constant model, the $F - t_{NL}$statistic for LNFPI is 1.92354, which is smaller than the 5% critical value in absolute terms (-3.67), indicating non-stationarity. However, the $F_\mu(\hat{k})$, statistic of 81.85614 exceeds the critical value of 4.651, confirming the significance of trigonometric terms. Similarly, in the trend model, the $F - t_{NL}$ statistic of -1.85523 indicates non-stationarity, but the $F_t(\hat{k})$ value of 400.39865 shows significance. After first differencing, stationarity is achieved in both models. The differenced $F - t_{NL}$ statistics are -4.02993 (constant) and -4.07950 (C&T), satisfying the stationarity conditions. $F_\mu(\hat{k})$, and $F_t(\hat{k})$ statistics also confirm this. These results validate the FKSS unit root test proposed by Christopoulos and Leon-Ledesma (2010), indicating that LNFPI follows an I(1) process.

MinSSR values significantly decrease after differencing (from 150.65545 to 0.15168 for the constant model, and from 7.53467 to 0.13714 for the C&T model), reflecting a better model fit.

Table 6 – FKSS Unit Root Test for LNEPI

LNEPI	**k**	$F - t_{NL}$	$F_\mu(\hat{k})$	**optimallag**	**MinSSR**
Constant	1	1.86934	65.18885**	1	117.20068
	k	$F - t_{NL}$	$F_t(\hat{k})$	optimallag	MinSSR
C&T	1	-1.80719	302.85973**	1	6.24205
	k	$F - t_{NL}$	$F_\mu(\hat{k})$	optimallag	MinSSR
ΔConstant	1	-12.12755**	6.14751**	0	0.26687
	k	$F - t_{NL}$	$F_t(\hat{k})$	optimallag	MinSSR
Δ C&T	1	-11.65276**	6.10070**	0	0.25394

Note: * and ** denote significance at the 10% and 5% levels, respectively. Δ denotes the first difference of the series.

In Table 6, for the constant model, the $F - t_{NL}$ statistic for the LNEPI series is 1.86934, smaller than the 5% critical value in absolute terms (-3.67), indicating non-stationarity. However, the $F_\mu(\hat{k})$ statistic is 65.18885, exceeding the 5% critical value of 4.651, confirming the significance of the trigonometric terms. In the trend-included model (C&T), the $F - t_{NL}$ statistic is -1.80719, also indicating non-stationarity, but the $F_t(\hat{k})$ statistic of 302.85973 confirms the significance of the trigonometric terms. After first differencing, stationarity is achieved in both models. The differenced $F - t_{NL}$ statistics are -12.12755 (constant model) and -11.65276 (C&T model), both satisfying stationarity conditions. Corresponding $F_\mu(\hat{k})$ and $F_t(\hat{k})$ statistics also support this conclusion. These results validate the FKSS unit root test by Christopoulos and Leon-Ledesma (2010), confirming that LNEPI follows an I(1) process.

The results of the Fourier cointegration test, which incorporates trigonometric terms to account for structural breaks, are presented in Table 7.

Table 7 – Fourier Cointegration Test

Dependent Variable: LNFPI					
With Constant			**Critical Values**		
Min SSR*	k	CI_f^0	%1	%5	%10
0.15470	1	0.04312	0.200	0.276	0.473
F-Statistics for Fourier Cointegration Analysis					
l_{opt}	k	$F^m(k^*)$	%1	%5	%10
6	1	16.92172	3.352	4.066	5.774
With Constant & Trend			**Critical Values**		
Min SSR*	k	CI_f^1	%1	%5	%10
0.15191	1	0.04325	0.078	0.099	0.163
F-Statistics for Fourier Cointegration Analysis					
l_{opt}	k	$F^m(k^*)$	%1	%5	%10
6	1	17.11439	3.306	4.019	5.860

Note: In the Fourier cointegration test, the critical values used to test the presence of a cointegration relationship and the critical values for the F-statistic used to test the significance of the trigonometric terms are obtained from Tsong et al. (2016: 1190). *SSR represents the sum of squared residuals.

Table 7 presents the frequency number k, the CI_f^0 test statistic for the constant model, the CI_f^1 test statistic for the constant and trend model (C&T), the $F^m(k^*)$ test statistic, the minimum sum of squared residuals (MinSSR), and the optimal lag length l_{opt} $\left(T^{\frac{1}{3}}\right)$. For the constant specification, the CI_f^0statistic (0.04312) is lower than the 5% critical value (0.276). Therefore, the null hypothesis of cointegration cannot be rejected, indicating the presence of a cointegration relationship between LNFPI and LNEPI. The $F^m(k^*)$statistic (16.92172) exceeds the corresponding 5% critical value (4.066), confirming the statistical significance of at least one trigonometric term.

Similarly, in the C&T model, the CI_f^1statistic (0.04325) is below the 5% critical value (0.099). Accordingly, the null hypothesis of cointegration cannot be rejected, indicating a long-run relationship between LNFPI and LNEPI. The $F^m(k^*)$statistic (17.11439) exceeds the corresponding 5% critical value (4.019), confirming the statistical significance of the trigonometric terms. These findings are consistent with the presence of a cointegration relationship as suggested by the Fourier cointegration framework of Tsong et al. (2016). Additionally, the low MinSSR values (0.15470 for the constant model and 0.15191 for the C&T model) further support the stability of the estimated long-run relationship.

Table 8 presents the long-term estimation results obtained using FMOLS, DOLS, and CCR methods, with LNFPI as the dependent variable and LNEPI as the independent variable.

Table 8 – Long-Term Estimation

Dependent Variable: LNFPI				
Long-run covariance estimate (Bartlett kernel, Newey-West fixed bandwidth = 5.0000)				
		DOLS		
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNEPI	1.133976	0.026362	49.71483	0.0000
SIN1	0.066522	0.007624	8.72490	0.0000
COS1	-0.049658	0.008095	-6.13416	0.0000
C	-0.573004	0.117116	-13.43114	0.0000
R-squared	0.9929931	Mean dependent var	5.7244206	
Adjusted R-squared	0.9924862	S.D. dependent var	0.8858281957	
S.E. of regression	0.0767856	Sum squared resid	1.3855695434	
Long-run variance	0.028569			

FMOLS				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNEPI	1.135595	0.014866	76.38875	0.0000
SIN1	-0.048303	0.016671	-2.897421	0.0041
COS1	0.095651	0.014433	6.627120	0.0000
C	-0.696335	0.084982	-8.193965	0.0000
R-squared	0.992938	Mean dependent var	5.756174	
Adjusted R-squared	0.992856	S.D. dependent var	0.959324	
S.E. of regression	0.081082	Sum squared resid	1.715884	
Long-run variance	0.025481			

CCR				
Variables	**Coefficient**	**Std. Error**	**t-Statistic**	**Prob.**
LNEPI	1.136126	0.015065	75.41369	0.0000
SIN1	-0.047859	0.016832	-2.843336	0.0048
COS1	0.096103	0.014142	6.795633	0.0000
C	-0.699196	0.085848	-8.144563	0.0000
R-squared	0.992931	Mean dependent var	5.756174	
Adjusted R-squared	0.992849	S.D. dependent var	0.959324	
S.E. of regression	0.081122	Sum squared resid	1.717586	
Long-run variance	0.025481			

The results reported in Table 8 indicate that the long-run coefficient of LNEPI is statistically significant across all estimation methods, suggesting the presence of a stable long-run relationship between LNEPI and LNFPI. The DOLS, FMOLS, and CCR estimators produce highly consistent coefficients (1.133976, 1.135595, and 1.136126, respectively), indicating robustness across alternative long-run estimation techniques. The statistical significance of the sine and cosine terms confirms the relevance of the Fourier components in capturing structural shifts and periodic fluctuations.

In particular, the DOLS estimator yields a coefficient of 1.133976 with a standard error of 0.026362 and a t-statistic of 49.71483, indicating statistical significance at conventional levels. Similar results are obtained under FMOLS and CCR specifications. Overall, the consistency of the estimated coefficients across methods suggests a stable long-run association between LNEPI and LNFPI.

Following these estimations, an asymmetric causality test was performed, and the results are presented in Table 9. The Hacker and Hatemi-J (2006) causality test builds on the Toda–Yamamoto (1995) augmented VAR framework and evaluates Granger-type predictive causality using bootstrap critical values. Accordingly, the results indicate predictive directional dependence within the specified VAR system and should not be interpreted as evidence of structural economic causality.

Table 9 – Causality Test Results

Hacker-Hatemi-J (2006) Causality Test Results

Null Hypothesis	Test Statistic	Bootstrap Critical Values		
		%1	%5	%10
Y≠>X Rejection	21.259***	18.398	13.186	10.992
X≠>Y Rejection	17.226**	18.372	13.454	11.106

Hatemi-J (2012) Asymmetric Causality Test Results

Null Hypothesis	Test Statistic	Bootstrap Critical Values			Null Hypothesis	Test Statistic	Bootstrap Critical Values		
		%1	%5	%10			%1	%5	%10
Y(+)≠>X(+) Rejection	55.78***	22.177	16.188	13.872	X(+)≠>Y(+) Rejection	22.272**	23.696	16.665	14.107
Y(-)≠>X(-) Acceptance	0.010	19.631	7.338	4.615	X(-)≠>Y(-) Acceptance	0.248	18.331	6.658	4.405
Y(-)≠>X(+) Rejection	11.794*	29.018	14.592	11.073	X(+)≠>Y(-) Rejection	17.939**	29.790	14.219	11.076
Y(+)≠>X(-) Acceptance	5.949	27.699	19.154	15.730	X(-)≠>Y(+) Acceptance	6.558	27.519	18.883	15.594

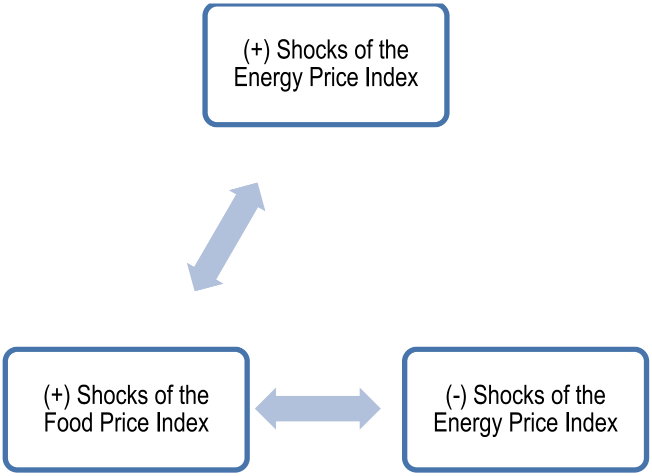
Note: In this table, Y represents LNEPI and X represents LNFPI. The expression X(+)⇏Y(+) corresponds to the null hypothesis stating that "positive shocks in LNFPI do not cause positive shocks in LNEPI". If the null hypothesis is rejected, it indicates the presence of directional causality. *, **, and *** denote significance at the 10%, 5%, and 1% levels, respectively.

According to Table 9, the results suggest bidirectional Granger-type predictive causality between LNEPI (Y) and LNFPI (X) at conventional significance levels. The null hypothesis that positive shocks in LNFPI do not Granger-cause positive shocks in LNEPI (X(+) ⇏ Y(+)) is rejected (Wstat = 22.272 > 16.665). Similarly, the reverse null hypothesis (Y(+) ⇏ X(+)) is also rejected, indicating bidirectional predictive dependence within the Granger framework. No statistically significant predictive causality is detected for negative shocks (X(−) ⇏ Y(−), Y(−) ⇏ X(−)), suggesting that negative price movements are not systematically followed by corresponding negative movements in the other sector.

Regarding cross-shock dynamics, the null hypothesis X(+) ⇏ Y(−) is rejected (Wstat = 17.939 > 11.076), indicating that positive shocks in food prices are followed by negative movements in energy prices. Similarly, Y(−) ⇏ X(+) is rejected at the 10% level (Wstat = 11.794 > 11.073), pointing to asymmetric cross-shock interactions. These findings reflect asymmetric predictive dynamics between positive and negative shocks. However, it should be emphasized that the results indicate Granger-type predictive causality and do not imply structural economic causality. Although the bootstrap approach enhances robustness against non-normal error distributions and small-sample distortions, the causality results remain conditional on model specification, lag selection, and the information set included in the VAR framework. Therefore, the findings should be interpreted within the limits of the econometric model.

The causality relationships are illustrated in Figure 2.

Figure 2 – Asymmetric Causality Diagram



These findings suggest that asymmetric Granger-type predictive relationships between positive and negative shocks appear only under specific directions and statistical conditions.

5. Discussion

The findings show that the relationship between energy and food prices in Türkiye is nonlinear, cointegrated, and asymmetric. The FKSS unit root tests (Tables 5 and 6) indicate the integration properties of the series, while the Fourier Cointegration Test (Table 7) points to a persistent long-run relationship between the variables. Long-term coefficient estimates (Table 8) suggest that a 1% increase in energy prices is associated with approximately a 1.13% increase in food prices in the long run. This result is consistent with studies such as Borrallo et al. (2024), Wehinger (2000), and Gartner & Wehinger (1998), which emphasize the role of energy costs in food price dynamics and the relevance of core inflation analyses for policymakers.

The Asymmetric Causality Test (Table 9) provides evidence of bidirectional Granger-type predictive causality for positive shocks, whereas no statistically significant predictive relationship is found for negative shocks. This asymmetric pattern may be consistent with price adjustment frictions, including potential price stickiness, as discussed by Fielding & Mizen (2000) and Borrallo et al. (2024). In this setting, upward adjustments appear to be transmitted more systematically than downward adjustments.

This study contributes to the literature by combining asymmetric causality analysis with Fourier transformations to examine how energy price fluctuations are transmitted to food prices. The results indicate that the interaction between the two sectors involves nonlinear and asymmetric predictive dynamics rather than purely symmetric short-term movements.

From a policy perspective, the findings suggest the importance of considering sectoral interdependencies and technological factors such as energy-efficient agricultural practices (Armah et al., 2009). Moreover, global shocks, including the COVID-19 pandemic and geopolitical tensions, highlight the need for flexible policy responses (Borisov, 2024; Irwin & Penn, 1975). The empirical results remain conditional on model specification, lag selection, and the information set included in the VAR framework. Therefore, they should be interpreted as evidence of predictive relationships rather than structural economic causality.

6. Conclusion

This study identifies a long-term relationship between energy and food prices using Fourier-based cointegration tests. The results indicate persistent linkages between these markets over the sample period. The findings suggest that shocks in energy and food prices are associated with sustained movements in the respective price indices, shaping inflation dynamics over time. Increases in energy prices are linked to higher food production costs, particularly in developing economies where such pressures can significantly affect living costs.

The long-term coefficient estimates imply an elasticity of approximately 1.13 between energy and food prices. Accordingly, a 1% increase in energy prices is associated with about a 1.13% increase in food prices in the long run. These results underline the importance for central banks and policymakers – especially those operating under inflation-targeting regimes – to monitor developments in both energy and food markets. The Hatemi-J asymmetric causality analysis further provides evidence of bidirectional Granger-type predictive causality and asymmetric predictive dynamics. Positive shocks appear to be followed by more persistent adjustments than negative shocks, which may be consistent with price stickiness. Upward price movements are transmitted more systematically than downward movements within the limits of the econometric framework.

Although the study contributes to the literature by combining Fourier methods with asymmetric causality analysis, the results remain conditional on model specification and the data structure for Türkiye. Future research may extend the analysis to additional countries and incorporate exchange rate dynamics, agricultural input costs, and global supply shocks. Further work on the implications of the energy transition and renewable energy adoption for food production processes could provide additional insights for economic policy design.

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Impact of plastic pollution on ecosystem dynamics and greenhouse gas emissions: Empirical evidence and policy implications

Leila Ben Ltaief [*]

Abstract

The present study undertakes an evaluation of the magnitude of plastic pollution and analyses its repercussions on aquatic, terrestrial, and atmospheric ecosystems, with a specific emphasis on the CO_2 emissions that are a consequence of this pollution. The empirical analysis focuses on a sample of twenty Asian and OECD countries in order to compare the dynamics of plastic production, consumption, and management during 2000-2023.

The findings indicate the presence of significant disparities between the two regions. The Asian economies are distinguished by a pervasive presence of plastic pollution, a phenomenon that is intricately intertwined with the pursuit of rapid economic growth and the dearth of comprehensive waste management systems. In contrast, OECD countries benefit from more structured environmental policies, yet continue to exhibit notably elevated levels of consumption. The analysis also reveals a significant correlation between plastic pollution and carbon dioxide emissions, illustrating the contribution of this pollution to the worsening of climate change. The findings emphasize the necessity for the implementation of integrated public policies that encompass a multifaceted approach to address the environmental and socio-economic challenges posed by plastic.

Keywords: climate change, plastic pollution, GHG emissions, Asian and OECD countries, system GMM.

JEL classification: P52, Q53, Q54, Q57

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1. Introduction

Plastic pollution has emerged as a significant environmental concern on a global scale. The increasing prevalence of microplastics across diverse ecosystems – including terrestrial, atmospheric, freshwater, and marine environments – reflects the combined effects of population growth, rapid urbanization, and the exponential expansion of plastic production. Once released into the environment, these particles undergo transport through atmospheric, hydrological, and biological pathways, resulting in

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habitat degradation, disruption of ecological processes, contamination of food webs, and significant threats to the survival of numerous plant and animal species.

Recent research increasingly positions plastic pollution as a critical structural driver of terrestrial ecosystem change. The accumulation of microplastics in soils has been demonstrated to effect alterations to key physicochemical and biological properties, including aggregate stability, porosity, water retention, and nutrient availability. These modifications have the potential to disrupt primary productivity and vegetation dynamics, thereby revealing indirect pathways through which plastic pollution shapes ecosystem functioning and resilience (De Souza Machado et al., 2018; Qi et al., 2018).

Furthermore, microplastics are increasingly recognized not only as pollutants but also as active agents with the capacity to reshape soil ecosystem structure and function. The presence of these substances has been demonstrated to induce alterations in the composition, diversity, and metabolic activity of microbial communities and soil fauna. This, in turn, has been demonstrated to disrupt fundamental biogeochemical cycles, including carbon and nitrogen turnover. From a theoretical standpoint, microplastics have been highlighted as mediators of indirect ecological effects. The interactions of microplastics with biological and physicochemical soil components propagate systemic changes that compromise ecosystem functionality, resilience, and service provision under combined anthropogenic and climatic pressures (Rillig et al., 2019).

The ingestion and accumulation of microplastics by soil organisms establishes a mechanistic pathway that links particle contamination to trophic and structural alterations. The process has been demonstrated to influence a variety of factors, including organismal behavior, physiological performance, and species interactions. The resultant effect of these changes is the intensification of soil structure degradation, which in turn triggers cascading ecological consequences (Huerta Lwanga et al., 2016). Conceptually, these findings advance a framework in which microplastics are not passive contaminants but dynamic disruptors capable of reshaping terrestrial ecosystem processes at multiple scales.

In the context of marine ecosystems, microplastics are increasingly recognized as a pervasive and systemic stressor that penetrates aquatic food webs, impacting organisms across multiple trophic levels. Mithun et al. (2024) provide empirical evidence that microplastic exposure has a detrimental effect on contaminant bioaccumulation and elicits direct toxic effects, including oxidative stress, reproductive impairments, and neurotoxicity in both invertebrates and fish. From a theoretical standpoint, this lends support to the concept of microplastics as vectors that amplify chemical stressors within ecological networks. Furthermore, recent studies have emphasised the interactive effects of microplastic pollution and climate change, particularly in freshwater systems, where elevated temperatures exacerbate negative outcomes on growth, reproduction, and stress physiology (Teggers et al., 2025). This emphasises the heightened vulnerability of aquatic organisms to multiple, concurrent anthropogenic pressures.

The presence of plastic pollution has expanded beyond terrestrial and aquatic environments, becoming pervasive in the atmosphere as well. In this novel domain, micro- and nanoplastics have emerged as contaminants of concern, with the potential to exert substantial ecological and climatic impacts. These particles are released from a variety of anthropogenic sources, including tire wear, the abrasion of synthetic textiles, and the mechanical fragmentation of plastic waste. This phenomenon facilitates long-range transport via atmospheric circulation (Yang et al., 2024).

From a climate-process perspective, Seifried et al. (2026) propose that atmospheric microplastics may actively participate in aerosol formation and modification, although the precise mechanisms remain under investigation. These particles have the capacity to indirectly modify cloud microphysics and potentially influence precipitation patterns, with cascading effects on regional and global climate systems. Theoretically, this positions atmospheric plastic pollution as a systemic disruptor, linking terrestrial, freshwater, and marine biogeochemical cycles, rather than merely an air quality issue. This underscores the necessity of incorporating microplastic dynamics into ecological models and international environmental policies that target the mitigation of atmospheric contaminants.

The present study is situated within the aforementioned context and is structured around two complementary objectives. Firstly, it provides a comprehensive theoretical analysis of the mechanisms of plastic production and degradation, as well as their effects on terrestrial, aquatic, and atmospheric ecosystems. Secondly, an empirical approach is employed to investigate the interactions between plastic pollution and socio-economic, environmental, and institutional variables across 20 Asian and OECD countries. This methodological framework encompasses a systematic evaluation of the contribution of plastic pollution to greenhouse gas emissions. The analysis covers the period from 2000 to 2023 and is founded upon a Generalized Method of Moments (GMM) model.

This research contributes to the extant body of experimental studies by adopting a more extensive analytical framework that integrates key macroeconomic variables, such as production, trade, and consumption patterns. This approach situates plastic pollution within global economic systems while identifying the structural forces that drive it. Furthermore, it introduces an innovative methodology that enhances analytical rigor and supports cross-scale comparisons.

By emphasizing the interconnected nature of environmental, economic, and social factors, the study provides a solid foundation for future research on the global impacts of plastic pollution. This systemic and interdisciplinary perspective is imperative for the development of effective public policies and sustainable management strategies, particularly given the transboundary nature of the issue.

The subsequent section presents a critical review of the relevant literature, followed by a detailed outline of the methodology and the specification of the econometric model. The empirical results are then presented and analyzed, before a discussion synthesizes the main findings and their implications, leading to the conclusion.

2. Literature review

Plastic pollution is acknowledged as one of the predominant anthropogenic pressures impacting global ecosystems. The presence of microplastics in significant quantities in marine environments is attributable to multiple factors, including the progressive fragmentation of large plastic debris, industrial effluents, and urban runoff. These organisms interact with a wide range of other organisms across different trophic levels, facilitating their incorporation into ecological networks. The ingestion and subsequent accumulation of these substances within biological tissues, along with their role in entanglement phenomena, constitute significant stressors that can impact the physiology, reproductive success, and survival of marine organisms.

In this context, Zahari et al. (2022) make a significant contribution to the expanding body of research that frames microplastics as dynamic agents within coastal sedimentary systems, as opposed to viewing them as passive pollutants. The present study was conducted empirically at two intertidal beach sites in Sabah, Malaysia, with the objective of assessing both the presence and the environmental significance of plastic contamination in coastal sediments. Sediment samples were systematically collected and processed using a density separation technique to isolate microplastics, ensuring methodological robustness and comparability with existing studies. The extracted particles were then subjected to complementary visual and chemical analyses, allowing for a detailed characterization of their abundance, size distribution, and polymer composition.

The results indicate a significant presence of microplastics, predominantly composed of small particles of polypropylene and polyethylene. It is of particular significance that these particles frequently co-occur with metals, providing empirical evidence that lends support to the theoretical assumption that microplastics can act as vectors for contaminant transport. By demonstrating this association in situ, the study not only documents pollution levels in a relatively underexplored region but also strengthens the conceptual understanding of microplastics as mediators of pollutant mobility and bioavailability. Consequently, it provides a substantial contribution to the wider discussion on the ecological risks posed by microplastics in coastal environments.

Building on this line of inquiry, Apete et al. (2024) examine fishing-related plastic debris within a socio-ecological framework that recognizes its environmental, economic, and health implications. Utilizing a meticulous examination of scientific and technical literature, which has been selected according to well-defined criteria, the authors synthesize evidence on the abundance, composition, and impacts of such debris. Their analysis identifies fishing residues, particularly nets, ropes and lines, as significant contributors to plastic pollution in specific marine regions. These materials pose a number of risks, including harm to marine fauna, the transport of contaminants, and negative socio-economic effects on coastal communities. The study also underscores substantial knowledge gaps, particularly with regard to long-term impacts and spatial distribution. This viewpoint is corroborated by Grewal et al. (2024), who demonstrate that these pollution pathways have the capacity to compromise the quality of seafood and to disseminate microplastics throughout the food chain, thereby giving rise to concerns regarding public health.

In their 2025 study, Liu and Li propose a novel conceptualization of aquatic ecosystems as dynamic reservoirs and active sinks of microplastics. This theoretical framework integrates the issue of microplastic contamination within a broader theoretical framework of multiple, interacting anthropogenic stressors. The analysis emphasizes that microplastic pollution cannot be comprehended as a standalone phenomenon; rather, it should be regarded as a component of a cumulative pressure system that encompasses thermal warming and other human-induced disturbances. In this context, it is demonstrated that such combined stressors have the capacity to destabilize both benthic and pelagic communities, to alter biogeochemical cycles and ultimately to reduce the resilience and adaptive capacity of aquatic ecosystems. The scientific contribution of their work lies in advancing an integrative perspective that links microplastic contamination to ecosystem functioning and stability, rather than merely documenting its occurrence. By emphasizing the synergistic effects between pollution and climate-related stressors, the study offers a more comprehensive understanding of ecosystem vulnerability. Furthermore, it identifies regions undergoing rapid urbanization and characterized by inadequate waste management as critical hotspots, thereby offering valuable insights for prioritizing future research and environmental management strategies.

The atmospheric accumulation of microplastics gives rise to significant concerns with regard to air quality and highlights their role as vectors of contamination across sensitive ecosystems. In this emerging research field, Gunthe et al. (2021) adopt an integrative atmospheric chemistry approach to examine microplastic-related aerosol dynamics in the urban environments of Delhi and Chennai. The present study combines in situ measurements of submicron aerosols using an Aerosol Chemical Speciation Monitor with thermodynamic simulations based on the ISORROPIA II model. This methodological approach enables the integration of empirical observations with process-based modeling. Their findings reveal a persistent presence of chloride in aerosols, which enhances hygroscopic growth under ammonia-rich conditions and contributes to the formation and persistence of haze events. Of particular significance is the co-occurrence of reactive chlorine species and plastic-derived particles, which indicates the potential for physicochemical interactions that could lead to alterations in the properties of aerosols. This suggests that microplastics could influence atmospheric processes by extending their residence time and modifying particle reactivity. The present study makes a significant contribution to the advancement of scientific knowledge in this field by offering a mechanistic understanding of the interaction between microplastics and atmospheric constituents. This, in turn, serves to expand current perspectives on the role of microplastics in air pollution and their broader environmental impacts.

Moreover, research conducted in protected and remote ecosystems, including the Mangroves and Sundarbans of Bangladesh and India, has demonstrated the presence of atmospheric microplastics even in the absence of direct urban influence. These observations are consistent with the findings of Sathyamohan et al. (2023), and support a growing theoretical perspective that frames microplastics as highly mobile contaminants capable of long-range atmospheric transport and deposition. This challenges the conventional perspective of plastic pollution as a predominantly local or coastal issue, emphasizing its transboundary nature.

In this context, Ammendolia et al. (2025) extend the analysis by examining the biological implications of atmospheric exposure. The research indicates that aerobic organisms, encompassing birds, pollinating insects, and other air-dependent fauna, are subject to continuous exposure to microplastics via inhalation. This exposure pathway introduces a critical, yet underexplored, dimension of ecological risk, as the persistence and small size of these particles may induce physiological stress and disrupt normal biological functions. Collectively, these studies contribute to a more integrated understanding of atmospheric microplastics, linking their dispersal dynamics to ecological vulnerability and reinforcing their significance within global pollution frameworks.

In the context of terrestrial ecosystems, the MICROSOF project (2024) provides a pioneering contribution by establishing the first national benchmarks for microplastic contamination in French soils. A systematic analysis of 33 soil samples drawn from the French soil quality monitoring network was undertaken, revealing the presence of microplastics in 76% of the sites, with a particularly high prevalence in agriculturally managed soils. By establishing a correlation between the presence of microplastic and its potential ecological and agronomic impacts, including alterations in soil biodiversity, inhibition of plant growth, and reductions in agricultural productivity, the research contributes to a theoretical understanding of soils as active sinks for persistent pollutants. The present study makes a significant contribution to the extant body of knowledge by conceptualizing microplastic pollution not merely as a chemical contaminant, but as a factor with tangible consequences for ecosystem functioning and food security. This framework provides critical data to guide both environmental monitoring and sustainable land management strategies.

In their study, Chen et al. (2025) investigated the interactions between polyethylene microplastics and aged biochar, in order to evaluate their combined effects on soil greenhouse gas dynamics. The research, which was conducted over the course of a 91-day laboratory experiment, has made significant contributions to the theoretical understanding of the ways in which microplastics interfere with biochemical processes in soil and carbon stabilization mechanisms. The findings indicate that the presence of microplastic has a detrimental effect on the efficacy of biochar, resulting in increased greenhouse gas emissions and diminished microbial necromass carbon sequestration. These findings provide support for the hypothesis that plastic pollution constitutes a significant barrier to effective carbon management and sustainable soil practices. The present study makes a significant contribution to the field by emphasizing the necessity of accounting for microplastic contamination in soil amendment strategies. It is imperative that pollution considerations are incorporated into ecosystem management and climate mitigation frameworks.

In their seminal study, Shi et al. (2025) employed controlled microcosm experiments to investigate the influence of microplastics on the bio-accessibility of dissolved organic matter and the dynamics of mineral-associated carbon in soils. The present study employs an experimental approach to investigate the interactions between synthetic particles and soil carbon processes. In order to achieve this objective, microplastics composed of diverse polymer types are subjected to incubation with mineral matrices, and the ensuing results are then compared with those derived from natural organic matter. This methodological approach offers mechanistic insights into the subject. The findings indicate that microplastics have a substantial impact on carbon dioxide (CO_2) emissions, exhibiting a range of 21% to 576% increase, while concurrently diminishing mineral-associated organic carbon by 34% to 83%. The findings demonstrate that microplastic contamination has the potential to destabilize soil carbon stocks and intensify greenhouse gas emissions, thus highlighting an hitherto underappreciated pathway through which plastic pollution can undermine soil ecosystem functioning and contribute to climate change.

Flood-Garibay et al. (2023) present a comprehensive review of the extant literature on the neurological impacts of suspended and ultrafine particles originating from urban plastic pollution. Utilizing a systematic review of epidemiological and experimental studies, the authors assess particle composition, concentration, and sources across diverse urban settings. The analysis demonstrates a correlation between exposure to fine and ultrafine particles and the accumulation of nanoparticles in the brain. This accumulation has been demonstrated to trigger inflammatory and oxidative responses, which may contribute to neurodegenerative diseases such as Alzheimer's and Parkinson's. Of particular significance is the study's finding that chronic exposure to plastic may also result in impaired cognitive function, delayed neurological development, and deterioration in mental health. This development serves to expand the established health risks associated with plastic pollution, extending beyond the respiratory and cardiovascular effects that have previously been documented. This work contributes to the theoretical understanding of environmental neurotoxicology and emphasizes the pressing need to incorporate plastic-derived particles into public health strategies.

This synthesis of the scientific literature underscores the systemic nature and complexity of the dynamics associated with plastic pollution and microplastics, as well as their multiscalar impacts on ecosystems and biogeochemical processes. In this context, the following section endeavors to address the identified knowledge gaps by proposing an integrated empirical framework. The overarching objective of this framework is to elucidate the socio-economic, environmental, and institutional dimensions that underpin plastic pollution. Furthermore, the model has been developed for the purpose of facilitating a quantitative assessment of their contribution to greenhouse gas emissions using advanced econometric models.

3. Model specification, variables definition, and methodological approach

The period from 2000 to 2023 has been characterized by a simultaneous expansion of plastic production, an increasing accumulation of microplastics in natural ecosystems, and a sustained rise in greenhouse gas emissions. The present study focuses on Asian countries and OECD member states, which were selected based on three key criteria. Firstly, it is imperative to acknowledge that these regions collectively contribute to more than 70% of the global greenhouse gas emissions (OECD, 2025). Secondly, the selected countries exhibit substantial heterogeneity in their ecological and socio-economic characteristics, providing a suitable analytical context for investigating the linkages between plastic production, environmental pollution, and greenhouse gas emissions. Thirdly, these countries offer reliable and internationally comparable data for the variables included in the system GMM framework, which is essential to ensure the robustness of the empirical analysis.

3.1. Problematic

This empirical research aims to address two fundamental questions:

- To what extent do socio-economic and institutional factors drive plastic pollution in contrasting regional contexts, specifically between Asian countries and OECD member states?
- How does plastic pollution contribute to the intensification of greenhouse gas emissions?

By addressing these inquiries, the study contributes to a more profound comprehension of the dynamic interactions between plastic pollution, and greenhouse gas emissions, offering insights that can inform targeted and effective policy interventions.

3.2. Model specification

Equation (1) is designed to explain the level of plastic pollution generated ($PP_{i,t}$) based on the selected socio-economic and institutional variables (Table 1). The dynamic model can be formulated as follows:

$$PP_{i,t} = \alpha_0 + \alpha_1 PP_{i,t-1} + \beta_1 AGE15\text{-}64_{i,t} + \beta_2 AGE65^{+}_{i,t} + \beta_3 URB_{i,t} + \beta_4 UPRI_{i,t} + \beta_5 MAN_{i,t} + \beta_6 SER_{i,t} + \beta_7 CC_{i,t} + \beta_8 GDPPCG_{i,t} + \mu_i + \lambda_t + \nu_{i,t} \quad (1)$$

Equation (2) examines the effects of carbon dioxide (CO_2), generated by plastic pollution, on greenhouse gas emissions ($GHG_{i,t}$):

$$GHG_{i,t} = \gamma_0 + \gamma_1 GHS_{i,t-1} + \delta_1 CO_{2i,t} + \delta_2 GDPPCG_{i,t} + \mu_i + \lambda_t + \nu_{i,t} \quad (2)$$

The model incorporates individual fixed effects (μ_i), time effects (λ_t), and an idiosyncratic error term ($\nu_{i,t}$). The selection of explanatory variables is grounded in a thorough review of the recent econometric literature, notably the studies by Pambudi et al. (2025) and Zhang et al. (2021), which are widely recognized as key references in this field. The estimation process employs the system generalized method of moments (System GMM) framework, which was developed by Blundell and Bond (1998) for dynamic panel models. This approach rigorously addresses endogeneity, reverses causality, measurement errors, and omitted variable bias by combining equations in first differences and in levels. It provides estimates that are consistent, efficient, and robust, as emphasized by Baum et al. (2007). The assessment of variable stationarity is conducted through the implementation of panel unit root tests, as proposed by Im et al. (2003). The evaluation of instrument validity is facilitated by the Hansen and Sargan tests. Finally, serial correlation in the residuals is examined via the Arellano-Bond AR(1) and AR(2) tests.

Table 1 – Definition of variables

Variables	Definitions	Sources
	Dependent variables	
$PP_{i,t}$: Plastic pollution	Plastic pollution (PP) is defined as the annual quantity of inadequately managed plastic waste. This includes waste discharged into terrestrial, atmospheric, and aquatic ecosystems, “unaccounted for” waste (for which the treatment category is unspecified), as well as “other” types of waste, i.e., those that do not fall into any of the categories defined by the World Bank. PP is measured in metric tons.	World Bank Group (2023a; 2023b)
$GHS_{i,t}$: Greenhouse gases	These gases are responsible for the trapping of heat within the atmosphere, thereby contributing to the phenomenon of global warming. As a consequence of human activities, there has been an increase in the number of these entities, which has the effect of intensifying this phenomenon and giving rise to climate change (Gallandat *et al.*, 2017).	World Development Indicators (WDI)
	Independent variables	
$AGE15\text{-}64_{i,t}$: Population age group 1	This demographic variable represents the percentage of the population aged 15–64 years. It reflects the active labor force, which is expected to influence both the consumption and production of plastic waste (Yan et al., 2024). The coefficient of this variable is anticipated to have a positive sign.	(WDI)
$AGE65^{+}_{i,t}$: Population age group 2	$AGE65^{+}$ represents the share of the population aged 65 and over in the total population. This demographic group is often associated with distinct consumption patterns and potentially different waste management practices. The coefficient of this variable is expected to be positive.	(WDI)
$URB_{i,t}$: Proportion of urban population in the total population	URB is measured as the percentage of the population residing in urban areas, where higher population density and urban lifestyles often lead to increased plastic waste generation (OECD, 2022; 2024). The expected sign is positive.	(WDI)
$UPRI_{i,t}$: Percentage of the largest city’s population in the urban population	The UPRI is defined as the percentage of the urban population in the largest city and is used to describe urbanization patterns. The coefficient of this variable is expected to be positive.	(WDI)
$MAN_{i,t}$: Value-added output of the manufacturing sector ; percentage of GDP	MAN represents the value-added MAN, as percentages of the GDP and is considered as proxy for the contribution of the manufacturing sector to the GDP. The expected sign of its coefficient is positive.	(WDI)
$SER_{i,t}$: Value-added output of the service sector ; percentage of GDP	SER represents the value-added of the service sector as a share of GDP and is used as a proxy for the sector’s contribution to the GDP. The expected sign is positive	(WDI)
$GDPPCG_{i,t}$: annual growth rate of GDP per capita at constant 2010 prices.	GDPPCG is a key economic indicator, defined as the change in average per capita wealth generated over a given period (Stern, 2004). The coefficient of this variable is expected to be positive.	(WDI)
$CO_{2i,t}$: Percentage of CO_2 emissions produced by plastic pollution	This variable denotes the greenhouse gases that are produced during the manufacturing, transportation, utilization, and disposal of plastics, with the majority of these gases being derived from fossil fuels (Geyer *et al.*, 2017; Royer *et al.*, 2018). The coefficient of this variable is expected to be positive.	(WDI)
CCi,t : Corruption Control Index	According to the Worldwide Governance Indicators, corruption is defined as the perception of the extent to which public power is exercised for private gain. This definition encompasses both petty and grand forms of corruption, as well as the "capture" of the state by elites and private interests. The coefficient of this variable is expected to be positive.	Worldwide Governance Indicators (WGI)

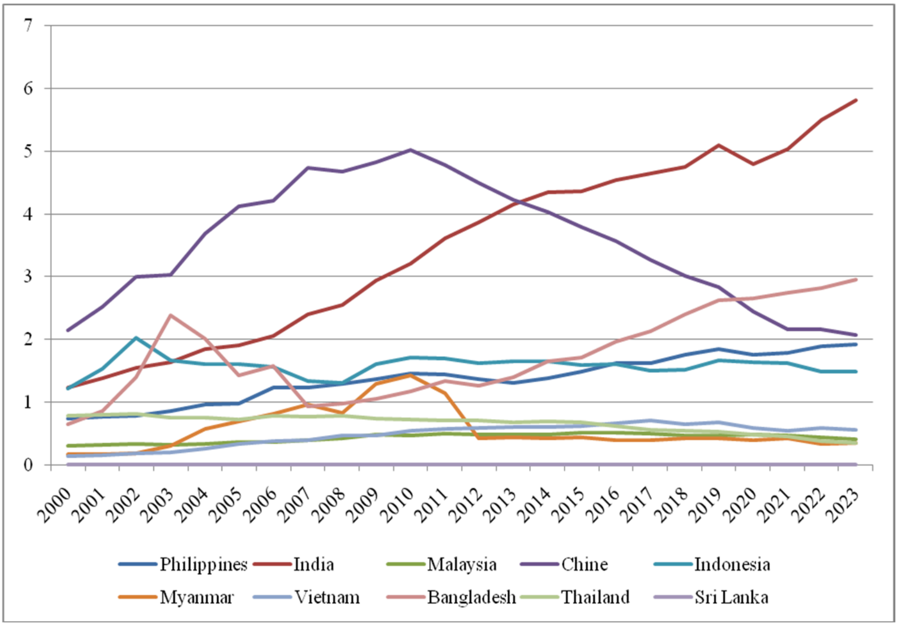
Note: Compiled by the author. The letter pairs employed in this article serve as the symbols used to denote the variables employed.

3.3. Sample description

The sample consists of twenty countries, which have been divided into two distinct groups. The objective of this division is to identify the factors driving plastic pollution and to highlight regional characteristics influencing plastic production and greenhouse gas emissions.

The ten Asian countries examined – Bangladesh, China, India, Indonesia, Malaysia, Myanmar, Philippines, Sri Lanka, Thailand, and Vietnam – are distinguished by their substantial populations and, since the 2000s, by accelerated economic growth, urbanization, and sustained industrial development. These changes have led to a significant increase in plastic pollution (see Figure 1), driven by the expansion of manufacturing industries, retail trade, and e-commerce, in a context of still limited environmental policies. China, Indonesia, and the Philippines are among the world's largest contributors to plastic waste, largely due to often insufficient waste management and relatively low recycling rates.

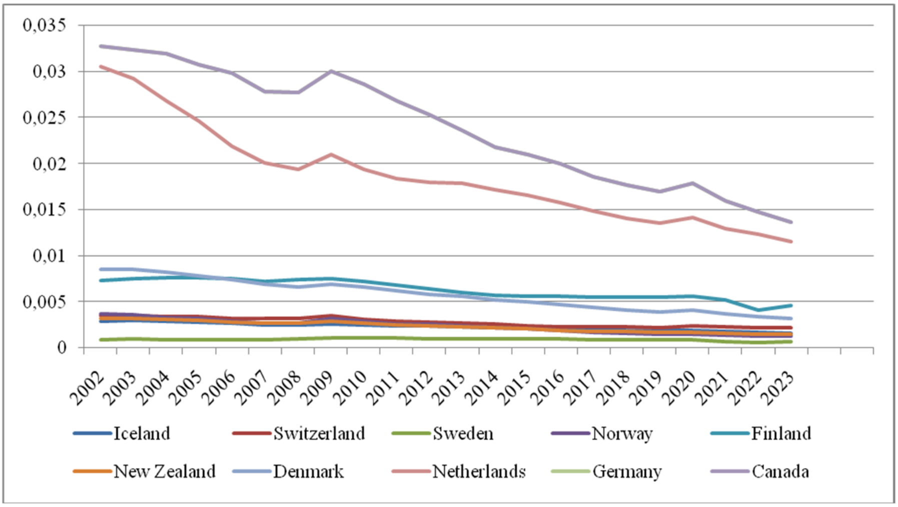
Figure 1 – Evolution of plastic pollution (Asian countries, 2000-2023)



Source: World Development Indicators (2024). Compilation of the author

The ten OECD member countries examined – Canada, Denmark, Finland, Germany, Iceland, New Zealand, Netherlands, Norway, Sweden, and Switzerland – are advanced economies characterized by high income levels, well-developed industrial and logistical infrastructures, and established institutional and environmental frameworks. These countries are distinguished by per capita plastic consumption that significantly exceeds the global average, while benefiting from more structured public policies for the reduction, management, and recycling of plastic waste. These policies are indicative of a commitment to mitigating the environmental impact of these countries (see Figure 2).

Figure 2 – Evolution of plastic pollution (OECD countries, 2000-2023)



Source: World Development Indicators (2024). Compilation of the author.

3.4. Descriptive study of variables

The descriptive analysis of the data collected over the period 2000–2023 allows for the characterization of the main variables considered for the Asian countries and the assessment of their dispersion, a crucial aspect for interpreting the subsequent econometric results. Table 2 presents a summary of the number of observations as well as the mean, standard deviation, minimum, and maximum values for each of the variables studied.

The analysis of the descriptive statistics indicates that the mean value of plastic pollution (PP) is 1.38, with a standard deviation of 1.33. This finding suggests a relatively high dispersion of observations and substantial heterogeneity among the Asian countries. The maximum value of the variable in question reaches 5.817, as observed in India in 2023 (see Figure 1), while the minimum value, which is found to be extremely low at 0.0002, is recorded in Sri Lanka during the same year. The observed variation in these metrics indicates the presence of substantial disparities among nations with respect to their levels of plastic waste generation. These disparities may be indicative of fundamental discrepancies in economic development, industrial dynamics, and environmental management policies.

From a demographic perspective, the active population (AGE15-64) constitutes, on average, 66% of the total population. This suggests a structural propensity that is conducive to economic activity and consumption, and consequently, potentially to plastic waste generation. The maximum value, 72.937%, was observed in China in 2009. This can be attributed to a relatively high active population density and an increased potential for production and consumption. Conversely, the minimum value of 58.533%, recorded in the Philippines in 2000, reflects a smaller active population.

Concurrently, the proportion of the aged population ($AGE65^+$) remains relatively modest, with a mean of 7%, yet exhibits substantial dispersion, reaching up to 50% in certain instances. This variability is indicative of substantial disparities in the stages of demographic transition across Asian countries. The maximum value of 50.06% was observed in India in 2009, indicating a rising share of the elderly population. Conversely, the minimum value of 3.761% was recorded in Bangladesh in 2000, suggesting a younger demographic structure. These cross-country variations underscore the crucial role of demographic structure in analyzing the determinants of plastic pollution and the pressure on ecosystems.

Urbanization (URB) has an average of approximately 40%, with primacy in the largest city (UPRI) at 20.57%, reflecting contrasting dynamics in population concentration. In 2023, Malaysia attained a high urbanization level of 78.716%, a development that is statistically significant. Such a level of urbanization is commonly associated with increased consumption and higher plastic waste generation. Conversely, the minimum value of 18.196%, documented in Sri Lanka in 2012, signifies a more rural demographic profile. These disparities across the country suggest a potential influence of urbanization on environmental pressures and plastic waste production.

An examination of the UPRI variable reveals a higher degree of urban primacy in Bangladesh (34.153% in 2000), while China exhibits a notably lower value (3.066% in 2000), suggesting a more balanced urban system.

From a structural perspective, the service sector (SER) is the predominant economic activity, with an average share of 48%. The manufacturing sector (MAN) is the second-largest contributor to the economy, accounting for approximately 21% of economic activity. This observation suggests a potential correlation between the level of economic development, goods consumption, and plastic waste generation.

In the year 2000, China was distinguished as a predominant actor in the manufacturing sector, with a 35.008% share, underscoring its significance in the global economy. Conversely, Myanmar demonstrated a notably lower percentage of 7.551% in 2001. With respect to the service sector, the Philippines attained a maximum share of 62.101% in 2023, signifying a predominantly service-oriented economy. Conversely, Myanmar recorded the minimum value of 32.549% in 2000, suggesting a pronounced emphasis on primary and manufacturing sectors. These disparities across the country highlight the hypothesis of a correlation between economic structure and goods production, and, by extension, plastic waste generation.

The average greenhouse gas (GHG) emissions are 1,641 kt CO_2-equivalent, with high dispersion (standard deviation of 3,455), reflecting significant disparities between low-emission countries and those with high industrialization or fossil fuel dependency. In 2023, China's energy consumption reached a peak of 15,943.99 kt, underscoring the magnitude of its industrialization and its reliance on fossil fuels. Conversely, Sri Lanka demonstrated notably diminished consumption in 2001, reaching a nadir of 25,499 kilograms. This decline can be ascribed to prevailing economic conditions that are distinct to the nation.

Carbon dioxide emissions demonstrate a comparable trend, exhibiting an average of 40.35 million tons, a maximum of 437 million tons in China in 2023, and a minimum close to zero in Myanmar in 2009. The data presented herein illustrate markedly divergent energy trajectories, with a concomitant focus on the nexus between plastic production and consumption.

The mean values of the Corruption Control Index (CC) and the GDP per capita growth rate (GDPPCG) are 0.36 and 4.4%, respectively. The (CC) value attained a high level in Malaysia (0.673 in 2013) and a very low level in Myanmar (0.00476 in 2010). A thorough examination of the economic data reveals a conspicuous divergence in GDP per capita growth rates, ranging from 13.636% in China in 2007, a period characterized by substantial economic expansion, to -12.629% in Myanmar in 2021, signifying an acute recession.

The study's findings indicate the presence of substantial structural and institutional disparities, as well as varied economic trajectories among the Asian countries. These observations may have implications for strategies aimed at managing plastic pollution in the region.

Table 2 – Descriptive statistics of variables, Asian countries

Variables	Obs	Mean	Std. dev.	Min	Max
PP	240	1.379378	1.335661	0.000192	5.817643
AGE15-64	240	0.6652754	0.0344248	0.58533	0.72937
$AGE65^{+}$	240	0.0690708	0.0367907	0.03761	0.5006
URB	240	0.405566	0.1512869	0.18196	0.78716
UPRI	240	0.2057461	0.1087453	0.03066	0.34153
MAN	240	0.2121778	0.0594745	0.07551	0.35008
SER	240	0.4794826	0.0694664	0.32549	0.62101
GDPPCG	240	0.0444786	0.0360025	-0.12629	0.13636
CC	240	0.358737	0.1588681	0.00476	0.67299
GHS	240	1641.149	3455.093	25.4987	15943.99
CO_2	240	40.34644	93.25629	0.2568819	437.5681

Source: Compilation of the author

A thorough statistical analysis of the variables presented in Table 3, concerning OECD member countries, unveils considerable heterogeneity in plastic pollution (PP) emissions. The mean value of these emissions is 0.0092, with a standard deviation of 0.0099. This indicates a relatively moderate average level, but significant variation across countries. The data reveal significant disparities within the OECD, as evidenced by the wide range of values reported, from as low as 0.00065 in Sweden in 2022 to as high as 0.0340 in the Netherlands in 2000 (see Figure 2). Such disparities are indicative of structural discrepancies in environmental pressure, the efficacy of public policies, and the economic mechanisms for managing plastic pollution.

Moreover, the working-age population (AGE15-64) constitutes an average of 65.8% of the total population, with a relatively low standard deviation (0.016). This finding suggests a degree of homogeneity among countries with regard to the demographic structure of this age group. Conversely, the proportion of the population aged 65 and over (AGE65^{+}) averages 16.6%, yet demonstrates greater variability (standard deviation = 0.0287). This higher dispersion underscores the presence of structural heterogeneity across countries, thereby suggesting that the demographic aging process manifests differently within the OECD.

The urbanization rate (URB) is high, with an average of 83.4%, confirming the predominance of urban populations in OECD countries. However, the relatively large standard deviation (0.058) underscores substantial heterogeneity among countries, juxtaposing highly urbanized economies with those where the rural component persists in significance. The urban primacy index (UPRI) reveals a mean of 20.435% and a substantial dispersion of 8.44%, indicative of structural diversity in urban systems. This variability mirrors heterogeneous patterns of urban hierarchy and spatial polarization, which can influence territorial dynamics as well as the production and management of environmental externalities, particularly those associated with plastic pollution.

An analysis of the economic structure of OECD countries reveals that the manufacturing sector (MAN) contributes relatively modestly to GDP, with an average of 13.4% and a standard deviation of 4.33%. This finding suggests the presence of significant cross-country variations in the degree to which industrial activity is relied upon, reflecting the broader processes of relative deindustrialization and sectoral restructuring that are characteristic of advanced economies. Conversely, the service sector (SER) has emerged as the predominant sector, accounting for an average of 62.9% of the total employment, thereby underscoring the ongoing process of tertiarization and the transition toward a post-industrial, service-oriented economic model.

Furthermore, the Corruption Control Index (CC) demonstrates a high mean value of 0.9706 with minimal variability (standard deviation = 2.17), indicating substantial institutional homogeneity across OECD countries. This phenomenon aligns with the consolidation of governance frameworks and the overall high institutional quality that characterizes these advanced economies.

The average annual GDP per capita growth in OECD countries has remained relatively modest, with a mean of 1.1% and a standard deviation of 2.39%. The presence of extreme fluctuations – ranging from a contraction of -8.5% in Finland in 2009 to an expansion of 6.8% in Iceland in 2004 – highlights the vulnerability of advanced economies to cyclical fluctuations and macroeconomic shocks. Furthermore, economic growth may directly impact plastic pollution emissions, particularly through increased production activity, heightened consumption of plastic-intensive goods, and shifts in urban and industrial lifestyles.

The mean value of total greenhouse gas emissions is 225 units, with a standard deviation of 310, suggesting significant cross-country dispersion. While certain countries have reported relatively low emission levels – for example, Iceland in 2000 (391 units) – others have exhibited exceptionally high emissions, notably Germany in 2001 (1,043.99 units). This pronounced heterogeneity underscores the uneven contribution of countries to atmospheric pollution and reflects structural differences related to levels of economic development and energy mix composition.

With regard to carbon dioxide (CO_2) emissions in particular, disparities are even more pronounced. The minimum observed value (0.094 units in Iceland in 2000) indicates that some countries generate virtually negligible emissions, whereas the maximum value (2.11 × 109 units in Germany in 2022) illustrates the magnitude of emissions in large industrialized economies. These disparities imply that carbon dioxide (CO2) exerts a pivotal influence on the variances in atmospheric contamination across OECD nations. Indeed, highly industrialized and fast-growing economies tend to exhibit higher levels of pollution, while service-oriented economies with cleaner energy mixes record comparatively lower emissions.

Table 3 – Descriptive statistics of variables, OECD countries

Variables	Obs	Mean	Std. dev.	Min	Max
PP	240	0.0092551	0.0099158	0.000652	0.034005
AGE15-64	240	0.6587632	0.0164447	0.61469	0.69524
AGE65^{+}	240	0.166409	0.0287596	0.11549	0.23618
URB	240	0.8348529	0.0581289	0.73375	0.94042
UPRI	240	0.2043548	0.0844158	0.05413	0.37909
MAN	240	0.1346716	0.0433547	0.05171	0.2415
SER	240	0.6299656	0.0561873	0.39633	0.72869
CC	240	0.9706144	0.0217406	0.91827	1
GDPPCG	240	0.0112869	0.0239051	-0.08513	0.0686
GHS	240	225.0088	310.0339	3.912	1043.991
CO2	240	9221361	1.36e+08	0.0941853	2.11e+09

Source: Compilation of the author

4. Results

Tables 4 and 5 present the empirical results derived from Equations (1) and (2). The Hansen and Sargan tests, which evaluate the validity of the instruments, in conjunction with the Arellano-Bond AR(1) and AR(2) tests for serial correlation in the residuals, substantiate the robustness and statistical validity of the selected dynamic model.

For both groups under study, the coefficients of the lagged variable (PP_{t-1}) are positive and statistically significant, revealing a strong inertia effect in plastic pollution. This finding suggests that past levels of plastic pollution have a significant impact on current outcomes, particularly in OECD countries, where waste persistence reflects historically intensive patterns of consumption and production. These results underscore the importance of structural interventions, such as policies aimed at reducing plastic use and the adoption of green technologies, to disrupt this dynamic and promote a more sustainable environmental trajectory (Senate Report, 2020; Barnes, 2019).

The demographic variables AGE15-64 and AGE65$^+$ demonstrate statistically significant effects on plastic pollution in OECD member countries. Specifically, the empirical results indicate that AGE15-64 has a positive effect, whereas AGE65$^+$ exerts a negative impact. The working-age population is more actively engaged in socio-economic activities and tends to adopt lifestyles associated with higher levels of plastic consumption, which explains the observed positive effect (Liddle, 2011).

Conversely, the adverse effects associated with the elderly population can be ascribed to reduced consumption patterns involving fewer plastic products and heightened engagement in pro-environmental behaviors, such as waste reduction and recycling (Gifford and Nilsson, 2014; Hartley et al., 2018). Consequently, an increased proportion of older individuals within a population tends to mitigate plastic pollution, underscoring the pivotal role of consumption choices and environmentally responsible behaviors in shaping pollution dynamics.

The coefficient of the urbanization variable (URB) is significantly negative; suggesting that poorly managed urbanization in certain Asian countries is associated with intensified environmental pressures. These findings are consistent with earlier studies showing that urbanization can deteriorate environmental quality and support the ecological modernization theory, which argues that societies tend to prioritize economic development over environmental quality at early stages of development (Poumanyvong and Kaneko, 2010; Zhu et al., 2022).

Conversely, in OECD countries, the URB variable demonstrates a negative yet less pronounced effect. Despite the considerable degree of urban concentration present, this region is distinguished by the presence of highly effective waste management systems and a rigorous environmental policy framework. This result aligns with the findings of Martínez-Zarzoso and Maruotti (2011) and more recent analyses by Chen et al. (2021), which suggest that urbanization in developed countries, may lead to the stabilization or even reduction of emissions through scale effects and technological innovation.

The findings suggest that the manufacturing sector (MAN) exerts a positive and statistically significant effect on plastic pollution in both groups of countries. This phenomenon is particularly evident in Asian countries, where a 1% increase in the manufacturing sector is associated with an approximate 11% rise in plastic pollution (see Table 4). The utilization of plastic-intensive inputs is pervasive across various manufacturing sectors, thereby exacerbating plastic pollution. This finding lends further credence to the argument that industrialization continues to be a primary driver of plastic pollution in Asian countries.

These results align with the findings of Cole and Elliott (2003) and Jirapornvaree et al. (2023), who demonstrate that the substantial reliance of developing countries on manufacturing activities tends to augment greenhouse gas emissions and environmental contamination. In OECD member countries, the impact of the manufacturing sector remains statistically significant, albeit to a comparatively lesser extent. This discrepancy can be attributed to the processes of relative deindustrialization and the gradual tertiarization of these economies.

However, the findings of the study suggest that the service sector may not be as environmentally neutral as previously assumed. In Asian countries, the service sector variable (SER) demonstrates a positive and statistically significant coefficient. A 1% increase in SER has been shown to result in an approximate 8% rise in plastic pollution, as illustrated in Table 4. Conversely, within the context of OECD member countries, the impact of the service sector appears to be statistically insignificant (Table 3).

The service sector, a broad category encompassing a wide range of activities, is a significant contributor to environmental degradation. On one end of the spectrum, there are activities with low environmental impact, such as banking and consultancy. On the other end of the spectrum are activities that generate substantial amounts of plastic waste, such as food services and tourism. Consequently, these opposing forces may counterbalance each other, resulting in an overall negligible effect on SER. This outcome can be attributed to the implementation of more stringent recycling and waste reduction policies, which mitigate the environmental impact of service sector growth in OECD countries (OECD, 2022).

The coefficient associated with the institutional variable (CC) is found to be negative and statistically significant for the OECD country sample (Table 4), indicating that institutional quality is a key determinant of plastic pollution. These results align with extant theoretical and empirical evidence, including the findings of Leitão (2010) and Cordier et al. (2021). As demonstrated in the research by Sulemana et al. (2017), higher levels of corruption have been shown to have a deleterious effect on public intervention in environmental quality issues and the effective implementation of environmental regulations.

The impact of economic growth on plastic pollution is not uniform across countries, exhibiting divergent effects that are contingent on the developmental levels of the respective nations. In the context of Asian economies, the coefficient associated with GDP per capita growth (GDPPCG) is found to be positive and statistically significant (see Table 4). This finding aligns with the Environmental Kuznets Curve (EKC) hypothesis, which posits that environmental degradation initially rises as income grows. This phenomenon can be attributed to the lower priority assigned to environmental quality in many Asian countries, as well as the relocation of pollution-intensive industries from developed to developing economies (Roca et al., 2001; Sulemana et al., 2019).

In contrast, a negative relationship between economic development and environmental pressure is observed in OECD countries. Specifically, a 1% increase in GDP per capita has been shown to result in a 3.21% reduction in plastic pollution, as illustrated in Table 4. This relationship is indicative of a context in which, beyond a certain income threshold, technological innovation and stricter environmental policies have been shown to mitigate – or even reverse – the adverse environmental effects of economic growth (Liddle and Messinis, 2015; Yan et al., 2024).

The present study demonstrates a statistically significant correlation between plastic pollution and greenhouse gas (GHG) emissions across both groups of countries analyzed (Equation 2). This finding signifies a substantial contribution to the field of research. In Asian economies, the CO2 variable demonstrates a positive and statistically significant coefficient (see Table 5), indicating that CO_2 emissions associated with plastic pollution contribute substantially to overall greenhouse gas (GHG) emissions. Additionally, research has demonstrated a robust correlation between economic growth, as quantified by GDP per capita (GDPPCG), and greenhouse gas emissions. This dynamic underscores the pivotal role of productive activities and increased consumption in driving the flow of these emissions.

In OECD countries, the effect of the CO_2 variable remains positive and statistically significant, although its magnitude is considerably lower than that observed in Asian economies. This discrepancy indicates that institutional frameworks, environmental policies, and technological advancements implemented in these countries contribute to mitigating the impact of plastic pollution on greenhouse gas emissions. However, it is crucial to acknowledge the persistent influence of economic growth on this phenomenon, suggesting that the relationship between economic development and environmental pressures remains only partially decoupled, despite advances in regulation and technology. These findings are consistent with projections by Lau et al. (2020), which identify the Asian region as the primary global hotspot for mismanaged plastic waste and atmospheric pollution. Furthermore, the empirical results support the conclusions of previous studies by Geyer et al. (2017), underscoring the inadequacy of global plastic recycling initiatives. This observation underscores the long-term environmental consequences, particularly regarding greenhouse gas emissions.

In summary, the present study underscores the notion that plastic pollution is the result of intricate interactions among socio-economic, environmental, and institutional factors, thereby reflecting its structural rather than cyclical nature. The empirical evidence indicates that plastic pollution exerts a considerable influence on greenhouse gas emissions, particularly carbon dioxide (CO_2), in both Asian economies and OECD countries. This relationship underscores the notion that plastic pollution is not merely a waste management issue but is intrinsically linked to the broader context of climate change.

Table 4 – Estimation of equation (1), PP: dependent variable

	Coefficients	**Std_error**	**Z**	**P>Z**	**Coefficients**	**Std_error**	**Z**	**P>Z**
	Asian countries				**OECD countries**			
PP_{t-1}	0.83786*	0.09664	8.67	0.000	1.53818*	0.28569	5.38	0.000
AGE15-64	-	-	-	-	0.20738**	0.09875	-2.10	0.036
$AGE65^{+}$	-	-	-	-	-0.06236**	0.02879	-2.17	0.030
URB	-1.76514**	0.76812	-2.30	0.022	-0.00587***	0.00333	-1.76	0.078
UPRI	-25.88612**	12.2984	-2.10	0.035	0.02912**	0.01464	1.99	0.047
MAN	10.8097**	5.00804	2.16	0.031	0.0089*	0.00308	2.89	0.004
SER	7.97183**	3.75021	2.13	0.034	0.0059	0.00399	1.48	0.138
GDPPCG	0.58569**	0.77988	0.75	0.0453	-0.03209*	0.01140	-2.81	0.005
CC	-	-	-	-	-0.03909**	0.01986	-1.97	0.049
_cons	0.14136	0.14503	0.97	0.330	0.09804**	0.04549	2.16	0.031
AR(1)	z = -1.01 Pr > z = 0.314				z = -1.79 Pr > z = 0.074			
AR(2)	z = -0.60 Pr > z = 0.550				z = -1.80 Pr > z = 0.272			
Test de Sargan	chi2(22) = 42.37 Prob > chi2 = 0.206				chi2(22) = 65.17 Prob > chi2 = 0.364			
Test de Hansen	chi2(22) = 0.64 Prob > chi2 = 1.000				chi2(22) = 0.00 Prob > chi2 = 1.000			

Source: Compilation by the author. *: $p < 0.01$; **: $p < 0.05$ and ***: $p < 0.1$

Table 5 – Estimate of equation (2), GHG: dependent variable

	Coefficients	Std_error	Z	P>Z	Coefficients	Std_error	Z	P>Z
	Asian countries				OECD countries			
GHS L1.	0.4141126*	0.15024	2.76	0.006	0.9619614*	0.01007	95.53	0.000
CO$_2$	21.58581*	5.18963	4.16	0.000	1.52e-08*	4.59e-09	3.31	0.001
GDPPCG	7140.754*	308.8405	23.12	0.000	587.0533*	176.2977	3.33	0.001
_cons	-221.6853*	32.1916	-6.89	0.000	-5.031347	4.30868	-1.17	0.243
AR(1)	z = -2.62 Pr > z = 0.129				z = -1.60 Pr > z = 0.110			
AR(2)	z = -1.20 Pr > z = 0.231				z = -2.07 Pr > z = 0.438			
Test de Sargan	chi2(22) = 0.44 Prob > chi2 = 0.801				chi2(2) = 4.90 Prob > chi2 = 0.186			
Test de Hansen	chi2(22) = 2.42 Prob > chi2 = 0.298				chi2(2) = 1.97 Prob > chi2 = 0.374			

Source: Compilation by the author. *: $p < 0.01$; **: $p < 0.05$ and ***: $p < 0.1$

5. Discussion

The results obtained from the system GMM model employed in this study have allowed the identification of key variables that can guide effective strategies for preventing future plastic pollution and reducing the externalities associated with greenhouse gas emissions. From this perspective, four policy implications emerge. Initially, South Asian countries and China are identified as priority targets, as they are projected to become the primary contributors to global plastic pollution, accounting for approximately 35% of the global total by 2050 – more than one-third of worldwide plastic pollution (OECD, 2025). Conversely, plastic pollutant emissions from OECD countries are projected to be nearly negligible by 2050 (Ministry of the Environment Japan, 2021). Consequently, these countries are called upon to intensify their efforts to reduce accumulated plastic waste before it degrades into microplastics, the removal of which proves particularly challenging.

Secondly, demographic shifts are anticipated to exacerbate plastic pollution, attributable to the rising proportion of the working-age population (15-64 years), notably in low- and lower-middle-income Asian countries. In this context, it is imperative for policymakers to devise targeted strategies that encourage these high-polluting countries to modify their behaviors. A combination of regulatory, economic, and behavioral instruments appears necessary to induce sustainable changes in pollution-generating practices (Alpizar et al., 2020).

Market regulation, particularly through the prohibition of single-use plastic products, constitutes an effective lever in many countries (Alpizar et al., 2020; Fadeeva and Van Berkel, 2021). Furthermore, recent literature emphasizes that behavioural instruments should complement regulatory policies and market mechanisms to produce enduring effects on polluting behaviors (Alpizar et al., 2020; Kirakozian, 2016). Consequently, public interventions should also incorporate softer informational instruments, such as awareness campaigns, educational programs, and guidelines (Uehara et al., 2022; 2023).

Indeed, developed countries can play a pivotal role in the transfer of technologies (De Mello, 1997) and the promotion of major innovations that could significantly contribute to the emergence of a circular economy based on the sustainable use of plastics (Lebreton and Andrady, 2019). In this regard, the development and diffusion of technological innovations in Asian countries could help sustain economic growth while limiting the intensification of plastic pollution.

Thirdly, the interdependence between urbanization and plastic waste management underscores the necessity of formulating and implementing effective policy responses to address this challenge (Bari et al., 2012). In this regard, urban planners are tasked with integrating plastic waste management at the core of urban development strategies, guided by circular economy principles. A comprehensive and integrated approach to plastic waste management is imperative, encompassing the entire life cycle of plastics – from production and consumption to waste management and pollution prevention (Nielsen et al., 2020). Urban spatial planning functions as a strategic instrument for implementing a circular approach. For instance, China has proactively promoted the emergence of a novel urbanization model aimed at optimizing the spatial structure of cities (Lin and Zhu, 2021). As previously indicated, OECD countries, distinguished by their high-income levels, are well positioned to assume a significant role in supporting lower-income countries in addressing the challenges associated with urbanization.

In the final analysis, public authorities are unable to adopt a passive stance regarding the control of plastic pollution and greenhouse gas emissions. It is therefore imperative that they design and implement sustainable policies and strategies that are compatible with economic growth objectives, in order to reduce plastic pollution and mitigate the impact of the accumulated stock of plastics in the environment since the 1950s.

6. Conclusion

Plastic pollution constitutes a significant and multifaceted challenge, converging at the nexus of economic, environmental, and climate-related issues. Addressing this issue necessitates the implementation of coordinated and differentiated actions among states, with the objective of reconciling the demands of economic development with the imperatives of sustainable environmental preservation. In this context, the present study seeks to analyze the impact of plastic pollution on terrestrial, aquatic, and atmospheric ecosystems, while highlighting its adverse consequences in terms of greenhouse gas emissions.

The empirical analyses reveal significant heterogeneity in impacts and confirm that the dynamics of plastic pollution are closely linked to the structural characteristics of the two groups of countries studied. Asian countries remain in a phase where demographic structure, income levels, urbanization, and industrialization are associated with increasing plastic pollution and greenhouse gas emissions. These findings appear to support the hypothesis that these nations are on the ascending phase of the Environmental Kuznets Curve, where economic development occurs at the expense of environmental quality (Yan et al., 2024).

In contrast, OECD countries have demonstrated a relative control over these phenomena, attributable to the implementation of more advanced environmental policies. However, these policies have not yet resulted in the complete elimination of the impact of plastics. Therefore, understanding these heterogeneities is crucial for policymakers, as it enables them to identify priority actions necessary for the effective and sustainable reduction of plastic pollution on a global scale.

The present study aspires to make a contribution to the academic debate while providing relevant insights for policymakers, international institutions, and economic actors engaged in combating plastic pollution. The approach adopted is integrated, distinguishing itself from traditional sectoral analyses by privileging a more holistic perspective that accounts for the interactions among various pollution drivers. Furthermore, this analysis provides an innovative empirical comparison between Asian countries severely affected by the plastic waste crisis and OECD countries with more developed institutional frameworks. The application of the system GMM model to a dynamic panel sample further enhances the robustness of the empirical results.

This investigation has enabled the formulation of several recommendations for future research. In subsequent studies, it would be pertinent to incorporate variables such as rural-to-urban migration, mixed land use, and monocentric versus polycentric urban forms. This approach would facilitate a more detailed analysis of the effects of urbanization on plastic pollution. It is also imperative to examine the spillover effects of plastic regulation policies in developing countries. For instance, China's prohibition on plastic waste imports in 2017 precipitated substantial alterations in the global trade dynamics of such waste, consequently engendering notable ramifications on the geographical distribution of plastic pollution (Lebreton et al., 2019).

This study sought to offer further insights into the nexus between plastic pollution and the deleterious effects of greenhouse gas emissions. To this end, a system GMM model was employed. Consequently, future research endeavours must encompass a more extensive array of factors and promote enhanced collaboration among a diverse array of stakeholders. Furthermore, the utilization of recently developed spatiotemporal data for the purpose of tracking plastic footprints has the potential to facilitate a more sophisticated evaluation of the implications proposed in this study (Potiracha and Baars, 2026; Rangel-Buitrago et al., 2024).

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The impact of environmental tax and emission trading system on environmental quality in OECD countries

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Abstract

Achieving sustainability requires a coherent policy mix to address the climate change problem. To internalize the cost of carbon emissions resulting from the existing mode of production, central market-based mechanisms, such as carbon taxes and emissions trading systems (ETS), can be applied. Nevertheless, structural and technological context may affect their effectiveness. In this context, the present study tries to assess the impact of carbon pricing instruments on CO_2 emissions while explicitly accounting for the structural and technological framework by integrating energy intensity and the usage of low-carbon energy in the energy mix, using a dynamic panel approach based on the Generalized Method of Moments for 31 OECD countries over the period 1997-2020.

The results show that the implementation of carbon taxes or ETS does not have a statistically significant impact on emission reductions. However, combining the two instruments alongside a higher penetration of low-carbon energy sources leads to a significant decline in emissions. These findings suggest that the effectiveness of economic instruments should be combined with complementary structural and technological transformations. An integrated policy mix that simultaneously promotes energy efficiency and accelerates the transition toward low-carbon energy systems may be embedded with carbon pricing.

Keywords: emissions trading system, environmental taxes, generalized method of moments.

JEL classification: C13, H23, Q58

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1. Introduction

The goal of sustainable development encompasses three fundamental dimensions. As for the economic dimension, the focus is on the transition to green growth by upgrading the energy efficiency of industrial activities, promoting the adoption of renew-

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able energy, and reconfiguring the economic structure. Concerning the ecological dimension, the main objective is to preserve biodiversity and wisely manage limited resources. The social dimension emphasizes the continued protection of the environment to enhance human security. However, the current configuration of energy consumption, which has evolved since the Industrial Revolution, raises questions about its environmental consequences. To address these concerns, the International Renewable Energy Agency (2018) estimates that energy efficiency and adopting renewable energy could account for up to 90% of the necessary carbon mitigation measures.

In this sense, the Energy Information Administration highlighted that energy efficiency progress is crucial for the transition away from fossil fuels. In a pathway aligned with the IEA's scenario for achieving net-zero energy sector emissions by 2050 (EIA, 2024). Besides, World Energy Outlook (2025) advanced that renewables accounted for around one-fifth of electricity generation worldwide a decade ago and that this level has risen now to about one-third, reflecting cost reductions in renewable energy technologies and policy support in many markets.

To fulfill this energy transition, environmental policies must be implemented through environmental instruments. These instruments can be fundamentally categorized into three distinct groups: regulatory instruments, economic instruments, and informational instruments Vedung (2025).

Economic instruments have a key characteristic: they operate within market mechanisms. Their objective is to correct market prices by internalizing external costs, thus incentivizing actors to consider these aspects in their choices.

Unlike regulatory instruments, economic instruments influence the prices of goods by establishing financial incentives. They define criteria related to environmental costs and benefits, in the form of quotas, restrictions on specific products, or standards for products offered for sale.

Finally, a third group of tools emerges as informational instruments. Unlike regulatory and economic instruments, informational instruments do not impose prices or constraints on production. Indeed, by providing actors with information about the negative consequences of the products consumed, these instruments influence the decisions of consumers, who eventually integrate this information into their consumption choices.

The Organization for Economic Cooperation and Development (OECD) first introduced the polluter pays principle in 1972. This organization emphasized the importance of this principle as an essential tool for reducing pollution and encouraging sustainable development. In 1992, the United Nations Conference on Environment and Development declaration, also known as the Rio Declaration, identified the polluter pays principle as one of the 27 guiding principles of sustainable development.

The OECD report (1975) defines the "polluter pays principle" as that fact that the polluter should be charged with the cost of whatever pollution prevention and control measures are determined by the public authorities, whether preventive measures, restoration, or a combination of both. The implementation of this principle takes various forms, notably through the application of environmental taxes and the creation of emission quota trading systems.

The theoretical foundations of emissions trading were developed in the work of Montgomery (1972), who demonstrated that under competitive conditions, the tradable permits are cost-efficient. At the empirical level, Bayer and Aklin (2020) showed that the EU ETS significantly reduces CO_2 emissions among regulated firms when supported by a reliable institutional framework.

According to OECD (2023), environmentally related tax bases comprise physical units that are directly linked to environmental pressures (e.g., emissions, pollutants). In the Pigouvian framework, environmental taxation is fixed according to a rule stipulating that the optimal corrective tax equals the marginal external damage of emissions. Recent contributions operationalize this principle by estimating the social cost of carbon through integrated assessment models and damage functions. These estimates provide quantitative benchmarks for carbon pricing consistent with marginal social damages and welfare maximization (Nordhaus, 2017; IMF, 2019; Rennert et al., 2022). Leading to optimal energy tax fixation.

Consequently, these economic methods incorporate environmental costs, or estimates of these costs, into market prices, creating a price signal to encourage economic actors to opt for more environmentally friendly products. Indeed, environmental tax increases the price of pollutants and energy-intensive products, leading enterprises to adopt energy-efficient equipment and to use renewable energies. As for Emissions Trading Systems, they operate by setting a cap on emissions and issuing tradable allowances, which are exchanged on the market, leading to a price signal that can encourage firms to adopt more efficient technologies if the abatement cost is lower than the market price.

Besides, Ji et al. (2022) stated that numerous theoretical discussions and quantitative simulations have shown that, under certain market assumptions, market-based instruments outperform command-based ones both in the scope of short-term economic costs and long-term dynamic incentives. Due to their effectiveness, the European Union actively supports the use of economic instruments and market mechanisms (Kosonen and Nicodemus, 2009).

Furthermore, the empirical literature studying the relationship between economic instruments used to resolve the climate change problem and environmental quality affords mixed evidence regarding their effectiveness in reducing CO_2 emissions. Furthermore, the distinction between policy adoption and emission coverage and the potential complementarity between carbon taxes and ETS have not been sufficiently assessed. Besides, the present study adopts a structured econometric strategy that distinguishes between the existing environmental tax revenues, emission coverage, and joint implementation of market-based instruments, while controlling for technological transition to lower-intensive and low-carbon technologies.

In this context, this paper aims to evaluate the impact of environmental taxation and emissions trading systems (ETS) on the environmental performance of 31 OECD countries from 1997 to 2020, with a specific focus on the proportion of CO_2 emissions covered by these instruments. Empirical evidence on their effectiveness remains mixed, highlighting the need for a more precise valuation. The present study contributes to the literature by quantifying the extent of emissions coverage under environmental taxes and ETS individually, while controlling for energy intensity improvements. Besides, it examines the simultaneous application of these instruments to assess whether broader coverage through concurrent implementation enhances environmental outcomes. Furthermore, this research tried to measure the impact of environmental tax measured by their related revenues as a percentage of GDP when controlling for energy intensity and low-carbon energy adoption. Employing a rigorous econometric framework, this research provides a systematic analysis of both individual and combined policy measures, in terms of the generated revenues from environmental taxes on one side and the covered emissions by environmental taxes and ETS, offering insights for designing more effective and sustainable climate policies.

The rest of the paper is organized as follows: The first section presents the literature review. The second exposes the empirical investigation by presenting data description and the methodology applied. The third section highlights empirical results, and the last section concludes.

2. Literature review

In alignment with the overarching goal of climate change mitigation outlined in the Paris Agreement, nations have committed to a range of short-term, medium-term, and long-term targets aimed at reducing greenhouse gas (GHG) emissions. Both production and consumption activities are principal contributors to pollution and GHG emissions, which represent negative externalities that are not typically internalized in market prices. To address these externalities, governments may implement carbon pricing mechanisms such as carbon taxes or emissions trading systems (ETS), thereby incentivizing market participants to account for environmental costs. As noted by Chameides and Oppenheimer (2007), market-based instruments have emerged as pivotal tools in the international policy landscape for achieving emission reduction targets.

Among these instruments, ETSs have been widely adopted as market-based solutions to mitigate global warming and reduce carbon dioxide emissions (Ouyang et al., 2020). The European Union Emissions Trading Scheme (EU-ETS), launched in 2005, represents the first and most developed global carbon market. By early 2021, 24 operational ETSs worldwide covered approximately 16% of global GHG emissions (ICAP, 2021).

Several scholars, including Bushnell et al. (2013) and Schmalensee and Stavins (2017), have argued that ETSs represent the most cost-effective mechanism for reducing emissions, based on both economic and environmental performance. However, empirical evidence remains mixed. While some studies affirm the efficacy of ETSs in lowering emissions, others question their effectiveness. For instance, Kill et al. (2010) argue that ETSs may facilitate the redistribution of emission allowances from low-emitting to high-emitting countries, thereby undermining global emission reduction goals. Moreover, Ben-David et al. (2021) and Bartram et al. (2022) contend that carbon pricing instruments can result in unintended consequences, such as emissions leakage, due to regulatory arbitrage by firms relocating activities to less-regulated authorities.

The literature underscores the nuanced and context-dependent impact of ETSs, with existing studies pointing to both significant and inconsistent outcomes related to energy conservation and emissions abatement. Importantly, much of the empirical research has concentrated on developed economies, particularly Europe and the United States (Calel and Dechezleprêtre, 2016; Hoffmann, 2007), with relatively limited attention paid to developing nations (Xie et al., 2017). For instance, Clò et al. (2017), through the analysis of panel data from 29 European electricity markets between 1990 and 2012, found that the ETS had only a limited impact on emission reductions, largely due to the overallocation of permits.

Conversely, other studies present more favorable findings. Jung and Song (2023) demonstrated the effectiveness of ETSs in reducing emissions across countries that adopted the mechanism. Similarly, Bian et al. (2024) evaluated the Chinese Carbon Emission Trading System (CETS) across 281 cities from 2006 to 2020, concluding that cities participating in CETS experienced greater progress in green development than those that did not.

Radulescu et al. (2025) examined the impact of carbon pricing and complementary factors – such as green technology, GDP, environmental taxes, green patents, renewable energy, and urbanization – on the ecological footprint of 26 EU member states during the 2011–2021 period. Their findings suggest that carbon pricing is effective in mitigating environmental pressures in upper quantile emission levels, but not in lower ones.

Parallel research also evaluates the role of environmental taxes as alternative or complementary instruments to ETSs. Scholars such as Martin et al. (2014), Andersson (2019), and Metcalf (2019) have found that carbon taxes can be more effective than ETSs in curbing emissions, a view supported by Ellerman et al. (2016).

The literature has extensively analyzed the impact of environmental taxes on energy efficiency and environmental quality, with mixed findings regarding the "double dividend" hypothesis. Some studies report positive environmental outcomes. For example, Wang et al. (2018) documented a 2.6% reduction in GHG emissions in Europe, a 10% reduction in waste production in Denmark, and a 5-15% decrease in air pollutants in the United States. Similarly, Hájek et al. (2019) employed multiple panel regression methods to assess the role of carbon taxes, allowance prices, household consumption, and renewable energy in the EU, highlighting the importance of carbon taxation in environmental protection and GHG mitigation.

Using system-GMM and quantile regression techniques, Bashir et al. (2020) found that environmental taxes, renewable energy, environmental technology, and financial development collectively contribute to emission reductions in OECD countries between 1995 and 2015. However, economic growth was shown to potentially counteract these environmental improvements.

He et al. (2021a) investigated the effects of environmental taxes on economic growth, energy use, and emissions in China, Finland, and Malaysia over the 1985-2014 period using an Autoregressive Distributed Lag (ARDL) panel analysis. The study found that taxes implemented in Finland and Malaysia were effective in reducing energy consumption and emissions, offering lessons for other developing countries. Similarly, Bashir et al. (2021) employed FMOLS, DOLS, and quantile regression models across 29 OECD countries (1994-2018), concluding that environmental taxes stimulate innovation in environmentally friendly technologies and contribute to emissions mitigation.

Additional support for the effectiveness of environmental taxation comes from Sarıgül and Topcu (2021), who found that such taxes had a statistically significant, albeit modest, impact on CO_2 reduction in Turkey between 1994 and 2015. Dogan et al. (2022) further analyzed the role of green growth policies and environmental taxation in 25 environmentally friendly countries between 1994 and 2018, using novel quantile regression methods. Their findings underscore the critical role of environmental taxes, renewable energy, and energy efficiency in reducing carbon emissions.

Nonetheless, some scholars question the universal effectiveness of environmental taxation. For example, Mardones and Flores (2018) highlight cases where these measures fail to significantly reduce emissions, suggesting a need for more nuanced policy design. Telatar and Birinci (2022) conducted a nonlinear analysis of Turkey's environmental tax policy from 1994 to 2019 and concluded that such taxes had no long-term impact on either the ecological footprint or CO_2 emissions, implying limited efficacy in curbing environmental degradation.

In examining the broader determinants of carbon emissions, it is important to integrate a comprehensive set of factors into the analysis to better understand their influence. The STIRPAT model, introduced by York et al. (2003), offers a robust framework for evaluating the effects of population, affluence, and technological development on environmental outcomes. Empirical studies, including those by Bargaoui et al. (2014) and Shafiei and Salim (2014), have confirmed that both population growth and increases in gross domestic product (GDP) are significant contributors to rising CO_2 emissions.

The role of technology in shaping emissions is often assessed through indicators related to industrial activities and energy consumption. Considerable scholarly attention has focused on improving the efficiency of fossil fuel use, motivated not only by concerns over long-term energy security but also by the imperative to reduce carbon emissions. Several studies have explored the connection between energy-related variables and CO_2 emissions. For instance, Aguir Bargaoui and Nouri (2017) analyzed how improvements in energy efficiency correlate with emission reductions, while Morales-Lage et al. (2016) highlighted how increased energy intensity and industrial output contribute to higher emission levels.

In the context of OECD countries, Tajudeen et al. (2018) conducted a two-stage analysis to evaluate the effects of energy efficiency on CO_2 emissions across 30 member countries over the period 1971-2015. Their findings indicate that gains in energy efficiency are associated with long-term emission reductions, averaging a 1.731% annual decline. Similarly, Yao et al. (2021a) investigated the interrelationships among technology, corruption, energy efficiency, and natural resource use in BRICS nations and 11 additional countries. Utilizing a combination of Data Envelopment Analysis (DEA) and the GMM estimator, their study underscored the importance of both institutional quality and energy efficiency in achieving environmental improvements.

Moreover, Yao et al. (2021b) expanded this line of inquiry by exploring the interactions among trade, energy efficiency, technological progress, foreign direct investment (FDI), and political institutions across various national contexts. Employing the Super-Slacks-Based Measure (Super-SBM) model alongside the GMM technique, their research revealed that technological advancement, institutional strength, and enhanced energy efficiency are pivotal in promoting sustainable economic growth while curbing carbon emissions.

3. Methodology and data

In this section, we will describe the applied methodology to analyze the impact of environmental taxes, the Emissions Trading Scheme, low-carbon energy, and energy efficiency on environmental quality in OECD countries. We will explain our choice of the dynamic panel method and the rationale behind using the system's two-stage GMM method.

3.1. Empirical model

The methodology used in the present paper is the Generalized Method of Moments (GMM), which accounts for the temporal dimension of our data. Indeed, this approach allows us to model relationships between variables over time and across countries to account for individual- and time-specific effects while addressing endogeneity biases in explanatory variables such as fossil fuel use, using instrumental variables generated by their lags.

Halkos (2003) highlights that the Generalized Method of Moments (GMM) estimation technique addresses issues of heteroscedasticity and provides estimates that are both unbiased and efficient. Blundell and Bond (1998), through Monte Carlo simulations, showed that the first-difference GMM estimator can yield biased results in finite samples when instruments are weak. To overcome this limitation, they introduced the system GMM approach, building on the level equation concept proposed by Arellano and Bover (1995). Their findings indicate that this alternative reduces both the finite sample bias and the asymptotic imprecision typically associated with the difference GMM estimator.

The reliability of the GMM method is contingent on two main assumptions. First, the instruments used must be valid, a condition tested using the Hansen or Sargan over-identification tests, as recommended by Blundell and Bond (1998). Second, there must be no autocorrelation in the error terms, which is checked using first- and second-order autocorrelation tests. The second-order test is particularly important, as first-differenced errors tend to be correlated at the first order, according to Levine et al. (2000). These characteristics make the system GMM estimator a suitable tool for evaluating OECD policy impacts on environmental performance – especially in areas like energy efficiency, environmental taxation, emissions trading systems (ETS), and the broader drivers of CO_2 emissions.

The objective of the dynamic panel data model proposed below is to determine the impact of environmental taxes, emissions trading schemes, low-carbon energy, and energy efficiency on environmental quality in OECD countries. Our empirical research is founded on a sample composed of a panel of 31 OECD countries, with annual data covering the period from 1997 to 2020. The choice of this time range is motivated by data availability.

3.2. Data description and data sources

Following a comprehensive analysis of existing research on the impact of environmental taxes, emissions trading schemes (ETS), and energy efficiency on environmental quality, we formulate the following hypotheses:

Assumption 1. Higher environmental taxes decrease carbon emissions by altering relative energy prices and incentivizing firms and households to adopt energy-efficient technologies or use lower-carbon energies.

Assumption 2. Emissions trading schemes (ETS) significantly contribute to CO_2 emissions reduction, based on previous research anticipating that ETS implementation will incentivize firms to invest in more sustainable practices to save on the cost of emission permits.

Assumption 3. Lower energy intensity is negatively associated with carbon emissions.

Assumption 4. Combining policies promoting energy efficiency, low-carbon energy forms, environmental taxes, and emissions trading schemes (ETS) will have a synergistic impact, amplifying the positive effects on environmental quality relative to the effect of each policy alone. The joint implementation of environmental taxes, ETS, energy intensity reduction, and low-carbon energy is expected to reduce carbon emissions.

We propose to estimate the following five models separately in order to confirm or refute our research hypothesis:

Model 1: $lnCO2_{i,t} = \beta_0 + \beta_1 lnCO2_{i,t-1} + \beta_2 lnEI_{i,t} + \beta_3 lnTax_{i,t} + \beta_4 lnPOP_{i,t} + \beta_5 lnURB_{i,t} + \beta_6 lnFF_{i,t} + \beta_7 lnGDP_{i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$

Model 2: $lnCO2_{i,t} = \beta_0 + \beta_1 lnCO2_{i,t-1} + \beta_2 lnEI_{i,t} + \beta_3 lnTax_{i,t} + \beta_4 lnPOP_{i,t} + \beta_5 lnURB_{i,t} + \beta_6 lnFF_{i,t} + \beta_7 lnGDP_{i,t} + \beta_8 lnLLOWCARBON_{i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$

Model 3: $lnCO2_{i,t} = \beta_0 + \beta_1 lnCO2_{i,t-1} + \beta_2 lnEI_{i,t} + \beta_3 lnLCARBONTAX_{i,t} + \beta_4 lnPOP_{i,t} + \beta_5 lnFF_{i,t} + \beta_6 lnGDP_{i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$

Model 4: $lnCO2_{i,t} = \beta_0 + \beta_1 lnCO2_{i,t-1} + \beta_2 lnEI_{i,t} + \beta_3 lnLCARBONETS_{i,t} + \beta_4 lnPOP_{i,t} + \beta_5 lnFF_{i,t} + \beta_6 lnGDP_{i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$

Model 5: $lnCO2_{i,t} = \beta_0 + \beta_1 lnCO2_{i,t-1} + \beta_2 lnEI_{i,t} + \beta_3 lnLCARBONTAXETS_{i,t} + \beta_4 lnPOP_{i,t} + \beta_5 lnFF_{i,t} + \beta_6 lnGDP_{i,t} + \mu_i + \theta_t + \varepsilon_{i,t}$

Based on the literature insights, five model specifications are designed to assess the effectiveness of market-based environmental instruments gradually. Model 1 evaluates the separate effect of environmental taxes as measured by the environmental tax revenue percentage of GDP. Model 2 outspreads this basis by incorporating low-carbon energy to account for technological transition. Models 3 and 4 introduce emission coverage indicators for carbon taxes and ETS, respectively, to capture their policy impact. Finally, Model 5 studies the combined effect of carbon taxes and ETS coverage to assess complementarity between instruments while applying low-carbon energy.

The used data is collected from reliable sources such as the Organization for Economic Cooperation and Development (OECD) database, ourworldindata, and the

World Bank (World Development Indicators (WDI)). Our database and sources are summarized in Table 1 below:

Table 1 – Description and data sources

Variable	Variable definition	Abbreviation	Source
Urban population	Urban population (% of total population)	**URB**	https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS
Fossil fuel	Fossil fuel energy consumption (% of total)	**FF**	https://data.worldbank.org/indicator/EG.USE.COMM.FO.ZS
GDP per capita	GDP per capita (constant LCU)	**GDP**	https://data.worldbank.org/indicator/NY.GDP.PCAP.KN
Population	Population, total	**POP**	https://data.worldbank.org/indicator/SP.POP.TOTL
CO_2 emissions	Carbon dioxide (CO2) emissions excluding LULUCF per capita (t CO2e/capita)	**CO_2**	https://data.worldbank.org/indicator/EN.GHG.CO2.PC.CE.AR5
Environmental tax	environmentally related tax revenues % of GDP	**TAX**	https://www.oecd.org/en/data/indicators/environmental-tax.html
Energy intensity	Primary energy consumption per GDP (kWh/$)	**EI**	https://ourworldindata.org/grapher/energy-intensity?tab=table
CO_2 emissions covered by a carbon tax or emissions trading scheme	CO_2 emissions covered by a carbon tax or emissions trading scheme as a percentage of the country's CO_2 emissions	**CARBONTAXETS**	https://ourworldindata.org/grapher/carbon-tax-trading-coverage
CO_2 emissions covered by a carbon tax	CO_2 emissions covered by a carbon tax as a percentage of the country's CO_2 emissions	**CARBONTAX**	https://ourworldindata.org/grapher/carbon-tax-trading-coverage?tab=line
CO_2 emissions covered by an emissions trading system	CO_2 emissions covered by an emissions trading system as a percentage of the country's CO_2 emissions	**CARBONETS**	https://ourworldindata.org/grapher/carbon-tax-trading-coverage?tab=line
Per capita consumption of low-carbon energy	Measured in kilowatt-hours per person. Low-carbon energy is the sum of nuclear and renewable primary energy	**LOWCRBON**	https://ourworldindata.org/grapher/per-capita-low-carbon-energy

Source: Author presentation

Table 1 presents an overview of the variables used in our research, including their definitions, measurement units, abbreviations, and data sources with links. Environmental pressure is proxied by CO_2 emissions that constitute the dependent variable. Carbon tax and emissions trading system (ETS) variables are introduced as variables capturing the implementation of market-based carbon pricing instruments. Energy intensity is included as an indicator reflecting the structural performance of the economy in terms of energy use. The low-carbon energy represents the degree of technological transition within the energy mix. Additional control variables, such as GDP per capita and population, urbanization, and fossil fuels are incorporated to account for scale, economic structure, and social effects, which may independently impact emission dynamics.

4. Results

4.1. Descriptive statistics

Before performing our model estimation, it is obvious to examine the descriptive statistics presented in Table 2.

Table 2 – Result of descriptive statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
URB	744	74.48535	10.89612	50.675	98.079
FF	744	1595.546	3934.466	29.40364	23576.99
GDP	744	41334.48	18278.08	10949.72	120647.8
POP	744	3.89e+07	5.90e+07	419450	3.32e+08
CO2	744	372807.9	943019.2	6928.3	5775807
TAX	744	2.402312	0.8631357	1.53	5.36
EI	744	1.443696	0.4963054	0.6488547	5.404991
CARBONTAXETS	744	31.00599	28.21035	0	93.81519
CARBONTAX	744	11.77872	21.22254	0	73.23335
CARBONETS	744	21.09633	21.88993	0	63.32411
LOWCARBON	744	12411.4	15757.2	17.96539	93578.22

Source: Our calculations under Stata

Descriptive data analysis for OECD countries from 1997 to 2020 reveals significant trends concerning environmental taxation, energy efficiency, and environmental quality. Urban population averages 74.49 with relatively small variation, indicating a relative stability in urban dynamics across OECD countries over the period considered. Fossil fuel energy consumption averages 1595.55, with significant dispersion represented by a standard deviation of 3934.47. This variability highlights substantial differences in fossil fuel dependence among OECD countries. GDP per capita averages 41334.48, with considerable variation, with a standard deviation of 18278.08. indicating significant differences in the level of economic development within OECD countries. Carbon dioxide emissions show a mean of 372807.9 CO_2 emissions in OECD countries. However, the high standard deviation (943019.2) highlights significant disparities between countries. Environmental tax has a mean of 2.40, with moderate variation illustrated by a standard deviation of 0.86. Energy intensity of consumption shows a mean of 1.44, with relatively low variation indicated by a standard deviation of 0.50, highlighting some stability in the energy efficiency level.

The results for CO_2 emissions covered by a carbon tax or an Emission Trading Scheme, and the combination of these two strategies, reveal respective averages of 11.78, 21.10, and 31.01, with high standard deviations indicating substantial variations in these environmental mechanisms' application.

Finally, the low-carbon energy consumption per capita standard deviation is 15757.2, illustrating the diversity of low-carbon energy sources adoption.

In conclusion, these statistics highlight the diversity of environmental and energy indicators within OECD countries over the period studied. They underscore the importance of considering this variability when analyzing the impact of environmental taxes, ETS, and energy efficiency on OECD's environmental quality.

Table 3 – Correlation matrix

	LCO2	**LPOP**	**LGDP**	**LFF**	**LURB**	**LEI**	**LTAX**	**LCARBONTAXETS**	**LCARBONTAX**	**LCARBONETS**	**LLOWCARBON**
LCO2	1.000										
LPOP	0.8396	1.0000									
LGDP	0.2123	0.1690	1.0000								
LFF	0.9917	0.8407	0.1494	1.0000							
LURB	0.3367	0.4164	0.5106	0.3058	1.0000						
LEI	-0.1918	-0.1175	-0.4514	-0.1940	0.0263	1.0000					
LTAX	-0.5147	-0.3345	-0.3609	-0.5089	-0.1786	0.0485	1.0000				
LCARBONTAXETS	0.1150	0.3671	0.3113	0.1087	0.1522	-0.3676	0.2513	1.0000			
LCARBONTAX	0.0996	0.2317	0.5836	0.0262	0.3035	-0.3232	0.0721	0.7271	1.0000		
LCARBONETS	-0.0263	0.2585	-0.0296	-0.0103	-0.0558	-0.1740	0.5115	0.8452	0.3882	1.0000	
LLOWCARBON	0.1211	0.1946	0.6442	0.0673	0.5141	-0.0539	-0.2371	0.2431	0.5635	-0.0144	1.0000

L denotes the natural logarithm of each variable

Source: Our calculations under Stata

Results of the correlation matrix highlight a high correlation between CO_2 and fossil fuel use, indicating that heavily dependent fossil fuel countries, such as coal, oil, and gas, show higher levels of CO_2 emissions, thus contributing to climate change.

The moderate positive correlation between urbanization and CO_2 emissions suggests that countries with higher urbanization, characterized by a concentration of population in urban areas, tend to emit more CO_2. This result can be attributed to an increase in energy demand to meet urban regions' needs, leading to an increase in CO_2 emissions.

The adverse correlation between energy intensity and CO_2 emissions indicates that countries that use energy more efficiently tend to emit less CO_2. Lower energy intensity reflects more efficient use of energy in economic production, which leads to lower CO_2 emissions.

The significant negative correlation between fossil fuel consumption and environmental tax suggests that nations that have implemented environmental tax policies are successful in reducing their dependence on fossil fuels. This reveals an inverse association between fossil fuel consumption and the implementation of tax measures to reduce CO_2 emissions. The moderate negative correlation between CO_2 emissions covered by an ETS and total CO_2 emissions indicates that countries implementing specific environmental policies based on ETS contribute to reducing their CO_2 emissions.

Results of the correlation matrix presented in Table 3 highlight the importance of environmental tax, energy efficiency, and ETS in achieving CO_2 emissions reduction targets. However, it is essential to note that correlation does not necessarily imply causation, and further analyses would be needed to fully understand the dynamics underlying these relationships.

According to the correlation matrix, we can conclude that we are in the presence of a probable multicollinearity between several variables. Indeed, according to Gujarati (2004), a multi-collinearity problem exists if the correlation between the independent variables exceeds 0.80, which is the case for the results of our study. To further analyze the multicollinearity problem, we apply the variance inflation factor (VIF) test. This test measures the degree to which the explanatory variable can be explained by the other explanatory variables.

Thus, if the VIF is greater than 10, there is a multicollinearity problem (Neter et al., 1985). According to Table 4 below, all the explanatory variables have a VIF less than the critical value of 10, hence the absence of a multicollinearity problem. Thus, we can conclude that there are no extremely high levels of correlation requiring the use of measures that can overcome this problem.

Table 4 – VIF test estimates

Variable	**VIF**	**1/VIF**
LPOP	5.85	0.170898
LFF	5.52	0.180997
LGDP	3.40	0.294034
LCARBONTAXETS	2.72	0.367425
LLOWCARBON	2.44	0.410214
LURB	1.98	0.505336
LCARBONTAX	1.94	0.514211
LEI	1.77	0.564376
LTAX	1.58	0.633414
Mean VIF	**3.02**	

Source: Authors' output from Stata

4.2. GMM estimation results

In this study, we estimate our models using the two-stage system GMM, developed by Arellano and Bover (1995) and Blundell and Bond (1998). Roodman (2009) confirmed that this method is more efficient and robust than other methods and that the statistical tests it allows are reliable. To ensure the validity of the method, we tested the instruments' validity using the Hansen test, first- and second-order autocorrelation using the Arellano-Bond test. These tests showed that the estimated models are valid. Consequently, our results are reliable. Table 5 below presents the estimated parameters and t-statistics.

Table 5 – Two-step system GMM estimation of the impact of environmental tax, ETS System, energy efficiency, and low carbon energy on CO_2 emissions for OECD countries

	Model 1	**Model 2**	**Model 3**	**Model 4**	**Model 5**
LCO_{2t-1}	0.122939 (2.65) **	0.0791706 (1.02)	0.063708 (0.52) **	0.0128558 (0.42)	0.2099423 (6.79) ***
LPOP	0.0434782 (0.44)	-0.0448849 (-0.40)	-1.409512 (-2.52)	-0.1526089 (-1.92) **	-0.1861102 (-3.03) ***
LGDP	-0.2936252 (-3.26) ***	-0.1884691 (-1.86) *	-0.1001533 (-1.18)	-0.2703996 (-7.27) ***	-0.2120903 (-9.31) ***
LFF	1.020806 (13.45) ***	0.9367323 (8.69) ***	0.6819503 (8.51) ***	1.016878 (34.10) ***	0.928704 (24.08) ***
LURB	0.4307252 (0.77)	0.8316417 (1.19) *			
LEI	-0.122216 (-2.87) ***	-0.0854369 (-1.69)	-0.0780486 (-1.63)	-0.0818503 (-4.21) ***	-0.1485873 (-7.31) ***
LTAX	-0.0083644 (-0.32)	-0.0155839 (-0.35)			
LCARBONTAXETS					-0.023715 (-3.18) ***
LCARBONTAX			-0.0291808 (-1.51)		
LCARBONETS				-0.0795126 (-1.50)	
LLOWCARBON		-0.1041972 (-2.65) **			
Constant	4.462919 (2.47) **	5.029379 (2.11) **	30.73739 (3.20) ***	10.83912 (6.75) ***	8.867992 (7.75) ***
Number of observations	706	706	250	419	490
Countries	31	31	17	27	30
Number of instruments	24	24	24	24	24
Hansen test	20.15 (0.213)	13.71 (0.548)	6.10 (0.992)	20.53 (0.248)	20.44 (0.252)
Arellano-Bond test AR (1)	-2.39 (0.017)	-1.70 (0.089)	-0.75 (0.456)	-1.79 (0.074)	-2.68 (0.007)
Arellano-Bond test AR (2)	-0.97 (0.333)	-1.26 (0.208)	-1.83 (0.068)	-0.94 (0.346)	-1.33 (0.184)

*, **, and *** indicate significance at 10%, 5%, and 1%

Source: Authors' output from Stata

Results of the overall models indicate that GDP per capita exerts a negative impact on emissions in OECD countries. Several structural and policy-related factors can explain this negative coefficient. Indeed, generally, structural economic transformation is associated with higher income levels. A tendency to switch from industrial, carbon-intensive to service and knowledge-based economies in OECD countries can be noticed. Furthermore, OECD countries implement environmental policies such as carbon pricing mechanisms and stricter emissions standards. Besides, high-income economies possess greater financial capacity to invest in cleaner technologies, energy-efficient equipment, and infrastructure.

Model 1 estimation results display that energy intensity leads to CO_2 emissions reduction, confirming that the adoption of more energy-efficient equipment in these wealthy economies leads to a reduction of energy intensity and thereby decreases emissions levels. These findings support the necessity of the development of more energy-efficient technologies and disseminating them to less developed countries to amplify their positive impact on CO_2 reduction, and thereby improve environmental quality. Indeed, the OECD aims to help these countries implement policies to mitigate climate change. This policy adoption would reduce fossil fuel consumption, improve environmental quality, ensure energy security for the current generation, and preserve fossil resources for future generations. This positive effect of adopting energy efficiency was proven by Aguir-Bargaoui et al. (2014) for 151 countries over the period 1980-2010 and by Tajudeen et al. (2018) for 30 OECD countries over the period 1971-2015.

Furthermore, the estimated results suggest that past emissions contribute to increased actual emissions. Indeed, producing more emissions today leads to future environmental degradation. Fossil fuel use also contributes to this degradation. A 1% increase in fossil fuel consumption leads to a 1.0208% increase in CO_2 emissions. This result is consistent with the findings of other studies, such as that of Shafei and Ruhul (2013), who analyzed data from OECD countries between 1980 and 2011.

As for population, urban population, and environmental taxes variables, they do not significantly impact emissions.

The second model's estimates, focused on detecting the impact of low-carbon energy consumption, reveal a promising conclusion: the adoption of Low-carbon energy significantly reduces CO_2 emissions. The analysis shows that a 1% increase in low-carbon energy use leads to a -0.104% decrease in CO_2 emissions. This finding offers a positive outlook and encourages the active promotion of increased integration of low-carbon energy to improve environmental quality.

This conclusion aligns harmoniously with previous results by Jebli et al. (2016), Bilgili et al. (2016), and Paramati et al. (2017), thus consolidating the validity and consistency of our results with trends observed in the scientific literature.

As for Model three, we used a variable that measures the proportion of emissions subject to a carbon tax, rather than the level or rate of the tax itself. Results indicate that the level of carbon tax coverage in OECD countries does not have a statistically significant effect on CO_2 emissions. These results do not imply that carbon taxes are ineffective; however, they can give evidence that limited coverage may be insufficient to generate a measurable impact on emissions. The breadth of coverage and the magnitude of the tax rate applied may be revised in order to ameliorate the effectiveness of carbon taxes. Furthermore, this finding underscores the need to explore complementary approaches to achieve meaningful environmental objectives. Previous work by Mardones and Flores (2018) supports this perspective by highlighting the limitations of carbon taxes' impact on CO_2 emissions. Thus, broadening our understanding of environmental policies to design more effective and sustainable solutions is imperative.

The estimation of Model 4 highlights an interesting finding: the presence of ETS policy does not appear to exert a significant influence, as evidenced by its coefficient of -0.079 with a p-value of 0.732. This result indicates that the studied phenomenon, namely the CARBONETS variable, does not have a statistically significant impact on CO_2 emissions.

This finding highlights the need to take a holistic approach in designing environmental policies and explore multiple mechanisms to achieve significant emission reductions.

The estimation of Model 5 reveals a significant finding: CO_2 emissions covered by a carbon tax or an ETS show a notable negative correlation, as indicated by a coefficient of -0.0237 and a p-value of 0.003. The negative correlation indicates that when CO_2 emissions are subject to a carbon tax or an ETS, CO_2 emissions tend to decrease. These findings support the idea that these instruments can help reduce greenhouse gas emissions. Aligning this observation with the findings of previous models, where other variables showed significant positive or negative correlations, it becomes clear that targeted policy implementation, such as carbon taxes or ETS, can be an effective lever to achieving environmental objectives. Thus, considering several variables, an integrated approach remains essential for sustainable environmental policy formulation.

The findings of this study significantly demonstrate the impact of several factors on CO_2 emissions, highlighting promising avenues for guiding environmental policies. Energy efficiency, low-carbon energy consumption, as well as the simultaneous implementation of a carbon tax and an Emissions Trading Scheme (ETS) policy, emerge as key elements that can positively influence emissions reductions.

These results are consistent with the findings of other studies on similar topics, reinforcing the idea that policies focused on improving energy efficiency, promoting low-carbon energy, and implementing carbon pricing mechanisms can play a crucial role in mitigating CO_2 emissions. However, the study highlights the inherent complexity of managing CO_2 emissions due to the simultaneous use of new policies and energy sources with fossil fuel consumption that contributes seriously to environmental quality deterioration.

This observation underscores the urgent need to reduce dependence on fossil fuels and adopt more sustainable alternatives. These findings call for an integrated approach to environmental policies. To achieve ambitious CO_2 emission reduction targets, governments should invest significantly in the research and development of more energy-efficient technologies. Actively encouraging renewable energy use and other low-carbon sources is also essential. Furthermore, carbon pricing schemes can play a key role in incentivizing more environmentally friendly behavior. This study highlights the need for a holistic approach, combining various policies and instruments, to effectively address the complexity of CO_2 emission challenges, while giving particular focus on reducing fossil fuel consumption due to its significant impact on environmental quality degradation.

In conclusion, holistic policies aimed at reducing fossil fuel consumption, improving energy efficiency, promoting sustainable economic growth, and implementing effective environmental policies are essential to address environmental challenges in OECD countries. An integrated approach that combines these different factors appears to be the key to progressing towards a greener and more equitable economy.

Two statistical tests are inherent to validate our estimates: the Hansen test for the validity of the instruments and the Arellano-Bond autocorrelation test. Indeed, Blundell and Bond (2000) stated that to test the validity of additional instruments, the best practice when applying the GMM system is to use the Sargan difference test, which checks the validity of a subset of instruments. The Sargan difference test is, according to Roodman (2007), closely related to the Hansen test for the validity of the set of all used instruments. In the present study, we use the Hansen test to test the validity of all the instruments used. We consider the validity of p-instruments if the p-value is higher than 5%, and we accept the null hypothesis.

Regarding our estimated models, the p-values are all greater than 0.05, which allows us to accept the null hypothesis. Furthermore, the instruments used are valid. Therefore, the used instruments are not asymptotically correlated with the disturbances in the estimated models.

The Arellano-Bond statistical test, which tests the null hypothesis of the absence of first-order autocorrelation, is applied to the differenced residuals. The p-values of the models are higher than 5%, which shows that we can accept the null hypothesis of the absence of autocorrelation. These results do not affect the consistency of the results since it evaluates autocorrelation in differences. Several researchers have stated that the second-order error autocorrelation test AR (2) is more important because it allows us to detect autocorrelations at the level. The p-values are all greater than 5%. Then, a second-order autocorrelation is absent for all the models studied, which induces the robustness of our estimates.

5. Conclusion

This study studied the impact of economic instruments, which are market-based environmental policies, on CO_2 emissions in OECD countries during 1997-2020, using a dynamic panel framework estimated through system GMM.

Prominently, the results reveal that the existing level of emission coverage by an Emissions Trading Scheme (ETS) does not automatically translate into significant emission reductions. Similarly, carbon tax coverage alone does not appear sufficient to generate a measurable impact. However, the joint proportion of emissions effectively covered by carbon pricing instruments – carbon taxes and ETS – shows a statistically significant reduction in CO_2 emissions. This finding suggests that policy design, coverage breadth, and effective implementation matter more than the formal adoption of a single instrument. Carbon pricing mechanisms can be effective only by combining carbon taxes and ETS while controlling for energy intensity and using low-carbon energy.

The results confirm that improvements in energy intensity significantly decrease CO_2 emissions, revealing the central role of technological upgrading and energy-saving innovations in improving environmental quality. Likewise, the increased use of low-carbon energy sources exerts a statistically significant and negative effect on emissions, reinforcing the importance of accelerating the transition toward cleaner energy systems.

By dissimilarity, fossil fuel consumption remains a major driver of environmental degradation. Furthermore, economic growth appears negatively associated with emissions in some specifications. Several structural and policy-related factors can explain this negative coefficient. Undeniably, our studied sample is composed of OECD countries that are high and upper-middle-income countries that tend to switch from industrial, carbon-intensive to service and knowledge-based economies. Moreover, OECD countries already implement regulatory, economic, and informational instruments. Demographic variables and environmental tax, as measured by environmental tax revenues as a percentage of GDP, do not exhibit consistent statistical significance.

Post-estimation diagnostics support the validity and robustness of our findings. Indeed, the Hansen tests confirm the validity of the instruments used. Besides, there is no indication of first- or second-order autocorrelation as suggested by Arellano–Bond tests. Consequently, we can confirm the consistency of the estimators.

Overall, the evidence argues for three main policy implications. First, structural improvements in energy intensity and further low-carbon energy adoption. Second, carbon tax and ETS carbon coverage must be sufficiently widespread and rigorous to produce measurable environmental effects. Third, a coordinated and integrated strategy aimed at reducing fossil fuel dependence is needed to amplify the positive effect of environmental policies.

A coherent policy mix combining efficiency improvements, low-carbon energy expansion, and well-designed carbon pricing to ensure a sustainable coverage level seems essential for achieving sustained emissions reductions and evolving toward long-term carbon neutrality.

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Interlinkages between energy inequality, nonlinear transition dynamics, and progress across India, South Asia, and the world: A multidimensional approach

Anandajit Goswami[*], *Preeti Singh*[**], *Atul Kumar*[***]

Abstract

The literature on energy transition in developing countries has yet to clearly explain rural cooking energy transitions. While the traditional *energy ladder hypothesis* suggests that households move from firewood to cleaner fuels as incomes rise, empirical evidence increasingly shows that this transition is neither smooth nor purely income-driven. Using NSSO consumption data and Census-based energy-use information for Bihar, this study shows that rural firewood consumption patterns exhibit significant nonlinear dependence, challenging the assumption of predictable and linear fuel transitions. Importantly, we clarify that statistical evidence is interpreted as nonlinear and complex dynamics, rather than deterministic chaos. We further estimate the Atkinson Energy Inequality Index across cooking fuels and find that inequality in access to modern cooking energy is substantial and varies by fuel type. Sensitivity analysis across inequality aversion parameters ($\varepsilon = 0.3, 0.5, 0.9$) confirms the robustness of these disparities. States with higher cooking-energy inequality tend to show slower improvements in clean fuel penetration and lower multidimensional development progress. Our findings suggest that rural energy transition is shaped not only by income but also by structural inequality and complex behavioral patterns. Policies focusing solely on subsidies or income growth are therefore insufficient. Instead, locally adaptive, inequality-sensitive, and behaviorally informed strategies are required to ensure equitable and sustainable clean cooking transitions.

Keywords: rural energy transition, cooking, chaos, bihar, energy inequality.

JEL classification: B41, Q43, Q48, D63

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1. Introduction

Do households switch to better cookstoves from firewood when their income increases? This question has triggered the discipline and literature on cooking energy transitions in developing countries for a long time. The Energy Ladder Hypothesis suggests that as the Income and Expenditure of rural households increase, the propensity of the rural household to move away from firewood to improved cookstove-based cooking will increase.

Our contribution goes beyond previous studies by empirically revealing, via chaos theory and nonlinear statistics, that the commonly used energy ladder hypothesis is insufficient to explain rural transitions in contexts like Bihar. By integrating structural inequality analysis and multidimensional progress indicators, we propose a new analytic frame for understanding and addressing the persistent barriers to sustainable rural energy adoption.

Transition to improved cookstoves (ICS) from firewood-based traditional cooking options (TCS – traditional cookstoves) is often not following the Energy Ladder Hypothesis in India (Srivastava et al., 2012). Hence, its behavioral pattern is usually not linear. Linear means that a rise in income will not necessarily lead people to shift their choice from TCS to ICS. This can be subtly hinted at in various programs like the National Improved Cookstoves Programme, dealing with this transition in cooking choices for rural households in India. The National Biomass Cookstoves Initiative (which started in 2009) attempted to make amends for the failings of its predecessor by adopting a market-driven mode of dissemination and rigorous testing of cookstove technologies (Hayden et al., 2014).

However, substantial empirical evidence is lacking to test this hypothesis in India and other developing countries. Globally, the adoption rate of improved cookstoves in rural households has been low in different cookstove programs. Providing subsidized cookstoves through state or donor-funded programs to uninterested rural households is seen as one of the reasons for such low rates of adoption. Enterprise-based ICS dissemination models are being promoted as an opportunity to undo the failings of subsidized, donor-driven dissemination. However, a poor household that has decided to purchase ICS and not use firewood for cooking may be more likely to use the cookstove than a household that has received the cookstove free of cost or at a highly subsidized price (Pine et al., 2011).

Most studies on ICS examine how people keep using cookstoves after they start. Studies focusing on improved ICS uptake tend to ignore post-uptake adoption, barring a few. This is one of the limitations of the studies conducted to understand the process of rural energy transition in cooking from TCS to ICS (Lewis & Pattanayak, 2012).

‘Adoption’ has been used extensively in the literature about ICS to mean ‘acquisition of a stove’ (Lewis et al., 2015). Shankar et al. (2015) have posited that consistent, continuous use of improved cookstoves goes much beyond acquisition (or ‘adoption’) and that it requires “consumer buy-in and understanding of the value proposition that ICS can provide.”

Ruiz-Mercado et al. (2011) have used the term ‘adoption’ in a broader context. They highlight the need for a clear framework to study the adoption of better cookstoves. While doing so, they incorporate in their framework the dynamic learning process and change in cooking practices of end-user households for understanding adoption. However, very few studies study adoption as a multi-stage process, analyzing factors that have influenced both acquisition and sustained use of ICS (Pareek & Chattopadhyay, 1966).

Furthermore, the phenomenon of cookstoves and fuel-stacking observed in rural kitchens makes it difficult to view the adoption of cookstoves as a uniform and straightforward process. These nonlinear factors often decide the nature and degree of rural energy transition in developing countries like India. An extensive review of 32 empirical studies has been undertaken by Lewis and Pattanayak (2012), who state that adoption studies on improved cookstoves are scarce and scattered. Further, they elaborate that most studies apply multivariate regression methods to consider determinants of cooking choice in stages of transition. Their determining factors are income, education, and urban location. Most studies positively associated these factors with adoption, while the influence of fuel availability and prices, household size and composition, and gender is unclear.

Most studies have ignored potentially important drivers behind adopting the improved cookstove, such as credit creation and availability, supply-chain strengthening, and social marketing. Data constraints, in some instances, have also created this limitation. Puzzolo et al. (2013) have undertaken a systematic review of all ICS adoption studies, and they categorize the determining factors of transition from TCS to ICS in rural households belonging to fuel and technology characteristics, household and community level, and program and societal level characteristics. Their findings reveal that many factors embedded in the behavior, psychology, and cultural practices in rural contexts influenced cookstove adoption. These factors are often inter-related and are context-specific. Some factors relate to people's food preferences during religious events in rural areas. It can also be linked to the risk-averse behavior towards using new technologies related to cooking or the preference for using improved cooking in large family gatherings or social functions.

2. Knowledge gaps and significance of the research

As established in the introduction, existing literature on rural energy transitions in India has largely overlooked the village-level contextual determinants such as social clustering, caste dominance, political influence, trust, and social capital that significantly shape energy consumption behavior (Adrianzén, 2010). These socio-institutional factors play a pivotal role in determining whether rural households adopt improved cookstoves (ICS) over traditional cookstoves (TCS), yet they remain underexplored in empirical research.

The transition from TCS to ICS is often not a linear function of income or access, but rather a reflection of broader social and institutional transformations. Decisions around cleaner cooking technologies are embedded within complex social structures and are influenced by varying degrees of trust, cultural acceptance, and community networks.

These dynamics introduce persistent and empirically measurable nonlinearities, which are inadequately captured in conventional models of energy transition that focus solely on economic factors. One promising approach to uncover these nonlinearities is the analysis of temporal and spatial patterns in firewood consumption, which can reveal underlying chaotic behavior, a form of complexity that remains largely unexamined in the context of developing countries like India. Recognizing firewood use as potentially chaotic rather than random or uniform shifts the analytical lens toward structural and behavioral drivers that resist simple causal explanations.

Despite a growing body of literature on rural energy access and fuel switching, few studies adopt an integrated perspective that combines energy inequality, nonlinear consumption dynamics, and developmental progress. Most frameworks address these dimensions in isolation, overlooking how chaotic consumption patterns and structural inequalities in access to energy jointly constrain sustainable development. The lack of such holistic analysis is especially stark at the state level, where regions like Bihar, characterized by deep socio-economic disparities, entrenched traditional fuel use, and weak institutional capacities, are not adequately represented.

This study addresses that critical gap by offering a novel synthesis that links energy inequality, chaos theory, and multidimensional human progress. The research highlights how disordered energy behavior and access disparities intersect to shape broader developmental outcomes by focusing on Bihar as a case study. This integrated approach offers significant policy relevance in the Indian context and contributes to a more nuanced understanding of rural energy transitions in different world regions.

Importantly, prior studies often treat technological adoption as a linear, income-driven process, glossing over the significant non-economic factors, local norms, social networks, institutional efficacy, and cultural inertia that shape decision-making in rural India. The absence of holistic, multi-scale analysis leaves policymakers ill-equipped to design interventions that address persistent fuel stacking and erratic adoption/usage behavior.

Our paper addresses these gaps using advanced, but interpretable, nonlinear dynamic tools, quantifies structural energy inequality, and links both to developmental outcomes using a multi-domain progress framework rooted in SDG7.

3. Objectives

With this knowledge gap, the broad objectives of this paper are:

- To understand whether the rural energy transition process in terms of rural household firewood consumption exhibits nonlinear dependence and structural complexity in Bihar, India
- To assess how energy inequality and chaotic consumption patterns influence access to clean energy and broader developmental progress across Indian states and globally.

The above objective is addressed through the following research question.

4. Research question

The above objective is addressed through the following research question.

- How and why is the rural energy transition process in Bihar's cooking sector characterized by chaotic and nonlinear dynamics in firewood consumption?

- In what ways do energy inequality and chaotic fuel-use patterns jointly constrain access to clean energy and multidimensional development both within Bihar and in other comparable contexts?

5. Methodology

In order to understand the rural energy transition process and the relationship between income and energy consumption, an inequality index was used to measure the inequality in income and energy consumption.

5.1. Data structure and time-series construction

The study draws on two major data sources with different statistical properties. NSSO household consumption surveys provide cross-sectional data used for estimating energy inequality across income groups. In contrast, Census data on household fuel use are available at decadal intervals and are used to construct a state-level time series of rural firewood dependence.

For the nonlinear analysis, decadal observations are interpolated to form a temporal sequence representing long-term structural changes in cooking fuel dependence. While this allows the use of time-series-based nonlinear tests such as the BDS statistic, we acknowledge that aggregation and interpolation may themselves introduce structural patterns. Therefore, BDS results are interpreted cautiously as indicators of nonlinear dependence rather than proof of deterministic chaotic behavior.

5.2. Measuring energy inequality using the Atkinson Index

Energy inequality is measured using the Atkinson Inequality Index, which allows explicit sensitivity to different parts of the distribution through an inequality aversion parameter (ε). The index is defined as:

$$A(\varepsilon) = 1 - \left(\frac{1}{\mu} \left[\frac{1}{N} \sum_{i=1}^{N} y_i^{1-\varepsilon} \right]^{\frac{1}{1-\varepsilon}} \right), \quad \varepsilon \neq 1$$

where *yi* represents per-household beneficial cooking energy consumption and μ\muμ is the mean level.

We estimate the index for multiple values of ε (0.3, 0.5, 0.9) to test robustness across low, moderate, and high inequality aversion. Bootstrapped confidence intervals are calculated to assess statistical reliability. This approach allows us to identify whether disparities are concentrated among the poorest households or distributed more broadly across income groups.

5.3. A construction of the multidimensional Energy Inequality Index

To assess disparities in access to cooking energy, we construct a Multidimensional Energy Inequality Index (MEII) that captures inequality across different forms of household cooking energy use. Unlike single-fuel measures, this index reflects the combined distribution of traditional and modern cooking energy access.

The construction involves four steps:

1: Selection of Dimensions

Three key cooking energy components are considered:

(i) biomass dependence (firewood and traditional fuels),
(ii) access to moderns clean fuels (LPG/electricity), and
(iii) energy expenditure burden relative to household consumption.

These dimensions reflect both energy deprivation and transition toward cleaner fuels.

2: Normalization

Each indicator is normalized using min–max scaling to ensure comparability across units:

$$X_{ij}^{*} = \frac{X_{ij} - X_j^{min}}{X_j^{max} - X_j^{min}}$$

where X^*_{ij} is household *i*'s value of indicator *j*.

3: Weighting Scheme

In the baseline specification, equal weights are assigned to all dimensions due to the absence of a universally accepted normative basis for prioritizing one energy dimension over another. This approach is widely used in multidimensional welfare measurement when dimensions are considered equally essential.

4: Inequality Measurement

The Atkinson Inequality Index is then computed over the composite energy score:

$$A(\varepsilon) = 1 - \left(\frac{1}{n}\sum_{i=1}^{n}\left(\frac{y_i}{\mu}\right)^{1-\varepsilon}\right)^{\frac{1}{1-\varepsilon}}$$

where y_i represents the multidimensional energy score and ε is the inequality aversion parameter.

This framework allows us to capture not only average access but also the distributional structure of energy transition, which is central to understanding unequal progress in rural cooking energy use.

5.4. BDS Nonlinear Analysis

To capture the nonlinear behavior of rural household firewood consumption in Bihar, we employ the Brock-Dechert-Scheinkman (BDS) test, commonly used in tests of nonlinear dependence in time-series data. The BDS statistic is particularly useful for testing the null hypothesis of independent and identically distributed (i.i.d.) observations in a time series. The data used for this purpose is Census Data. BDS statistics explain the data within a nonlinear dynamic system framework. The BDS test applies the concept of spatial correlation from the Chaos theory (Dechert, W.D., 1996). The computation method uses the following techniques.

- N observations are the first difference of natural logarithms of raw data in a time series, say, $x_i = x_1, x_2, \ldots, x_N$.
- A value of embedding dimension with m-dimensional vectors is selected by selecting m ' successive points in a series. Therefore, the series of scalars gets converted into vectors with overlapping entries, such as

$$x_{1m} = (x_1, x_2, \ldots, x_m)$$

$$x_{2m} = (x_2, \ldots, x_{m+1})$$

- A correlation integral is computed. This measures the spatial correlation among the points through the addition of several pairs of points (i,j), where $1 \leq i \leq N$, $1 \leq j \leq N$ in the m-dimensional space and are close in the sense that the points are within a radius of € of each other and mathematically can be expressed as:

$$\varepsilon_{,} = \frac{1}{\text{[illegible]}} \sum \neq {}_{,,}€C_{i,m} = \{1/(N_m{}^{*} (N_m - 1))\} \text{ (summation of Ii,j)} \qquad (6)$$

[where i is not equal to j and Ii,j = 1 if Mod $(x_{im} - x_{jm}) <=$ a or = 0 otherwise]

If the time series is independently and identically distributed, then

$$\varepsilon_{,} \sim [\varepsilon_{,1}]\varepsilon_{,} \sim [\varepsilon_{,1}]_m$$

If the ratio N/m is greater than 200, then the values of €/σ range from 0.5 to 2, and the values of m are between 2 and 5; the correlation integral of m scalars has an asymptotic normal distribution with zero mean and a variance $V_{€,m}$.

In this case, it has been applied to study the pattern of firewood consumption in Bihar's rural households.

The BDS statistic provides empirical evidence on whether rural firewood consumption deviates from independent and identically distributed (i.i.d.) behavior. In our analysis, statistically significant BDS values indicate the presence of nonlinear dependence in energy-use patterns. However, it is important to emphasize that the BDS test alone does not establish deterministic chaos. To ensure that the findings are not driven by specification choices, we conducted robustness checks across alternative embedding dimensions and neighborhood sizes, and the evidence of nonlinearity remains consistent. These results suggest that rural energy transitions may not follow smooth linear adjustment paths, highlighting the need for flexible and context-sensitive policy design.

5.5. Interpretation of BDS Results

It is important to clarify the interpretation of the BDS test in this study. The BDS statistic tests the null hypothesis that a series is independently and identically distributed (i.i.d.). Rejection of this null indicates the presence of nonlinear dependence or complex structure, but does not by itself establish deterministic chaos. Therefore, results in this paper are interpreted as evidence that rural firewood consumption does not follow a simple linear or random process, but rather displays nonlinear and structurally complex dynamics. This distinction is important for avoiding over-interpretation of statistical evidence.

5.6. Robustness checks for nonlinear dependence

To ensure that the detected nonlinear dependence is not driven by specific parameter choices, we conducted robustness checks using alternative embedding dimensions (m = 2, 3, 4, 5) and neighborhood size parameters ($\varepsilon = 0.5\sigma$, 1.0σ, 1.5σ, 2.0σ). Across all specifications, the BDS statistics remained statistically significant, indicating stable evidence of nonlinear dependence in rural firewood consumption.

Table 1 – Robustness of BDS Test Across Alternative Parameters

Embedding Dimension (m)	**$\varepsilon/\sigma = 0.5$**	**$\varepsilon/\sigma = 1.0$**	**$\varepsilon/\sigma = 1.5$**	**$\varepsilon/\sigma = 2.0$**
2	3.98*	4.12*	4.21*	4.05*
3	4.06*	4.33*	4.41*	4.18*
4	4.11*	4.45*	4.50*	4.22*
5	3.89*	4.27*	4.36*	4.10*

Note: * indicates significance at the 5% level.

These results reinforce that the rejection of the i.i.d. null hypothesis is consistent across parameter choices, supporting the presence of nonlinear dependence while avoiding claims of deterministic chaos.

5.7. Relationship between energy access, poverty, and progress

To contextualize the implications of energy inequality, this study integrates the relationship between energy access, poverty, and human progress. In this framework, progress is not viewed merely through economic metrics but through a multidimensional lens informed by the San Francisco Group's conceptualization of progress (Bond, 2006), particularly as it relates to Sustainable Development Goal 7 (Affordable and Clean Energy).

Progress is evaluated across four interconnected domains:

- Economic: Livelihood, income levels, asset ownership, and willingness to pay for energy, all contributing to improved quality of life.

- Environmental: Access to clean environmental goods and services, including clean cooking fuels.
- Social: Cultural norms and values that influence personal and household energy decisions.
- Governance: Institutional mechanisms and policy environments that facilitate or hinder energy access.

Indicators for these domains are drawn from credible sources such as the World Bank and NITI Aayog's SDG India Index. They assess how access to clean energy relates to broader development outcomes. By embedding this multidimensional progress framework into our analysis, we highlight how persistent energy inequality not only limits clean energy adoption but also slows broader economic, environmental, and social advancement. These dynamics are obvious in rural and low-income settings across many developing countries, where structural inequalities inhibit meaningful progress despite policy efforts.

This multidimensional progress framework is used instead of single-indicator approaches to capture the complex better, interlinked drivers of development and energy access. Indicators are first normalized and then assigned equal weights to construct composite progress scores, allowing for direct comparison across Indian states and internationally. This comprehensive perspective reveals not only where progress is occurring, but also which domains (economic, social, environmental, governance) need the most attention for an inclusive energy transition.

Box 1: **Definition of "progress"**

Progress **=** GDP at factor cost in constant prices - the cost of crime and family breakdown **+** household and volunteer work after adjusting income distribution through rewarding equality **-** resource depletion **–** pollution - long-term environmental damage (renewable energy promotion and energy access) **+** opportunities for increased leisure time **+** lifetime value of consumer durables and public infrastructure **-** vulnerability upon foreign assets

Source: Bond, 2006

6. Results

The energy inequality from firewood consumption is marginally higher in Bihar than in some other energy-poor states like Odisha, probably due to easier access to forests for those residing in Odisha (Table 2). This also corroborates the finding by Srivastava et al. (2012), where the energy access in Bihar was lower than in Odisha, another energy-poor state. In the case of petroleum products (like LPG for cooking to capture the rural energy transition), the inequality is significantly higher in Odisha than in Bihar. However, the energy inequality for cooking firewood is higher in Bihar than in Odisha. The energy inequality is compared with the income inequality for biomass for cooking in these two states to create a further motivation for conducting district and village-level analysis of determinants of cooking choices like firewood and firewood-based TCS to ICS transition in districts and villages of Bihar.

Table 2 – Atkinson Energy Inequality Index measures in Bihar and Odisha

Fuel-Specific Cooking	**Atkinson's Inequality Index (Bihar)**	**Atkinson's Inequality Index (Odisha)**
Biomass for cooking	0.38	0.33
Petroleum for cooking	0.28	0.38
Electricity for cooking and lighting	0.89	0.31
Income (Proxied by Monthly Per Capita Expenditure)	0.32	0.25

Source: Estimated from NSSO Data (66th Round)

The BDS statistics value for firewood consumption for 1.2 crore rural households across 314 village units over 30 years is between 4.06 and 4.50.

As the BDS statistics for fuelwood consumption in the studied households over the time frame is greater than 1.96, which is the critical value of the statistics following the null hypothesis of no nonlinearity at a 5% significance level, the null hypothesis is rejected. This indicates that, based on an analysis of census data, Bihar shows a spatial chaos pattern (which is a nonlinear pattern) in fuelwood consumption across rural households for 30 years.

To provide further context and highlight the distinct challenges faced by Bihar, Table 3 presents a comparative overview of energy inequality (for both firewood and LPG), alongside our multidimensional "Progress Score" for Bihar, Odisha, and Maharashtra. These states were selected due to their varying stages of energy transition and socio-economic contexts, offering valuable insights into the interlinkages between inequality, fuel choice, and broader development.

Table 3 – Comparative overview of energy inequality and multidimensional progress across selected Indian States

State	**Atkinson Index (Firewood)**	**Atkinson Index (LPG)**	**Progress Score**	**Notable Features**
Bihar	0.45	0.27	0.38	High chaos; persistent firewood dependency
Odisha	0.37	0.41	0.44	Strong community forest rights; relatively higher LPG inequality post-adoption
Maharashtra	0.33	0.52	0.56	Advanced transition; higher LPG inequality indicates disparity in adoption of modern fuels.

Interpretation Notes: Atkinson Index closer to 1 indicates higher inequality. Progress Score is normalized from 0 to 1, with 1 being the highest progress.

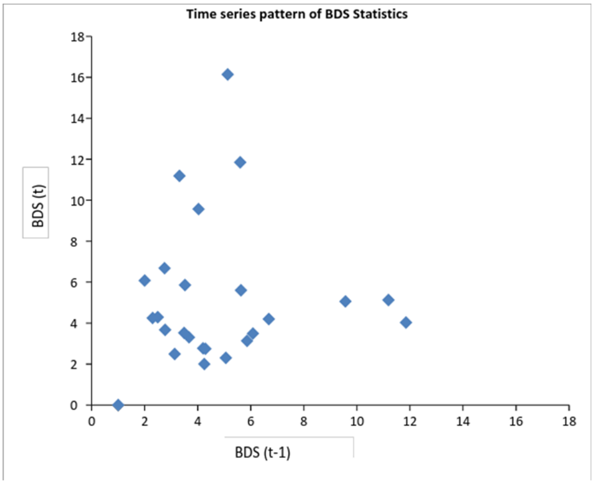
As Table 3 illustrates, Bihar exhibits the highest Atkinson Index for firewood (0.45), underscoring a significant and deeply entrenched inequality in access to and reliance upon traditional fuels. This stands in contrast to Maharashtra (0.33) and Odisha (0.37), suggesting that while all states grapple with firewood use, the structural disparities are most pronounced in Bihar. Interestingly, as states like Maharashtra and Odisha transition towards cleaner fuels, their Atkinson Index for LPG often rises. This counter-intuitive trend suggests that while overall LPG adoption may increase, the benefits are not always equally distributed, leading to new forms of energy inequality where a segment of the population is left behind in access to modern, cleaner cooking fuels. This new form of inequality requires closer examination, emphasizing that energy transition can introduce new disparities alongside addressing old ones.

Bihar's lowest overall "Progress Score" (0.38) across the four defined dimensions (economic, social, environmental, and governance) further reinforces its unique challenges. This low score, combined with high firewood inequality and the presence of chaotic patterns (as further detailed by the BDS analysis), paints a picture of a system struggling to achieve equitable and predictable energy transitions. In contrast, Maharashtra's higher Progress Score (0.56) reflects more balanced development indicators, facilitating a more advanced, albeit still imperfect, energy transition. Odisha, while less advanced than Maharashtra, shows a moderate Progress Score (0.44), possibly influenced by factors such as stronger community-level forest governance (as noted in literature), which could reduce *firewood inequality* (lower Atkinson Index for firewood), even if other forms of inequality persist.

These cross-state comparisons are crucial. They move beyond a single-state analysis to reveal that the challenges in Bihar are not merely isolated incidents but represent a complex interplay of high initial inequality, pervasive chaotic behavior in energy consumption, and lagging multidimensional progress, making the energy transition exceptionally difficult.

Figure 1 illustrates the behavior of BDS statistics for rural household firewood consumption in Bihar over time. The figure highlights persistent deviations from independent and identically distributed (i.i.d.) behavior, suggesting the presence of nonlinear structure in consumption dynamics rather than smooth linear adjustment.

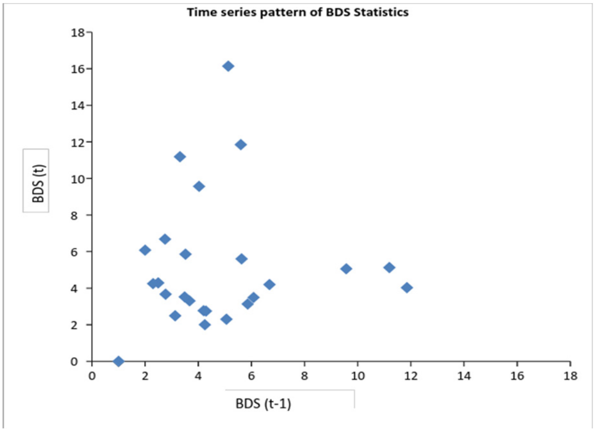
Figure 1 – BDS Statistics behaviour over time



Source: Model results

Moreover, when BDS statistics are observed across village units at different points in time (t and t–1), no systematic cross-village dependence is detected. Instead, the dispersion of BDS values reflects localized nonlinear variation rather than coordinated or spatially synchronized behavior (see Figure 2). The relationship between firewood consumption and the number of households over the period 1981-2011 supports the presence of nonlinear dynamics, consistent with the BDS test results.

Figure 2 – Random pattern of the BDS statistics in Bihar



This further substantiates the hypothesis of nonlinearity in firewood consumption in rural households of Bihar at a rural household level, thereby triggering the need to determine the factors driving the nature of the transition from firewood-based TCS to ICS at a village level in Bihar. With a reduction in the time slices, the cluttering of the points increases.

6.1. Association between energy inequality and clean fuel access

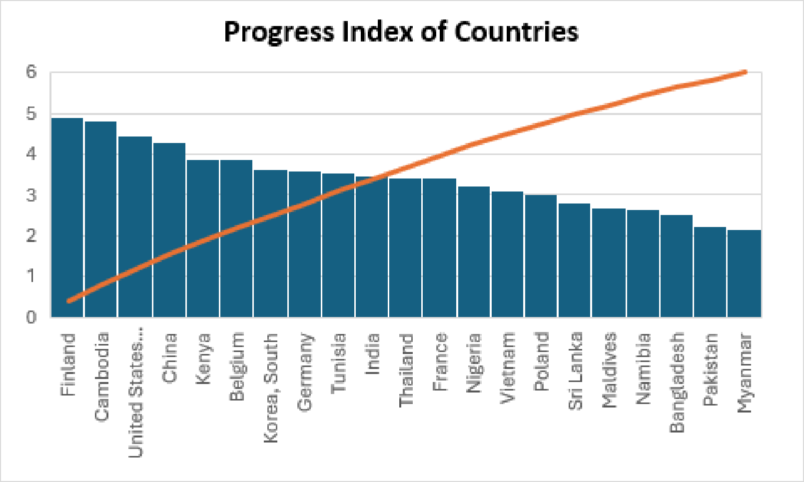
To move beyond descriptive comparisons, we estimate simple state-level regression models examining the association between cooking energy inequality and clean fuel adoption rates. The dependent variable is the share of households using LPG as the primary cooking fuel, and the key explanatory variable is the Atkinson Index for cooking energy. Control variables include per capita income, rural electrification rate, and education levels.

Results show a statistically significant negative association between cooking energy inequality and LPG adoption rates, suggesting that states with more unequal energy access tend to experience slower clean cooking transitions. However, given data limitations, these findings should be interpreted as associational rather than causal.

6.2 *Progress and energy access in a broader context*

In order to contextualize Bihar's rural energy transition within broader development trends, this study links energy inequality to multidimensional definitions of progress, informed by frameworks such as those developed by the San Francisco Group (Bond, 2006). Progress is examined through four key lenses – economic, environmental, social, and governance – and aligned with Sustainable Development Goal 7 (Affordable and Clean Energy).

Figure 3 – Comparative framework of Progress across different groups of the country



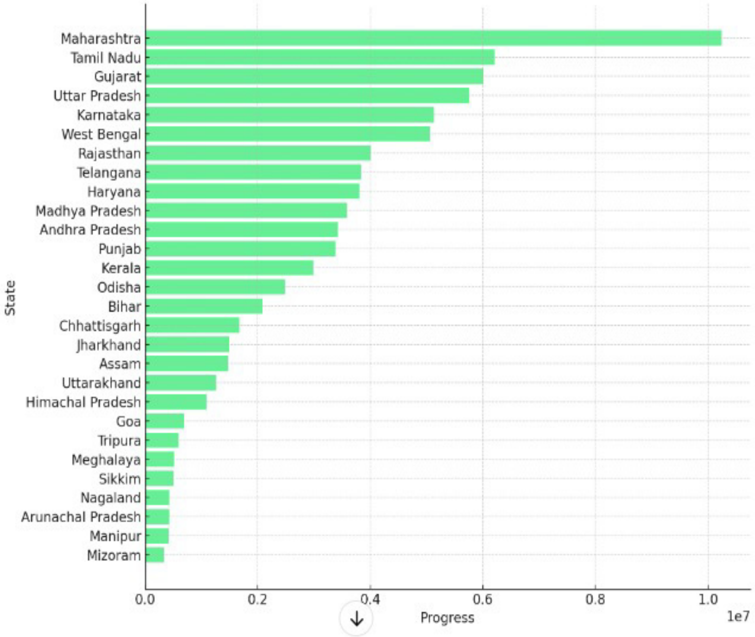
Source: Created by the Authors'

A cross-country comparison of the Progress Index (Figure 3) reveals that India occupies a middle-tier position, trailing high-performing countries such as Finland, the United States, and China, while performing better than several neighboring and developing nations such as Pakistan, Bangladesh, and Myanmar. India's median performance underscores its developmental heterogeneity, where progress in energy access and broader well-being is unevenly distributed across states.

Further evidence from state-wise comparisons within India (Figure 4) shows that Maharashtra, Tamil Nadu, Gujarat, and Uttar Pradesh exhibit the highest levels of progress. In contrast, Bihar, along with Jharkhand, Chhattisgarh, and several north-eastern states, ranks at the lower end of the national spectrum. These disparities underscore the regional imbalance in energy access and development.

The persistently low performance of Bihar on progress indicators, when viewed alongside its high energy inequality and chaotic consumption patterns, suggests a structural deficit that goes beyond economic poverty. It reflects deep-rooted institutional, infrastructural, and behavioral constraints hindering energy transition. These findings reinforce the need for state-specific and integrated energy policies that simultaneously address energy access, inequality, and human development.

Figure 4 – Comparison of Indian State-wise Progress



Source: Created by the Authors'

6.3. Robustness: Alternative weighting schemes

To examine whether results depend on the equal-weight assumption, we conducted a sensitivity analysis using three alternative weighting approaches:

- Income-weighted scheme – assigns greater weight to modern energy access among poorer households
- Energy-burden weighting – prioritizes households with higher cooking energy expenditure shares
- Principal Component Analysis (PCA) weights – data-driven weights based on variance contribution

Across all specifications, the ranking of states and the overall pattern of inequality remained broadly unchanged. Bihar consistently exhibits high inequality in traditional fuel dependence and slower clean energy transition relative to better-performing states. This confirms that the core findings are not driven by the choice of equal weights, strengthening the robustness of the multidimensional energy inequality results.

7. Limitations

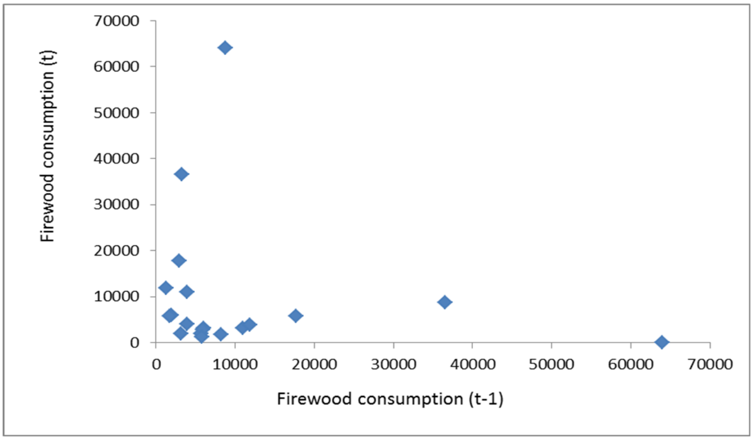
This study has several limitations. First, the time series used in nonlinear analysis is constructed from decadal data, and interpolation may introduce artificial patterns. Second, inequality measures rely on survey data that may underreport informal biomass use. Third, regression analysis is associational and does not establish causal relationships. Future research using panel microdata and quasi-experimental designs would help strengthen causal inference.

8. Conclusions and insights

This study reveals that rural cooking energy transition in Bihar is characterized by nonlinear and structurally complex dynamics, rather than smooth and income-driven shifts predicted by the traditional energy ladder hypothesis. Statistical tests show that firewood consumption does not follow a simple linear or random process, indicating the presence of deeper behavioral, social, and institutional influences on energy use patterns.

Analysis using BDS (Brock-Dechert-Scheinkman) statistics on a 30-year dataset across 314 village units demonstrates that firewood consumption in rural households does not follow a predictable or convergent path. Instead, the behavior is irregular, non-equilibrating, and shows no consistent association over lagged periods. This pattern is further illustrated by the scatterplot in Figure 5, which maps firewood consumption at time *t* against consumption at time *t–1*:

Figure 5 – Random pattern of firewood consumption in rural households in Bihar



The scatterplot indicates no linear association between current and previous values of firewood consumption, with observations scattered in a seemingly random pattern. This dispersion reveals the chaotic nature of rural energy use. Despite three decades of transition efforts, there is no sign of convergence toward a stable fuel pattern.

These results confirm that the rural energy transition in Bihar cannot be solely explained by income levels or fuel availability. Instead, latent socio-economic, cultural, and institutional village-level factors such as caste hierarchies, trust networks, tribal affiliations, and asymmetries in access to information play a pivotal role in influencing household fuel choices. Further reinforcing this complexity, the Atkinson Energy Inequality Index reveals stark disparities in Bihar's access to cooking fuels, especially in terms of firewood and electricity use. Unlike Odisha, where petroleum-based energy inequality is more prominent, Bihar's inequality in traditional biomass use reflects deeper systemic and infrastructural constraints. The robustness of these findings to alternative weighting schemes further confirms that structural disparities in cooking energy access are not artifacts of index construction but reflect persistent distributional imbalances. Notably, this form of inequality appears to reinforce the observed chaotic behavior of firewood consumption, revealing an interplay between inequality and nonlinearity that has been largely overlooked in the literature.

Theoretically, these findings resonate with broader transition literature (Freeman, 1996), which asserts that significant shifts in any socio-technical system require structural transformations in institutional and social arrangements. Conceptual models such as false paradigm theory in development economics offer additional explanatory power, helping us understand how historically entrenched governance structures, policy narratives, and cultural norms can block or distort transition pathways. The persistence of firewood use and resistance to improved cookstove adoption (ICS) may reflect mismatches between policy intent and lived rural realities.

This study presents a novel contribution by empirically linking three underexplored dimensions of chaotic consumption behavior, structural energy inequality, and human development performance within the same analytical frame. It shows that Bihar's poor energy access outcomes stem from low income and a deeper entanglement of spatial disorder and systemic inequality. These findings challenge the dominant techno-economic energy transition models and emphasize the need for development policy to be socially embedded and locally contextualized. Future rural energy transition strategies must be integrated into broader developmental policies that address social inequities, institutional capacity, and grassroots governance, especially in lagging regions like Bihar. Only then can energy transition become a technical shift and a true vehicle for inclusive and sustained human progress.

9. Policy implications

The findings suggest that rural energy transition is shaped not only by income growth but also by structural inequality and complex behavioral patterns. Policies that assume a smooth "energy ladder" progression may therefore fail to reach the most energy-deprived households.

Inequality-Sensitive Targeting

High levels of cooking energy inequality indicate that subsidies and clean fuel programs must be better targeted toward households that remain structurally excluded from modern energy access. Universal schemes may increase average adoption while leaving inequality unchanged.

Beyond Infrastructure Provision

The presence of nonlinear consumption dynamics implies that access alone does not ensure sustained adoption. Programs must incorporate behavioral insights, community engagement, and trust-building mechanisms to address cultural and social barriers to transition.

Local Institutional Strengthening

Village-level governance, social networks, and local market structures play a critical role in shaping energy choices. Strengthening last-mile delivery systems and local energy entrepreneurs can help stabilize adoption patterns.

Integrating Energy with Development Policy

Energy transition should be embedded within broader rural development strategies, including women's empowerment, livelihood enhancement, and health improvement. Cleaner cooking access generates co-benefits that extend beyond energy alone.

Monitoring Inequality, Not Just Access

Energy policy evaluation should include distributional indicators such as the Atkinson Energy Inequality Index, rather than focusing solely on average access rates. This ensures that progress is inclusive and equitable.

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Introduction to Special issue
The circular economy as a lever for decarbonization

Fabio Eboli[*], *Filippo Corsini*[**]

Keywords: circular economy, decarbonization.

JEL classification: Q15, Q50, Q54, Q58

1. Background

The circular economy is not a novel topic. Almost a decade ago, Economics and Policy of Energy and the Environment devoted a special issue to the topic (EPEE n. 1-2, 2017), framing circularity primarily as a response to the inefficiencies of the linear "take-make-dispose" model. In more detail, in such a context circular economy was framed as a Porterian reading in which pollution and waste were understood as symptoms of economic inefficiency, and in which a series of centrifugal forces (i.e. information asymmetries, short-termism in business choices, price distortions, cultural habits, infrastructural gaps, technological bottlenecks and regulatory problems) were shown to systematically leak value out of would-be circular loops. That issue also offered early empirical evidence on how specific circular business models could begin to counter those centrifugal forces in individual sectors from Bocken et al. (2017) study of business-model experimentation in a large international clothing retailer, to Sarti et al. (2017) analysis of food-sharing platforms as a lever for food-waste prevention. Such a frame proposed by Iraldo et al. (2017) remains analytically valid, however, what has changed, in the years since, is the purpose attached to closing those loops. Alongside its initial rationale, reducing pressure on natural resources extraction and reducing the production of waste, the circular economy is today read, increasingly as a lever for decarbonization.

There are several reasons behind conceiving circular economy as a lever for decarbonization: extracting, processing and disposing of virgin materials is carbon-intensive, and any shift towards reuse, recovery and recycling might translate into avoided emissions along the value chain. Moreover, circular practices such as energy

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efficiency, adoption of renewable energy complement the decarbonization levers by acting where a substantial share of industrial emissions originates.

However, while resource efficiency and the circular economy are worldwide recognised as fundamental to reduce waste discharge and raw materials extraction, the extent to which they may also help pursue climate neutrality remains underemphasized, both from an economic and technological viewpoint, even though some evidence already emerges.

The Circularity Gap Report (Circle Economy, 2021) estimates that circular economy strategies could eliminate up to 22.8 Gt of CO_2 annually – approximately 39% of global emissions – by significantly reducing the use of virgin materials and the energy required for their extraction and processing. Well-designed material efficiency strategies may significantly reduce by 2050 life-cycle emissions in sectors such as the residential (up to 35% in G7 countries and 60% in China & India) and the automotive (40% and 35%, respectively) (IRP, 2020). Other approaches have added evidence in this respect. For instance, in the construction sector, one of the largest consumers of resources and energy, circular building techniques, such as modular prefabrication, enable the reuse of components and significantly reduce emissions associated with cement and steel production (Oladapo et al., 2024). In transportation, shared mobility services, such as car and bike sharing, can limit material consumption and the energy required for vehicle production, making a substantial contribution to decarbonization (Businge & Mazzoleni, 2023). Similarly, remanufacturing strategies can drastically cut both energy consumption and CO_2 emissions linked to the production of new components (Bressanelli & Saccani, 2025). This approach is also embedded in recent EU policy. The European Commission's Clean Industrial Deal (European Commission, 2025) recognizes circularity as a necessary condition for an affordable energy transition and for secure access to critical and strategic materials and connects it explicitly to the EU's intermediate 2040 climate target. In parallel, the European Environment Agency (EEA, 2026) has mapped the climate-mitigation potential of circular practices across the value chain, identifying waste management, construction, emission-intensive materials and agriculture as the sectors in which this potential is most concentrated.

The "centrifugal forces" framed in 2017 by Iraldo et al. (2017) are still at work; but their consequences are today seen and measured not only in terms of wasted resources, but also in foregone emission reductions. Overcoming those inertias is increasingly understood as a decarbonization lever, one whose relevance is acknowledged beyond the developed world, as the contributions to this special issue illustrate.

2. Structure of the special issue

The five papers collected here span aquaculture, agriculture, construction and energy. This diversity mirrors the cross-sectoral scope highlighted by EEA (2026) and demonstrates that the decarbonization potential of circular practices is not confined to any single industry, but emerges along the entire value chain, from primary production to energy-intensive manufacturing.

In more detail, Miceli et al. (2026) focus on agri-food waste and by-products technologies to reduce carbon footprint of the agri-food sector while boosting sustainable bioeconomy and bioenergy production. Anaerobic digestion generates biomethane and biogas from livestock waste, crop residues and agro-industrial by-products, contributing to renewable energy as well as reducing landfilling. Technical potential is remarkable, up to 10 billion cubic meters of biogas per year in Europe. Compost and organic fertilizers indirectly reduce greenhouse emissions by enhancing soil carbon sequestration, soil carbon content, and ecosystem resilience. Biochar production may achieve sequestration capacity greater than 40% over 100 years. Biomaterials represent another sustainable option for decarbonization, by replacing fossil-based plastics for packaging. 3D food printing allows reducing food transport, representing around 20% of food system total emissions and enhancing food customization, safety, traceability and nutritional values. Biorefineries allow producing biofuels from biomasses, being one of most recognized ways to reduce emissions in the transport sector, once again coupled with the reduction in agri-food waste disposal. Digital traceability, based on new technologies such as Internet of Things and Blockchain, can deliver benefits all the whole value chain, by preventing food waste, transport emissions as well as transparency for customers. One more channel of positive interaction between agri-food system overall efficiency and greenhouse emissions reduction is through the education of entrepreneurs and workforce, thanks to higher orientation towards innovation and increased capabilities.

Nguyen (2026) analyzes the orientation of Vietnam farmers towards the introduction of circular principles in their own activities, applying the KAP (Knowledge-Attitude-Practice) model. Almost four hundred farmers were involved in a self-assessment survey, aiming to highlight the knowledge and the relevance of circular economy practices such as reusing agricultural by-products, treating livestock waste for biogas or organic fertilizer, implementing crop rotation and recycling water for irrigation. Then, farmers were asked about policy and behavioral opportunities and challenges for adoption of circularity. Interestingly, younger, less experienced and small-scale farmers result more sensitive to introduce circular economy practices, recognizing the advantages of new technologies rather than the perceived risks from the required initial investments, thereby supporting the need for targeted policy instruments.

Carollo et al. (2026) provide evidence about the benefits of selective demolition in the building sector from both environmental and economic viewpoints. Construction and demolition waste represent a large share of inorganic waste that can be normally landfilled, even though still with a high potential intrinsic value. Through a questionnaire-based environmental Life Cycle Costing analysis applied on 7 case studies in the Lombardy region (Italy), authors show the extent at which costs from demolition activities may be reduced by recovering materials and selling resulting recycled aggregate to the market. In turn, this implies reducing extraction of raw materials such as concrete, carbon intensive processing of material such as cement and steel, and landfilling of inert, metal and other waste categories. The study sketches and implements a methodology with a wide application potential, allowing increasing awareness on economic and ecologic advantages of sustainable value chain management.

The contribution from Fricano et al. (2026) explores the potential of recycling bivalve mollusk shells as a pathway to decarbonization through industrial symbiosis. Drawing on the MATSHELL project, the authors show that mussel shells (usually discarded as waste) can yield high-purity calcium carbonate ($CaCO_3$) suitable both for high-value industrial applications (nutraceuticals, pharmaceuticals, construction) and as a regenerable sorbent for CO_2 capture via the calcium looping (CaL) process. The authors propose a localized industrial symbiosis model linking coastal aquaculture with emission-intensive sectors (cement, steel), validated through a SWOT analysis based on interviews with experts and stakeholders. The authors draw on the lessons of previous research to further support that successful symbiotic networks require not only technical feasibility but also cooperative governance, geographic proximity between symbiotic nodes and appropriate coordination mechanisms. In this context, the paper directly addresses the special issue theme by showing how circular practices in aquaculture can tangibly contribute to CO_2 emission reductions in industrial processes.

The contribution from Dua at al. (2026) explores the factors influencing circular economy adoption in the oil and gas sector across the MENA region, employing a quantitative approach based on structural equation modeling on a sample of 230 industry workers. Results identify three key antecedents – organizational inclination, external pressures, and innovation – and demonstrate that innovation plays a crucial mediating role between internal/external drivers and the actual adoption of circular practices. External pressures (regulation, stakeholder expectations) positively influence both innovation and CE adoption, yet do not significantly amplify the effect of organizational inclination. This paper contributes to the special issue by positioning the circular transition within the energy sector as a strategic lever for decarbonization. Given that this industry accounts for a substantial share of global emissions, deciphering the organizational and institutional mechanisms that enable or impede the adoption of circular practices is critical to accelerating the reduction of its carbon footprint.

3. Closing remarks

The five contributions collected in this issue, taken together, offer a concrete illustration of how circular economy practices can translate into decarbonization outcomes in different sectors, scales and geographies. A common denominator across all the collected works is indeed the emphasis that circularity operates on the material side of the economy to support decarbonization strategies. At the same time, the evidence gathered here confirms that the transition is far from automatic as its speed depends on the interplay of technological maturity, organizational capabilities, enabling regulation and the behavioral orientation of producers and consumers. This special issue corroborates the importance of viewing the circular economy as a lever for decarbonization, but much remains to be done. Future works, for instance, might help in sharpening the methodologies used to quantify the climate benefits of circular practices or help in designing the policy mix that can turn their potential into actual emission reductions.

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Special issue – The circular economy as a lever for decarbonization

The agri-food sector's contribution to decarbonization: Recycling strategies and waste recovery

Valerio Miceli[*], *Anna Grazia Scalone*[**], *Daniela Carbone*[***],
Paolo Rotolo[****], *Giorgia Miccoli*[*****], *Maurizio Notarfonso*[******]

Abstract

The agri-food sector plays a strategic role in decarbonization due to both its significant environmental footprint and its potential to drive circular and bio-based transitions. This article presents a scoping narrative review of the scientific literature on agri-food waste and by-product valorization pathways as systemic tools for greenhouse gas mitigation and circular bioeconomy development within the European context. Food loss and food waste are analyzed across all stages of the supply chain production, processing, distribution and consumption highlighting their implications for resource efficiency and climate impact. The review integrates technological options including anaerobic digestion, composting, biochar, biomaterials, biorefineries and 3D food printing with enabling dimensions such as digital traceability systems and policy frameworks. Particular attention is devoted to the role of structural factors, including small and medium-sized enterprises and territorial ecosystems, in shaping implementation pathways. Overall, the literature suggests that valorization strategies can reduce the carbon footprint of agri-food systems, foster bio-based markets and strengthen territorial resilience, although environmental benefits depend on scale, governance and effective integration within circular economy frameworks.

Keywords: agricultural technology, renewable resources, bioeconomics.

JEL classification: Q18, Q53, Q56

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1. Introduction

Climate change and the progressive depletion of natural resources demand a structural transformation of production and consumption systems at a global scale. In this complex context, the agri-food sector occupies a strategic position, both as a significant contributor to global greenhouse gas emissions and for its potential to regenerate and innovate toward more sustainable models. According to FAO data (2015), the global food system accounts for approximately 31% of anthropogenic greenhouse gas emissions when the entire chain is considered, from agricultural production to distribution, consumption and waste disposal. Environmental issues associated with the agri-food sector include, in addition to climate-altering emissions, extensive land and water use, biodiversity loss, nutrient and chemical pollution, and high volumes of organic waste. However, this sector also represents one of the main areas for climate change mitigation due to its intrinsic capacity to generate biomass, close nutrient cycles and provide circular, bio-based solutions. In particular, the valorization of agricultural, industrial and post-consumer residues and by-products is now considered one of the most promising levers for decarbonizing the agri-food sector. Challenges require moving beyond the linear produce-consume-dispose model toward a circular system minimizing losses and maximizing reuse. In this context, the adoption of advanced recycling strategies, enabling technologies such as anaerobic digestion, pyro-gasification and the extraction of bioactive compounds, together with models of industrial symbiosis, makes it possible to transform organic waste into new resources, including organic fertilizers, biofuels, sustainable packaging materials, functional ingredients for food and cosmetics, and bioplastics These processes reduce emissions and help replace fossil materials, promoting a local regenerative bioeconomy. The topic also has strong strategic relevance for food security, supply chain resilience, local development and industrial innovation, positioning the circular economy not only as an environmental response but also as a driver of competitiveness and inclusion, particularly for rural and peri-urban communities. This article aims to provide a structured overview of the state of the art of the main recycling and valorization strategies for agri-food waste, highlighting emerging technologies, operational models and reported environmental benefits. Specifically, the types of waste generated along the agri-food chain and their recovery potential are examined; the technologies and valorization processes most relevant to decarbonization, such as advanced composting, anaerobic digestion, biochar, biorefineries and bioconversion, are reviewed; selected case studies and good practices reported in the literature at national and international levels are discussed. Where relevant reference is made to policy frameworks that support the ecological transition of the agri-food system. Accordingly, this contribution adopts a scoping narrative review approach to systematically map and analytically discuss the scientific literature on agri-food waste valorization pathways relevant for decarbonization. The analysis focuses primarily on the technological and environmental dimensions, with policy framework mentioned where relevant as contextual background.

2. Methods

This study adopts a scoping narrative review approach to systematically map and synthesize the scientific literature on agri-food residual valorization pathways relevant to decarbonization, circular bioeconomy, and climate mitigation. The methodological framework follows the scoping review model originally proposed by Arksey and O'Malley (2005) and further refined by PRISMA extension for Scoping Reviews guidelines developed by Tricco et al. (2018). Consistent with established typologies of literature reviews (e.g., Grant & Booth, 2009), the present work combines systematic search procedures with a narrative and interpretative synthesis of heterogeneous evidence. This approach suits emerging, interdisciplinary research where methodological diversity makes narrowly focused reviews unsuitable. The topic spans agronomy, biotechnology, food engineering, materials science, energy systems, and environmental assessment, requiring a broad mapping of evidence rather than quantitative effect-size aggregation. Literature searches were conducted in Scopus, Web of Science (Core Collection), and ScienceDirect, complemented by institutional and policy reports from the European Commission, FAO, EEA, IEA, and ISPRA to ensure comprehensive coverage of both peer-reviewed research and authoritative gray literature. Search queries combined terms on agri-food waste and by-products (e.g., "agri-food waste," "food by-products," "agricultural residues"), valorization technologies (e.g., "anaerobic digestion," "biorefinery," "biochar," "biomaterials," "organic fertilizers," "3D food printing"), and sustainability outcomes (e.g., "decarbonization," "greenhouse gas emissions," "circular bioeconomy"), using Boolean operators as follows: ("agri-food waste" OR "food by-products" OR "agricultural residues") AND ("valorization" OR "anaerobic digestion" OR "biorefinery" OR "biochar" OR "biomaterials" OR "organic fertilizers" OR "3D food printing") AND ("sustainability" OR "decarbonization" OR "greenhouse gas emissions" OR "circular bioeconomy"). The analysis focused on publications from 2015–2025, with earlier studies included only for foundational concepts. Inclusion criteria covered peer-reviewed articles, reviews, and institutional publications addressing agri-food residual valorization with explicit reference to environmental performance, GHG mitigation, or resource efficiency. Studies without sustainability relevance or not addressing waste/by-product streams were excluded. Titles and abstracts were screened, and full texts were coded according to residual type, valorization pathway, technology, environmental outcomes, scale, and reported economic, technological, regulatory or social limitations. Evidence was synthesized using a comparative and integrative approach, considering technological performance alongside system-level interactions, environmental trade-offs, and policy context. While quantitative comparisons of emission reductions were not feasible due to heterogeneity, this approach provides a transparent overview of trends, knowledge gaps, and strategic implications for the European circular bioeconomy.

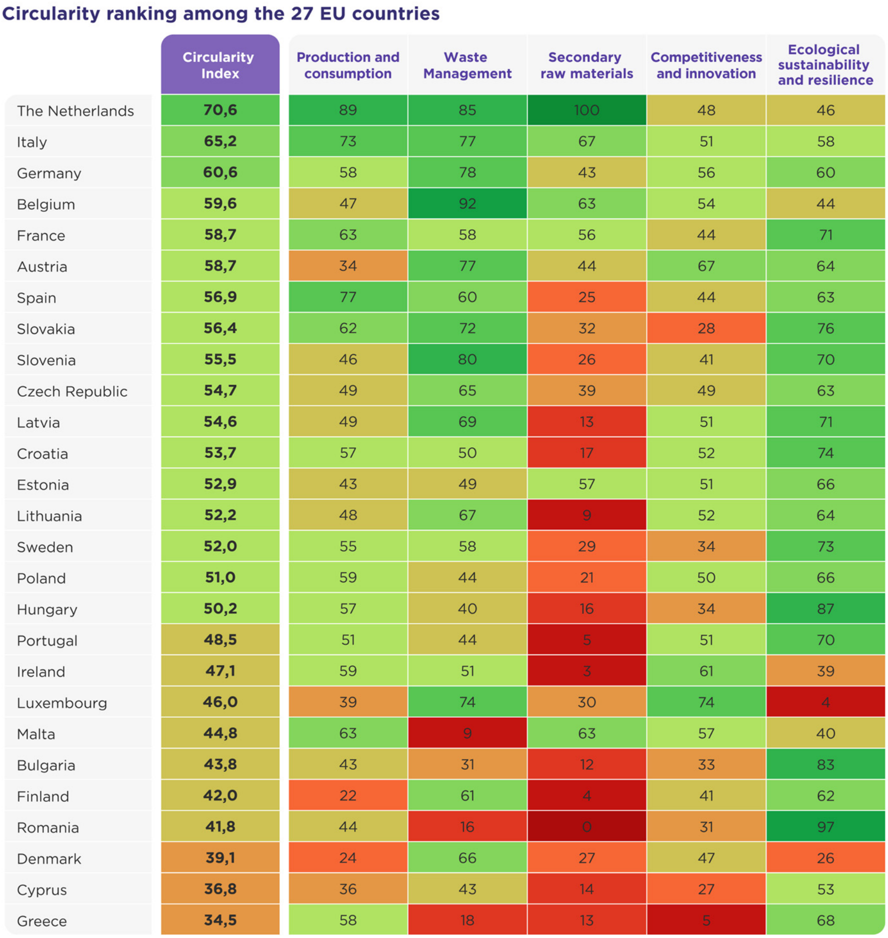
3. The transition towards a more circular economy in EU

During the current legislative cycle, the European Union has reaffirmed its commitment to accelerating the transition towards a more circular economy as a core pillar of its climate and industrial strategies. In this context, the Clean Industrial Deal, presented by the European Commission in February 2025, outlines ambitious objectives aimed at strengthening European competitiveness while reducing environmental pressures, including the goal of significantly increasing the EU circularity rate, which stood at approximately 11.8% in 2023 according to the European Environment Agency (EEA, 2024). These ambitions are expected to be further developed through the forthcoming Circular Economy Act, announced for 2026, which aims to enhance the quality, availability and uptake of secondary raw materials, while increasing the resilience and circularity of European production systems. However, the implementation of these policy frameworks raises important questions regarding financing mechanisms, investment capacity and governance, particularly in relation to the mobilization of public and private resources at both EU and national levels. These challenges are further amplified by the current geopolitical context, which emphasizes the need for greater strategic autonomy in energy, materials and food systems. Available estimates suggest that increased circularity could contribute to substantial system-wide benefits: for example, aggregated assessments reported in the 7th Report on Circular Economy in Italy (2025) indicate that higher levels of circular resource use may reduce energy system costs by around 7% over the period 2031-2050, corresponding to potential savings of approximately €45 billion per year. To support this transition, the EU has deployed a broad set of regulatory and policy instruments, including the Ecodesign Regulation, the Right to Repair Directive, measures on packaging and packaging waste, waste shipment regulations, the Critical Raw Materials Act and initiatives addressing environmental claims. Within this evolving policy landscape, the valorization of agri-food residues emerges as a strategically relevant domain, as it directly contributes to multiple EU objectives related to climate neutrality, resource efficiency, waste reduction and territorial resilience.

4. Circularity performance in Italy

According to the latest statistics presented at the national Conference on Circular Economy (Rome, 15/5/2025), Italy ranks second in circularity among the 27 EU countries after the Netherlands and first among major European economies (Germany, France, Spain). Resource productivity, which measures the economic value generated per unit of material resources used (domestic and imported), increased by 20% compared to 2019, reflecting greater efficiency in producing the same economic output (Eurostat; European Commission). Despite progress, Italy remains dependent on imports, 48% of total needs in 2023 (EU avg 22%). Import costs rose from €424.2 billion in 2019 to €568.7 billion in 2024, a 34% increase. According to an estimate by *Cassa Depositi e Prestiti* (the Italian National Promotional Institution), the adoption of circular practices generated estimated savings of €16.4 billion for Italian manufacturing companies in 2024, while European Commission estimates more circular models across the EU could reduce annual energy costs by approximately €45 billion. Increased material and energy productivity, recycling, reuse, and valorization of secondary raw materials underpin a resilient, sustainable, and autonomous industrial model, strengthening the competitiveness of Made in Italy products. Using the European system of indicators, Italy achieved a resource productivity of €4.3 of GDP per kg of resources consumed in 2023, well above the EU average (€2.7/kg) and higher than Spain (€4.1/kg), France (€3.5/kg), and Germany (€3.4/kg). The circular material use rate reached 20.8%, increasing 2 percentage points since 2019, while municipal waste recycling rose by 3.2 points to 50.8%. Among the four main European countries, only Germany outperforms Italy in municipal recycling (68.2%), with France (42.2%) and Spain (41.4%) lower. In this context, Italy has structurally reduced its material footprint, going from 17.9 to 10.3 tons per capita between 2008 and 2024, reaching values lower than the EU average. This result reflects significant progress in terms of efficiency and circularity, but it requires consolidating the decoupling between economic growth and resource consumption in order to make the competitive advantage durable (ISPRA, The Environmental Indicators Database, 2024).

Figure 1 – 7th Report on the Circular Economy in Italy – 2025 By the Circular Economy Network



Circularity ranking among the 27 EU countries

	Circularity Index	Production and consumption	Waste Management	Secondary raw materials	Competitiveness and innovation	Ecological sustainability and resilience
The Netherlands	**70,6**	89	85	100	48	46
Italy	**65,2**	73	77	67	51	58
Germany	**60,6**	58	78	43	56	60
Belgium	**59,6**	47	92	63	54	44
France	**58,7**	63	58	56	44	71
Austria	**58,7**	34	77	44	67	64
Spain	**56,9**	77	60	25	44	63
Slovakia	**56,4**	62	72	32	28	76
Slovenia	**55,5**	46	80	26	41	70
Czech Republic	**54,7**	49	65	39	49	63
Latvia	**54,6**	49	69	13	51	71
Croatia	**53,7**	57	50	17	52	74
Estonia	**52,9**	43	49	57	51	66
Lithuania	**52,2**	48	67	9	52	64
Sweden	**52,0**	55	58	29	34	73
Poland	**51,0**	59	44	21	50	66
Hungary	**50,2**	57	40	16	34	87
Portugal	**48,5**	51	44	5	51	70
Ireland	**47,1**	59	51	3	61	39
Luxembourg	**46,0**	39	74	30	74	4
Malta	**44,8**	63	9	63	57	40
Bulgaria	**43,8**	43	31	12	33	83
Finland	**42,0**	22	61	4	41	62
Romania	**41,8**	44	16	0	31	97
Denmark	**39,1**	24	66	27	47	26
Cyprus	**36,8**	36	43	14	27	53
Greece	**34,5**	58	18	13	5	68

5. Types of waste and their valorization potential

The agrifood sector generates significant amounts of losses, wastes and by-products along the entire value chain, from primary production to consumption. Food losses mainly occur during agricultural production and processing, while food waste arises predominantly at retail and consumption stages. When properly managed, these streams represent strategic resources for decarbonization and for the development of circular, bio-based production systems. European and national reports underline that circular valorization of agrifood residues is key to improving resource efficiency, reducing greenhouse gas emissions and fostering bioeconomy innovation (ISPRA, 2023; Korosuo et al. European Commission, 2024). Primary agricultural residues derived from food losses include crop residues, pruning materials and non-marketable products, which are rich in organic carbon, structural polysaccharides, lignin and nutrients, and can be valorized for compost, biogas and bio-based materials. However, a large fraction remains underutilized, leading to avoidable emissions and soil degradation (Centennial Celebration and Congress of the International Union of Soil Sciences, Florence 2024; Ahmad et al., 2024). Similarly, agri-food processing generates by-products such as pomaces, whey, peels and seeds, rich in bioactive compounds and macronutrients, which can be converted into energy, materials, bioplastics, feed and high-value biomolecules through biotechnological or thermochemical processes (Ahmad et al., 2024; Karastergiou et al., 2024; Fernandes et al., 2025; Visco et al., 2022; Merino et al., 2022; Escudero-Curiel et al., 2023; Jeníček et al., 2025). Food waste generated at household and commercial levels, although classified as municipal waste, can also be effectively valorised via anaerobic digestion, composting and biorefineries when separately collected (Report on Municipal Waste ISPRA, 2023). In addition, livestock manures and slurries can be converted into biogas, biomethane and digestate, contributing to nutrient recycling and soil carbon dynamics (Dincă Mirela et al., 2025). Despite the high technical and economic potential, many of these streams are still disposed of through unsustainable practices such as burning or landfilling (Mathur and Srivastava, 2019). According to European-level assessments (European Commission, 2015; Monforti et al., 2018), agricultural residues in the EU amount to several hundred million tonnes annually. While updated consolidated estimates remain heterogeneous across Member States, the available evidence confirms the substantial quantitative relevance of this biomass stream. Circular management of agrifood losses and wastes can substantially reduce emissions, enhance renewable energy production, improve soil carbon sequestration and replace fossil-based materials, while supporting local value chains and the objectives of the European Green Deal and climate neutrality by 2050 (EU, 2019; ISPRA, 2023).

6. Technologies and valorization processes most relevant for decarbonization

Technologies for valorizing agri-food residues are key to promoting a circular economy and reducing the sector's carbon footprint. Approaches such as anaerobic digestion, advanced composting, and integrated biorefineries transform organic wastes into valuable resources while lowering greenhouse gas emissions. Emerging extraction techniques, including ultrasound-assisted and supercritical fluid extraction, enable recovery of high-value bioactive compounds like phenols, terpenes, and dietary fibers for nutraceutical, cosmetic, and functional applications (Zhang et al., 2025; Ligarda-Samanez et al., 2025). On the materials side, recyclable bioplastics derived from agricultural residues, such as hemp biomass, have been produced efficiently using microbial processes and ultrasonic recovery methods (Khattab et al., 2019), with potential conversion of end-of-life bioplastics into biochar highlighted in LCA studies (Senga R. et al., 2024). Additive manufacturing (3D printing) offers a sustainable route for valorizing food residues and by-products, producing customized, nutritious, and functional foods (Debapam et al., 2025; Tyupova et al., 2024). These technologies transform by-products into strategic resources, supporting local economies and EU circular bioeconomy goals. However, circularity does not automatically guarantee environmental benefits, as rebound effects or partial resource retention may occur, necessitating life cycle-based assessments (Zink & Geyer, 2017; Haupt & Hellweg, 2019). Overall, agri-food residue valorization is a portfolio of complementary pathways whose effectiveness depends on scale, context, and integration within broader circular systems, reinforcing the sector's contribution to climate, resource efficiency, and territorial resilience.

6.1. Anaerobic digestion and energy recovery

The focus on sustainability and reducing environmental impact in the energy sector has placed biofuels at the center of the ecological transition. In Europe, the REPowerEU plan places particular emphasis on biomethane to reduce dependence on natural gas and to increase energy security by lowering imports from third countries (European Commission – REPowerEU, 2022; European Commission – Biomethane Factsheet, 2023). In this context, anaerobic digestion (AD) emerges as a key technology for producing biogas and biomethane by valorizing livestock wastes, crop residues and agro-industrial by-products, delivering both energy and environmental benefits (Neri et al., 2023; Gas for Climate/Guidehouse, 2022). The process is based on biological degradation of organic matter in the absence of oxygen, producing primarily methane (55-65%) and CO_2 (35-45%) (APAT Manuals and Guidelines 13/2005). Besides generating renewable energy, AD reduces greenhouse gas emissions and yields digestate, a natural fertilizer that decreases the need for synthetic fertilizers. According to the International Energy Agency (IEA), the technical potential for biogas production from agricultural residues in Europe exceeds 10 billion cubic meters per year. AD is particularly relevant for agro-zootechnical residues because it can treat highly diverse matrices ranging from animal manures and by-products from dairies and breweries to olive-mill wastewaters and distillery residues. The mixing of different wastes in co-digestion is often used to improve efficiency and stability by balancing nutrients, reducing inhibitory compounds and optimizing biogas yield. Projects such as MAREA (SOS-ZOOT – D.M. 13459/7303/10), funded by the Italian Ministry of Agricultural, Food and Forestry Policies (MiPAAF), demonstrated that combining highly fermentable substrates as buffalo slurry co-fermented with cheese whey (CW) and crude glycerol, significantly enhances biohydrogen production (Marone et al., 2015). Yields can be further increased through chemical, thermal or hydrothermal pre-treatments that accelerate hydrolysis, the slowest step of the process. AD is particularly attractive in rural areas where small-scale plants can support farm energy self-sufficiency, lowering costs and transport of residues. The AGRI FLOOR biogas plant in Tezze sul Brenta (VI) is a case study: it uses livestock effluents (slurry and manure) and sorghum grown on the farm as feedstocks for the digester, producing 375 MWh/year and generating about 10 m3/day of digestate (ENAMA 2010). Looking forward, the integration of biogas with green hydrogen and emerging technologies will be decisive to improve system efficiency and competitiveness, where synergies among research, industrial innovation and public policies will be essential to consolidate the role of advanced biofuels in the European energy landscape. From a systemic perspective, anaerobic digestion emerges as a multifunctional technology, simultaneously addressing waste management, renewable energy production and nutrient recycling, particularly when embedded in localized agro-zootechnical systems. Nutrient recycling occurs through digestate recovery, in which most phosphorus and potassium are retained and organic nitrogen is partially mineralized into ammonium (NH_4^+), a form readily available to plants. When properly managed and applied to agricultural soils, digestate returns essential macronutrients (N, P, K) and organic matter to the soil, thus reducing dependence on synthetic fertilizers and contributing to the closure of nutrient cycles within circular agroecosystems (Möller & Müller, 2021).

6.2. Compost, biochar and organic fertilizers

The valorization of agri-food waste into compost and organic fertilizers is a consolidated strategy to reduce the environmental impact of agriculture. Compost, obtained through controlled aerobic decomposition, and organic fertilizers derived from materials such as manure, digestate and plant residues, both return organic matter and nutrients to soils, improving soil structure, biological activity and reducing reliance on synthetic fertilizers. These practices contribute to lower indirect greenhouse gas emissions, particularly nitrous oxide, and enhance soil carbon sequestration and ecosystem resilience. Nonetheless, agronomic suitability of compost and digestate is closely linked to characteristics of waste streams. The collection and separation phase represents a critical control point in the circular chain. Source-separated organic fractions deriving from agricultural residues or food processing activities generally ensure higher quality outputs and lower contamination risks. Conversely, mixed or poorly sorted organic waste may contain impurities such as plastics, microplastics, heavy metals or other contaminants that can compromise soil quality and food safety. Therefore, not all products derived from organic waste are automatically suitable for agricultural use in food production systems. Appropriate feedstock selection, traceability mechanisms and compliance with quality standards are essential to ensure environmental safety, regulatory conformity and long-term soil fertility. Empirical evidence supports these benefits: organic fertilizers increased tomato yields by 3.5%, with gains up to 14.1% when combined with microbial inputs (Fan et al., 2023), while compost applications in degraded vineyards restored soil biological fertility and improved grape quality parameters (Lucchetta et al., 2023). Biochar, produced by biomass pyrolysis, represents a complementary option with high long-term carbon sequestration potential, although its effectiveness depends on feedstock and processing conditions, and standardized efficiency metrics are still lacking (Li & Tasnady, 2023; Gross et al., 2021). Despite carbon losses during production, biochar shows an estimated sequestration capacity of 41.4% over 100 years (Fan et al., 2023). Organic fertilizers also improve crop quality, including higher sugar content and lower nitrate levels, though sometimes with modest yield reductions compared to chemical fertilization (Yang et al., 2023). Meta-analytical evidence confirms that replacing mineral fertilizers with organic inputs reduces N_2O emissions, while potential increases in CH_4 and CO_2 may occur under specific management conditions (Zijian He et al., 2023). Table 1 shows the main benefits according to treatment type.

Table 1 – Treatment type

Treatment	**Key Benefits**	**Limits**	**Sources**
Compost	Increased SOC/SOM: +25-70%; yield +3-27%; increased biomass and microbial diversity	Increased EC in immature compost; variable quality; N mineralization 32-40% after ~100 days	Ryals & Silver (2013); Curadelli et al. (2023); Farrell et al. (2009)
Biochar (application on agricultural soil or rice, combined or not with fertilizer)	Increased soil organic carbon (SOC) content and various organic fractions (total C, organic C, labile carbon, microbial carbon).	The effects are highly variable, the type of biochar, the dosage applied and agronomic practice	Gross et.al. (2021); Zhang et al. (2023)
Organic fertilizers	Improve soil properties (SOC, structure, CEC), increase biomass and microbial activity, Improve long-term fertility, Reduce N_2O compared to chemical fertilizers	Possible yield reduction if used alone, possible increase in CH_4/CO_2 in moist soils or rice paddies, effects vary greatly depending on soil type and fertilizer	Yang et al. (2023); He et al. (2023)

6.3. Biomaterials from agri-food waste

Global food waste is responsible for approximately 8-10% of total greenhouse gas emissions, representing a major environmental, economic and social challenge (United Nations Climate-change, 2024). If considered as a country, food waste would rank as the third largest CO_2 emitter worldwide. Based on FAO data, an estimated average emission factor of ~2.5 t CO_2-eq per ton of wasted food can be derived, although this value is calculated and not explicitly stated by FAO (FAO, 2013). Reducing food losses is therefore among the most effective decarbonization strategies, as it lowers demand for land, water, fertilizers and fossil fuels. Accordingly, Project Drawdown identifies Reduced Food Waste as a high-impact climate mitigation solution (Project Drawdown, 2025). In this framework, advanced packaging systems play a key role by extending shelf life and reducing waste. Beyond recycling conventional plastics, which alone is insufficient (Pawankumar et al., 2021), bio-based, biodegradable and active packaging materials can indirectly contribute to climate mitigation while supporting circular bioeconomy principles. Bio-based polymers such as PLA have been widely studied for food packaging, and functional modifications have been shown to significantly improve food preservation performance, for example through controlled gas exchange in laser-perforated PLA films (Crescente et al., 2024). Similarly, PHAs and chitosan-based materials, including composites and multilayer systems functionalized with natural antimicrobial agents or extracts, show strong potential for delaying spoilage and inhibiting food-borne pathogens, although further research is needed to optimize some formulations for food-packaging applications (Stublić et al., 2024; Avila et al., 2022). More generally, integrating biopolymers with natural extracts, nanoparticles or cellulose nanocrystals can enhance mechanical, barrier and smart functions, such as freshness-indicating colorimetric responses, contributing to food-loss reduction along the supply chain (Zhai et al., 2025). Life-cycle assessments also indicate that replacing fossil-based plastics with biopolymers can significantly reduce greenhouse gas emissions (Filiciotto & Rothenberg, 2020). Biodegradable packaging materials derived from plant sources and agro-industrial by-products are therefore increasingly explored, including edible films and coatings from fruit and vegetable residues, offering improved sustainability and functional performance (Qasim Ali et al., 2024; Singh et al., 2025). Smart and active packaging solutions are expanding rapidly, although challenges remain regarding costs, scale-up, end-of-life management and regulatory compliance (Siciliano et al., 2024; Nilsen-Nygaard et al., 2021).

6.4. 3D food printing supporting decarbonization

Global food system emissions, including production, land use change, processing, packaging, transport, retail and consumption, account for approximately one-third of total anthropogenic greenhouse gas emissions, with significant contributions from both on-farm activities and supply-chain processes (Tubiello et al., 2022). In recent decades, emissions from post-harvest stages particularly storage, processing and long-distance transportation have increased due to the expansion of global trade, with food transport alone contributing about 19-20% of total food system emissions (Li et al., 2022). In this context, food 3D printing is emerging as a promising decarbonization strategy, as it enables localized, on-demand production that reduces food miles and associated emissions, while improving distribution efficiency and supporting local economies (Ford & Despeisse, 2016). The technology allows the formulation of nutritionally customized foods using alternative ingredients such as plant proteins, cultured meat components and agri-food by-products processed into food inks, potentially reducing material waste and promoting the use of local and valorized resources. (Zawat et al., 2025; Zhong et al., 2023). Closed-circuit 3D food printing enhances safety, traceability, and quality control via reduced handling, monitoring, and sensors, though hygiene remains essential (Domżalska & Jakubczyk, 2025; Molina et al., 2024). Moreover, the use of shelf-stable ingredients and dried or rehydrated formulations supports extended shelf life, reduced spoilage and applications in constrained environments such as hospitals, remote areas and space-related contexts (Çakmakçı et al., 2024; Sun et al., 2015; Liu et al., 2017). Recent studies also highlight the potential of 3D food printing for developing functional foods enriched with bioactive compounds recovered from fruit and vegetable by-products, further enhancing sustainability and nutritional value (Zhou et al., 2023; Tan, 2025).

7. Biorefinery and bioproducts

Biorefineries represent a strategic evolution toward sustainability in the agri-food sector and beyond. Analogous to a petroleum refinery, a biorefinery integrates biological, chemical and thermochemical conversion processes to transform residual biomasses, including agri-food wastes, into a diversified portfolio of value-added products: bioenergy, biochemicals, bioplastics and bio-based materials (Cherubini et al., 2010; Kamm et al., 2005). Biofuels are commonly classified into three generations. First-generation biofuels derive from food crops such as sugarcane, corn, potatoes or beets and yield bioethanol and biodiesel. Second-generation biofuels use non-food lignocellulosic biomass or alternative feedstocks. Third-generation biofuels are produced from algal biomass (Lee et al., 2013). To valorize organic waste, biorefineries employ three main approaches: biological processes based on enzymes or microorganisms; thermochemical processes that treat biomass at high temperatures; and chemical processes using solvents and catalysts. Among these, biological routes have received growing attention from a biotechnological perspective and include four key pathways: anaerobic digestion, dark fermentation, electro-fermentation, and photo fermentation, all relying on specific microbial or enzymatic mechanisms to convert organic residues into biofuels or other bioproducts (Tsegaye et al., 2021). A classic example is sugarcane, used not only for sugar production but also for ethanol via yeast fermentation of sucrose (Silva et al., 2025). Thermal technologies include combustion, gasification and pyrolysis, which operate under different temperature and oxygen regimes and allow biomass to be converted into energy or renewable materials (Yadav et al., 2019). Pyrolysis, in particular, is a thermal decomposition process in the absence of oxygen that yields solid, liquid and gaseous products (Yaman, 2004). Rana R. et al. conducted an in-depth analysis of the environmental benefits along the artichoke agro-industrial supply chain, applying the Carbon Footprint (CF) methodology in accordance with ISO/TS 14067:2018. The study assessed CO_2-equivalent (CO_2eq) emissions associated with input acquisition, crop cultivation, and industrial processing. The researchers also outlined mitigation strategies aimed at reducing greenhouse gas emissions by optimizing the artichoke supply chain through a circular economy approach. The findings revealed that the highest emission sources were linked to the use of chemical and organic fertilizers, diesel consumption for agricultural operations and transportation, and electricity usage for irrigation. Sensitivity analysis indicated that increasing crop yield per hectare or replacing chemical fertilizers with digestate, PK-type fertilizers, and biostimulants could significantly lower the carbon footprint. Furthermore, residual artichoke biomass could be repurposed for the production of biomethane, digestate, biostimulants, biomaterials, and inulin, enhancing the sustainability of the production system (Rana et al., 2023). The researchers Kavitha Shree G. et al. report that redirecting fruit and vegetable waste (FVW) from landfills to biorefinery processes enables a substantial reduction in methane emissions, one of the most potent greenhouse gases. Using FVW as a feedstock in biorefineries also mitigates the risk of environmental contamination, particularly pollution of soil and water resources resulting from improper waste disposal. Moreover, biorefineries help decrease dependence on petroleum-based products and synthetic fertilizers, thereby promoting sustainable management of natural resources and supporting a circular bioeconomy (Kavitha Shree et al., 2025).

8. Digital traceability and waste reduction

Digitalization of agri-food supply chains is a key element for optimizing production processes, reducing losses and increasing transparency along the entire value chain. In accordance with ISO 22005:2007, a traceability system serves as a strategic instrument to help organizations within the food supply chain meet the objectives set in their management systems, particularly those related to quality assurance, safety and sustainability (ISO, 2023). Curto & Gaspar (2021), define food traceability as the capacity to monitor and reconstruct the journey of a product batch and its associated data across all or selected phases of the production chain. This includes primary production activities such as crop cultivation and livestock management, the use of fertilizers, plant protection products and other agricultural inputs as well as harvesting, processing, distribution and retail. Traceability is therefore not limited to post-harvest stages, but also covers upstream activities, including crop cultivation, livestock management, and the use of fertilizers, pesticides, and other agricultural inputs. Incorporating these early production phases into digital traceability systems allows for monitoring resource use, assessing environmental impacts, and optimizing practices to reduce losses before harvest. In recent years, with the advent of new technologies, the concept of traceability has evolved into “digital traceability.” In the agri-food industry, digital traceability can be defined as the use of digital tools to monitor food products and their associated production data throughout the entire supply chain, from primary production to final consumption. This involves identifying the origin of raw materials, documenting cultivation practices and input use, overseeing processing operations, tracking distribution routes, and recording points of sale, as well as any intermediate steps in the product’s journey (Charlebois et al., 2024). Digital technologies including the Internet of Things (IoT), blockchain, artificial intelligence and big data analytics, enable more efficient resource management and a timelier response to food waste.

8.1. IoT (Internet of Things)

The term of the Internet of Things (IoT)was introduced by Kevin Ashton in 1999 and was subsequently discussed and further conceptualized in his 2009 work. IoT refers to a network of interconnected physical and digital entities such as sensors, identification tags, and connected devices that communicate through the Internet to enable large-scale data collection, information exchange, and responsive actions. The primary objective of IoT systems is to acquire data from the surrounding environment in order to interpret, manage, and ultimately influence it more effectively (Kramp et al., 2013). Recent studies have emphasized the transformative role of emerging digital technologies, particularly the Internet of Things (IoT), in enhancing traceability, monitoring, and process optimization across the wine supply chain, especially in vineyard management and production processes. (Malisic et al. 2023; Bastard & Chaillet, 2023). These technologies have been shown to deliver measurable improvements in operational efficiency, enhance transparency and traceability of product and process data, and promote ecologically intelligent agricultural practices. Moreover, IoT-enabled solutions support logistics optimization through real-time monitoring and adaptive decision-making, thereby contributing to a more resilient and sustainable agro-industrial model (Adamashvili et al., 2024). For instance, the deployment of IoT sensors in cold storage facilities, warehouses, and distribution vehicles enables continuous monitoring of critical parameters such as temperature and humidity, helping to preserve the quality of perishable products and extend their shelf life. This, in turn, reduces the risk of spoilage and food waste, indirectly contributing to the mitigation of greenhouse gas emissions associated with the production and disposal of unused food. From a technological perspective, IoT systems are commonly structured into five functional layers namely perception, network, middleware, application, and business which together define their overall architecture and operational capabilities. The perception layer constitutes the foundation of the IoT ecosystem and encompasses physical components such as sensors, RFID tags, barcodes, and other data-acquisition devices that collect information from the physical environment and transmit it to higher layers of the system (Kumar et al., 2019).

8.2. Blockchain

Blockchain technology has emerged as a transformative force across numerous economic sectors. It functions as a decentralized, distributed ledger in which data is organized into blocks linked together through cryptographic hashes and timestamps. Widely adopted as a proactive measure, it helps ensure the integrity of information throughout supply chain operations (Adamashvili et al., 2024). Yogarajan et al. analyzed several studies on the factors that can drive blockchain adoption in agri-food supply chains, including traceability, transparency, food safety, procurement and logistics, integrity, food waste, and environmental awareness (Yogarajan et al., 2023). Blockchain also enables immutable and transparent tracking of origin, route and storage conditions of products, allowing targeted interventions in case of quality issues and optimizing logistic flows. Such traceability is essential to ensure compliance with environmental and social standards throughout the supply chain (Verdouw et al., 2016). Beyond its core advantages of universal traceability, data permanence, and reinforced trust, blockchain technology also drives improvements in sustainability performance and helps advance the Sustainable Development Goals (SDGs). The global agri-food supply chain alone generates roughly one quarter of total greenhouse gas emissions, while food loss, soil degradation, and resource overuse represent its most serious environmental drawbacks. Consequently, researchers have turned their attention to how blockchain adoption can mitigate these impacts and steer agri-food systems toward the SDGs.

9. A bottom-up innovative effort: The role of SMEs

The European agri-food sector is largely composed of small and medium-sized enterprises (SMEs), alongside approximately 9.1 million agricultural holdings managing about 155 million hectares of land, and employs around 8.7-9 million people across the EU (Eurostat, 2025; Eurostat, 2024). Despite structural limitations related to firm size, these actors are key contributors to the European economy and play a central role in innovation. Contrary to the perception of agri-food firms as slow innovators, innovation in the sector is predominantly incremental, involving continuous experimentation and gradual improvements in products, processes, packaging, digitalization and stakeholder engagement (Martin et al., 2024; FAO, 2023). Such practices support both operational efficiency and sustainable development objectives across the agri-food value chain. A substantial share of innovation activities carried out by agri-food SMEs remains statistically underrepresented, as incremental and informal innovations are often not captured by traditional indicators such as R&D expenditure or patent data (Taalbi, 2025). Empirical evidence further indicates that investments in workforce training and internal capability building significantly enhance the likelihood of introducing product, process, organizational and marketing innovations (Kussainova et al., 2021). In addition, local communities, including social and urban farming initiatives, contribute to expanding the environmental and social functions of the agri-food sector. These dynamics align closely with European skills and training strategies aimed at strengthening innovation ecosystems and accelerating competence transfer across the sector (European Commission, Pact for Skills annual report, 2024).

10. Discussion and conclusions

This work highlights how agri-food residual valorization can support decarbonization through complementary technological pathways. The agri-food sector plays a central role in achieving European sustainability and climate objectives due to its economic weight, territorial reach, and strong links with rural development (Eurostat 2024; Eurostat 2025). Residue reuse and valorization are increasingly recognized as relevant strategies within broader decarbonization frameworks by closing material and energy loops and advancing circular economy goals (Ahmad et al., 2024). Among available technologies, anaerobic digestion is particularly effective, converting organic residues into renewable energy while improving nutrient recycling and reducing reliance on fossil fuels (Neri et al., 2023). Bio-based and biodegradable materials derived from agri-food by-products also serve as alternatives to fossil-based plastics, contributing to emission reductions and improved sustainability of food packaging systems (Singh et al., 2025; Filiciotto & Rothenberg, 2020). Important challenges remain, including mechanical performance, scalability, and regulatory compliance, which require further research and development. Digital technologies, including IoT and blockchain, enhance monitoring, traceability, and logistics, reducing food losses and improving resource efficiency. Food 3D printing has been explored as a potential tool for optimizing ingredient use and enabling localized production models; however, its actual contribution to emission reduction remains context-dependent and requires further life-cycle assessment evidence (Ford & Despeisse, 2016; Li et al., 2022; Zawat et al., 2025; Zhong et al., 2023; Domżalska & Jakubczyk, 2025; Molina et al., 2024). A critical aspect that emerges from the analysis is the bottom-up role of small and medium-sized enterprises (SMEs), which constitute the majority of agri-food actors in the EU. Despite structural constraints related to firm size, limited access to capital, and lower formal R&D intensity, SMEs are key contributors to the European economy and play a central role in incremental innovation processes. Beyond innovation, they are essential to EU food security, ensuring territorial coverage, supply continuity, and the resilience of local food systems (Eurostat, 2024; Eurostat, 2025). Innovation is mainly incremental, improving ingredients, processing, packaging, digitalization, and engagement rather than disruptive R&D. (Martin et al., 2024; FAO, 2023). Such innovation is often not captured by traditional indicators such as the number of patents or formal R&D expenditure, despite its substantial contribution to sustainability and resilience (Taalbi, 2025). Investments in workforce training and skills development further strengthen the adaptative capacity of agri-food SMEs. Local communities, urban and peri-urban farming, and social agriculture initiatives also expand the sector's environmental and social value. Programs like the European Pact for Skills support competence transfer and ecosystem-based innovation (European Commission, Pact for Skills annual report, 2024). Despite these opportunities, barriers persist, including economic constraints, regulatory complexity, social acceptance, and technological scalability. The review is limited by the available literature, the focus on incremental innovations, and gaps in life cycle data, so caution is needed when generalizing outcomes. Policymakers should promote the integration of agri-food residual valorization into climate, energy, and bioeconomy strategies, supporting decentralized circular infrastructures and SME-driven innovation. Policies encouraging digital technologies, sustainable packaging, food-waste reduction, and innovative production models should align with regulatory frameworks addressing end-of-life management, biodegradability standards, and food-contact compliance (FAO, 2023; European Commission, 2018; ISPRA, 2023). Future research should address long-term performance of bio-based materials, 3D food printing scalability, and life cycle-based assessments of circularity interventions. Overall, decarbonizing the agri-food system is both an environmental necessity and a strategic opportunity. Rather than a single solution, this work provides a framework to help researchers, practitioners, and policymakers navigate the complexity of agri-food waste valorization and sustainable transition pathways.

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Special issue – The circular economy as a lever for decarbonization

Using the KAP model to support legal policy development for circular economy practices in agriculture: A case study from Northern Vietnam

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Abstract

This study examines farmers' Knowledge, Attitudes, and Practices regarding legal frameworks for circular economy practices in agriculture in northern Vietnam. Based on a cross-sectional survey of 365 farmers, the research applies the Knowledge-Attitude-Practice approach to assess how legal awareness and perceived regulatory barriers influence the adoption of circular agricultural practices. Exploratory Factor Analysis and Generalized Linear Models are used to analyze relationships among demographic characteristics, awareness, attitudes, and behavioral intentions. The findings reveal a clear gap between farmers' general understanding of circular economy principles and their knowledge of specific legal provisions, with legal and policy-related constraints exerting a negative impact on adoption behaviors. Younger farmers and those with moderate levels of farming experience show greater willingness to continue circular practices, while positive attitudes significantly enhanced participation in training and peer promotion. At the policy level, the results indicate that existing legal arrangements for circular economy practices in agriculture remain fragmented, characterized by dispersed regulations, limited enforcement mechanisms, and insufficient policy communication. This fragmentation limits farmers' ability to translate positive attitudes into sustained practice. The study highlights the need for an integrated and agriculture-specific policy framework, supported by binding technical standards, strengthened monitoring and enforcement, and complementary market-based instruments to facilitate the transition toward more sustainable agricultural systems in Vietnam.

Keywords: circular agriculture, legal awareness, farmer behavior, sustainability transition, Vietnam.

JEL classification: K32, Q18

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1. Introduction

The rapid advancement of industrial revolutions has introduced substantial challenges and obstacles to achieving a sustainable economy(Nguyen et al., 2024). Additionally, studies suggest that global agricultural production needs to rise by 70%

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to satisfy the food demand projected for 2050 (Aznar-Sánchez et al., 2019). These developments pose risks such as the depletion of natural resources, population growth pressures, climate change, and environmental pollution. Addressing these challenges requires fundamental changes in production and consumption systems rather than incremental improvements to existing agricultural practices.

The prevailing linear food production system incurs substantial environmental and social costs, including biodiversity loss through land-use change and environmental degradation (Batlles-delaFuente et al., 2022; Lal et al., 1988; Singh & Mahanta, 2021), which ultimately translate into significant economic costs. If there are no changes to the existing unsustainable food systems and consumption habits, food-related CO_2 emissions could potentially double by 2050 (Helgason et al., 2021).

In this context, the circular economy (CE) offers a promising strategy for conserving vital resources, mitigating the negative environmental impacts of agricultural activities, and enhancing economic performance (Kuisma & Kahiluoto, 2017; Stegmann et al., 2020). Rather than focusing solely on waste management or end-of-pipe solutions, the CE emphasizes systemic change through resource efficiency, material circulation, and value retention across production and consumption systems. A comprehensive synthesis of CE definitions by Kirchherr (2023) shows that, despite conceptual diversity, most definitions converge on principles such as reducing resource inputs, extending material use, and minimizing waste generation.

It represents an innovative economic model aimed at eliminating waste and promoting the continual use of resources, diverging from the traditional linear 'take-make-dispose' approach (Dagevos & Lauwere, 2021; Homrich et al., 2018; Morseletto, 2020). By prioritizing the design of products and processes that minimize waste and pollution, maintaining the use of products and materials through practices such as reuse, repair, remanufacturing, and recycling, and regenerating natural systems, CE fosters resource efficiency, economic growth, and environmental sustainability (Batlles-delaFuente et al., 2022).

Within the agricultural context, the principles of the CE are increasingly reflected in sector-specific policy and practice. Circular agriculture (CA), as delineated by the United Nations (UN), prioritizes the utilization of minimal external inputs to facilitate soil regeneration and mitigate environmental repercussions (Lima et al., 2021; Wysokińska, 2020). Its primary objectives encompass the reduction of land utilization, curtailment of chemical fertilizer application, and mitigation of waste generation to alleviate global emissions and address the exigencies of climate change. Recent literature further emphasizes that circular approaches in agriculture extend beyond specific production techniques to encompass the reconfiguration of production systems and resource flows (Chiaraluce et al., 2021).

Accordingly, the transition toward CA should be understood as a systemic shift from a linear to a circular production logic, rather than as the adoption of a single farming model. CA, thus, refers to the application of CE principles within agricultural production systems, with particular attention to resource efficiency, the utilization of agricultural by-products, and the reduction of environmental impacts (Rukundo et al., 2021). It is noteworthy that the term "agricultural by-products" is used as an overarching concept, encompassing crop residues and livestock by-products.

Despite the momentum in CE adoption, Vietnam currently operates without a standardized set of objectives, or a well-structured legal framework dedicated to CE. Regulations are scattered across various documents, lacking specificity and practical applicability. Although the Environmental Protection Law is in effect and provides a legal basis for the development of CE in Vietnam, the sanctions are not strong enough to prevent actions that affect the environment. CA is also being conducted without specific evaluation criteria. Standards and regulations regarding scientific and technological aspects remain unclear, making implementation challenging. Policies regarding agricultural by-products are still directional. Legal framework for implementing CA and recycling agricultural by-products have not been established. There is a lack of standardized systems and policies prioritizing models using agricultural by-products within the current regulations.

Most previous studies on the circular economy in Vietnamese agriculture have focused on international experiences and lessons for Vietnam, or on evaluating current CE models and proposing solutions for improvement (Lan, 2021; Nhu, 2023; Pham, 2024). Empirical research analyzing barriers faced by farmers in adopting CE practices is still limited (Nguyen et al., 2024), and studies specifically addressing legal and policy aspects are almost absent.

This study employs the KAP model to assess farmers' awareness and attitudes towards legal policies related to the circular economy practices in agriculture in several provinces in northern Vietnam. By focusing on how farmers perceive and respond to regulatory frameworks promoting circular agricultural practices, the research evaluates the extent to which these perceptions and attitudes influence their actual behaviors and willingness to adopt circular economy approaches on their farms. Furthermore, this research seeks to identify influential factors and existing barriers associated with their adoption. Based on these analyses, the study proposes certain policies for legislative managers to assist and promote the transition from linear economy to CE in agriculture.

2. Theoretical framework and literature review

2.1. KAP model overview

The KAP (Knowledge-Attitude-Practice) model is rooted in learning theory (Bandura, 1977) and the diffusion of innovation theory (Roger, 1995). According to Rogers (1995), innovation adoption within a social system unfolds through four sequential stages: knowledge acquisition, persuasion, decision, and confirmation. Bandura (1977) also posits that individual behavior is shaped by social contexts. Additionally, the theory of planned behavior by Ajzen (1991) offers another perspective for examining behavioral change, as it explains how behavioral intentions are influenced by attitudes.

The KAP model represents a theoretical framework widely utilized in behavioral and social science research. Originally formulated to evaluate knowledge, attitudes, and practices within the field of public health (Li et al., 2020), the KAP model was designed to investigate the impact of health education interventions on health-related behaviors in populations. Over time, its application has extended beyond public health to encompass areas such as education, agriculture, and environmental protection. Notably, the interactions among knowledge, attitudes, and practices are understood to be cyclical rather than strictly linear. The KAP model is therefore valuable in uncovering the intricate dynamics between these components, thereby informing the development of more effective environmental policies and public education initiatives (Ahmad et al., 2020). Furthermore, it provides empirical evidence to support policymakers in formulating improved strategies for waste management and in promoting the broader adoption of circular economy principles (Owojori et al., 2022).

2.2. Circular economy practices in agriculture

CA refers to an agricultural system that applies CE principles to agricultural activities, emphasizing the recycling of agricultural waste and by-products, and the implementation of closed-loop systems to minimize waste. It also involves sustainable practices such as crop rotation and agroforestry to enhance biodiversity and improve soil fertility (Bianchi, 2020; Van Berkum et al., 2018). From the perspective of circular agriculture, the motto "reuse and recycle" is translated into the conversion of waste streams into valuable resources. The development of waste valorization chains may include several steps, such as the practical segregation of waste into upgradable and non-upgradable streams; establishing processing facilities capable of producing upgraded products, developing markets for these products, and organizing commercial logistics. What was previously considered waste or surplus thus becomes a revalued resource (Van Berkum et al., 2018). This process requires the participation of multiple stakeholders and may create business opportunities for each party involved.

A prominent feature in discussions of CE practices in agriculture is sustainability. The essence of the circular economy lies in pursuing economic and social development while safeguarding the environment by preventing pollution—forming the basis for sustainable development (Bencomo et al., 2019). Therefore, circular agriculture must ensure the following objectives: (i) to be a core contributor to the national economy, rather than a subsidized sector, thereby ensuring economic sustainability (Bos & Broeze, 2020); (ii) to maintain biodiversity and productivity over time within local agro-ecosystems, thus ensuring environmental sustainability (Jun & Xiang, 2011); and (iii) to contribute to food security, poverty reduction, and improvements in health and living conditions, thereby ensuring social sustainability (Bencomo et al., 2019; Kristensen et al., 2016). Ultimately, circular agriculture is regenerative in nature, meaning it is a system capable of sustaining and enhancing ecosystems (Morseletto, 2020). In developing CA models, the agricultural sector also requires development strategies aimed at creating regenerative systems that close nutrient cycles, minimize losses, and maximize long-term value within each cycle (Morseletto, 2020).

2.3. Legal and policy landscape of circular economy in agriculture in Vietnam

In recent years, Vietnam has actively transitioned from broad environmental strategies toward a more defined legal structure for the CE and green growth. The legal landscape is currently characterized by a multi-layered approach involving primary laws, guiding decrees, and sector-specific development projects that prioritize agriculture as a key sector for implementation. Table 1 provides a chronological overview of the primary legal instruments and policies that currently govern or promote circular practices within the agricultural sector.

Table 1 – Legal and policy framework for circular economy in Vietnamese agriculture

Year	Legal/Policy Document	Key Provisions for CE Adoption
2015	- Directive No. 03/2015/CT-NHNN - Decree No. 55/2015/NĐ-CP	Establishes green credit promotion and credit policies for agricultural and rural development.
2016	Action Plan to Respond to Climate Change (2016–2020)	Outlines initial sectoral responses to environmental degradation and climate goals.
2018	Law on Crop Production	Regulates the collection, treatment, and reuse of crop residues; encourages the use of agricultural by-products as inputs for production and commercial purposes; supports sustainable crop production systems.
2018	Law on Animal Husbandry	Requires livestock producers to collect and treat animal waste; promotes recycling of manure and by-products for fertilizer, biogas, and other circular applications; aims to reduce environmental pollution from livestock farming.
2018	- Decree No. 57/2018/NĐ-CP - Decree No. 116/2018/NĐ-CP	Provides mechanisms to encourage enterprise investment and expands rural credit access.
2020	Environmental Protection Law 2020	Provides the first official legal definition and comprehensive basis for CE development in Vietnam.
2021	Sustainable Agriculture and Rural Development Strategy (2021–2030)	Integrates CE into long-term planning, focusing on waste management and resource reuse.
2021	Circular No. 12/2021/TT-BNNPTNT	Provides technical guidance on collecting and treating agricultural by-products for reuse.
2022	Decree No. 08/2022/NĐ-CP guiding the Environmental Protection Law	Provides detailed guidance on the implementation of CE provisions; introduces responsibilities for waste management, recycling, and resource efficiency; includes incentives such as land-use support and green credit for environmentally friendly projects
2022	Decision No. 687/QD-TTg Approving the CE Development Project	Establishes national objectives and orientations for CE development; identifies agriculture as a priority sector; promotes pilot models and institutional coordination.
2023	Decision No. 1490/QD-TTg Approving the High-Quality Low-Emission Rice Project (1 million hectares)	Targets sustainable rice farming linked to green growth and carbon emission reduction in the Mekong Delta.

Despite this extensive list of regulations, the framework remains fragmented and is characterized by a lack of unified technical standards. Current provisions are dispersed across multiple legislative documents rather than being integrated into a singular, cohesive legal instrument dedicated to circular agriculture. This lack of specificity and standardized evaluation criteria often results in limited practical applicability for farmers and stakeholders attempting to transition toward circular models.

2.4. Research hypotheses

Based on the KAP framework and the Theory of Planned Behavior (TPB), which posit that cognitive understanding (Knowledge/Awareness) and emotional evaluation

(Attitude) are precursors to specific actions (Practice), we formulated the following hypotheses to examine the drivers of farmers' circular economy adoption:

H1 (Cognitive Drivers): Farmers' awareness of circular economy concepts and legal policies has a positive influence on their adoption behaviors. Specifically, higher awareness is expected to increase the likelihood of continued adoption (H1a) and motivate participation in training courses (H1b). In contrast, higher awareness of policy barriers may negatively affect adoption behaviors (H1c).

H2 (Attitude Drivers): A positive attitude towards circular economy legal policies positively influences the continued adoption of these practices (H2a). We hypothesize that farmers with a more positive attitude are more likely to participate in training programs to improve their skills (H2b) and a positive attitude significantly enhances not only individual adoption but also social advocacy (encouraging others) (H2c).

H3 (Perceived Barriers): Awareness of barriers arising from legal policies is hypothesized to have a negative impact on farmers' willingness to continue adopting circular practices.

H4 (Demographic Controls): Farmers's demographic characteristics significantly influence their engagement.

These hypotheses form the basis for the General Linear Model (GLM) analysis presented in the subsequent methodology section.

3. Methodology

The survey was conducted from October to December 2024 and employed a cross-sectional descriptive correlational survey design to collect data from farmers in northern provinces of Vietnam who are aware of and have adopted circular economy in agriculture. The questionnaire was distributed both directly and online through colleagues and research groups focusing on circular economy in agriculture. Most of the survey samples were from farmers in Hanoi and provinces with large agricultural areas implementing circular economy models, such as Bac Ninh, Hai Duong, and Hung Yen (246 responses – 68%), while the remainder were from farmers in Thai Binh, Son La, and Lao Cai (119 responses – 32%). Participants had to meet the following criteria: (1) Currently engaged in agricultural production in northern Vietnam; (2) Over 18 years of age; (3) Consent to the use of certain personal demographic information for research purposes; (4) Have knowledge of and apply circular economy in agriculture; (5) Able to understand all survey questions. During the data collection process, we obtained an initial total of 391 responses. After screening and processing raw data, we excluded 26 responses due to an invalid answer sheet. Thus, the final sample consists of 365 valid responses.

The questionnaire for this survey was based on previous studies (Kirchherr et al., 2018; Liao et al., 2022; Velasco-Muñoz et al., 2021) and had four sections. Section one included items on demographic characteristics. To evaluate the dependent variable Practice,we employed a guided self-assessment approach. Rather than asking a generic question about circular economy adoption, participants were presented with a list of specific, illustrative circular practices relevant to the local agricultural context. These examples included: (1) reusing agricultural by-products (including crop residues) for composting or animal feed; (2) treating livestock waste for biogas or organic fertilizer; (3) implementing crop rotation and intercropping; and (4) recycling water for irrigation. Section two comprised questions related to farmers' knowledge regarding several issues: the concept of the circular economy in agriculture, their awareness of legal policies on the circular economy in agriculture, and their perception of policy-related barriers to the implementation of circular economy practices in agriculture. Section three contained questions addressing farmers' attitudes towards legal policies on the circular economy in agriculture, while section four focused on assessing their behaviors regarding the adoption of circular economy practices in agriculture. Farmers were asked to respond to three key behavioral dimensions: Continued Adoption: intend to continue applying these circular practices in your future production? (reusing crop residues for composting or animal feed; treating livestock waste for biogas or organic fertilizer; implementing crop rotation and intercropping; recycling water for irrigation); Training Participation: willing to participate in training courses to improve your technical skills in these practices; Encouraging Others: actively encourage other farmers in your community to adopt similar circular practices. We asked participants the level of agreement for each option typically in five points (1-strongly disagree, 2-disagree; 3- neutral; 4-agree; 5-strongly agree).

After gathering all the completed questionnaires from the respondents, data cleaning and coding were done using Microsoft Excel 365.

We used STATA 16 (StataCorp. LLC), a statistical software package, to examine farmers' knowledge and attitudes regarding the circular economy in agriculture, as well as relevant legal policies in this field. First, we conducted the Kaiser-Meyer-Olkin (KMO) measure and Bartlett's test. With a KMO coefficient of 0.924 and a Bartlett's test significance of 0.00, the data satisfied the requirements for applying Exploratory Factor Analysis (EFA). The analysis followed the eigenvalues-greater-than-one rule and considered factor loadings greater than 0.4 (Cliff, 1988). We then employed the General Linear Model (GLM) to identify factors associated with farmers' behavior in adopting circular economy practices in agriculture, using three sub-scales: (1) continue adopting circular economy practices in agriculture (such as reuse of by-products and waste, crop rotation, and water reuse); (2) participation in training courses on the application of circular economy in agriculture; and (3) encouraging other farmers to adopt circular economy practices in agriculture. A p-value of less than 0.05 was considered statistically significant.

To examine the determinants of farmers' adoption behaviours, we employed the General Linear Model (GLM) using a logistic regression framework. The empirical model is specified as follows:

$$\ln\left(P(Y\_k = 1)/(1 - P(Y\_k = 1)\ )\right) = \alpha + \beta\_1\ \mathbf{Aw} + \beta\_2\ \mathbf{Att} + \sum\_(j = 1)\text{^}n + \delta\_j\ \ \mathbf{X}\_j + \varepsilon$$

Where:

- Y_k denotes the binary dependent variables (Y_1: Continued adoption; Y_2: Training participation; Y_3: Encouraging others);
- Aw represents the vector of awareness sub-scales (Conceptual, Legal policies, Barriers);
- Att represents the farmers' attitude score;
- X$_j$ is the vector of control variables (Age, Gender, Education, Experience, Land size, Cultivation type, Location);
- α is the intercept, β, δ are the regression coefficients, and ε is the error term.

4. Results and discussion

4.1. Results

Table 2 shows demographic information from 365 valid responses.

Table 2 – General information of participants (n=365)

Characteristics	n	%
Sex		
Male	223	61%
Female	142	39%
Age		
From 18 to under 30	83	23%
From 30 to under 40	97	27%
From 40 to under 55	104	28%
Above 55	81	22%
Education level		
Primary school	35	10%
Secondary school	85	23%
High school	231	63%
Bachelor and above	14	4%
No schooling	0	0
Agricultural Experience		
No more than 5 years	59	16%
5–10 years	109	30%
11–15 years	112	31%
More than 16 years	85	23%
Size of cultivated land		
< 3500 m^2	173	47%
3600 - 6000 m^2	102	28%
> 6000 m^2	90	25%
Type of cultivation		
Crop cultivation	97	27%
Livestock farming	112	31%
Mixed	156	43%
Location		
Ha Noi city	81	22%
Bac Ninh Province	74	20%
Hai Duong Province	43	12%
Hung Yen Province	48	13%
Lao Cai Province	41	11%
Son La Province	37	10%
Thai Binh Province	41	11%

Table 3 presents the construct validity and reliability of the factor "Farmers' awareness," which covers the following aspects: "The concept of the circular economy in agriculture," "Legal policies on the circular economy in agriculture," and "Barriers arising from legal policies". Cronbach's alpha coefficients were accepted as 0.587, 0.843, and 0.901, respectively. The overall KMO of the sample was 0.912.

Table 3 – Factor loadings of "Farmers' awareness"

Theme	Items	Factor loading	Cronbach's alpha	Domain mean (SD)	KMO
Conceptual awareness of circular agriculture	Agricultural production without the use of chemicals	0.456	0.587	3.76 (0.83)	0.912
	Agricultural production aimed at maximizing short-term profits	0.682			
	Maximizing the utilization of agricultural by-products and reuse of materials	0.725			
	Small-scale agricultural production at the local level	0.665			
Awareness of legal policies on circular agriculture	Government and local authorities have policies to encourage circular agriculture adoption	0.487	0.843	3.64 (0.76)	
	Credit policies support circular agriculture development	0.669			
	Policies promote circular agricultural products	0.532			
	Legal policies are clear and easy to understand	0.457			
	Policies support innovation and technological upgrading	0.554			
Awareness of legal and policy-related barriers	Lack of understanding of legal policy information	0.608	0.901	3.82 (0.75)	
	Lack of specific guidance for implementation	0.797			
	Policies do not adequately meet farmers' needs	0.758			
	Policies are difficult to understand and apply	0.514			

Pseudo R^2 ranges from 0.198 to 0.237; Omnibus test Prob > $Chi^2 = 0.001^{***}$; Hosmer-Lemeshow test p-value > 0.05. Multicollinearity check: Max VIF = 3.5 (Age), Mean VIF = 2.9 (< 5).

Source: Author's analysis of survey data using Stata

Table 4 shows the construct validity and reliability of "Farmers's attitude" and "Farmers' practice" about legal policies on the circular economy in agriculture

Cronbach's alpha coefficients are 0.908, 0.733. The overall KMO of the data was 0.882.

Table 4 – Factor loadings of "Farmers' attitude" and "Farmers' practice"

Construct	Items	Factor loading	Cronbach's alpha	Domain mean (SD)	KMO
Attitudes toward legal policies on circular agriculture	Implementation of legal policies on circular agriculture is essential	0.736	0.908	2.82 (0.81)	0.882
	Legal policies supporting farmers play an important role	0.742			
	Policy enforcement improves economic and environmental efficiency	0.767			
Practices and behavioral intentions	Continue applying circular economy practices	0.814	0.733	3.49 (0.79)	
	Participate in training programs	0.404			
	Encourage other farmers to adopt circular practices	0.593			

Source: Author's analysis of survey data using Stata

The Generalized Linear Model (GLM) was employed to identify factors associated with CE practices (CEP) in agriculture, focusing on three behavioral dimensions: continued adoption, participation in training programs, and encouragement of others to adopt similar practices. A p-value of less than 0.05 was considered statistically significant. Table 5 presents the survey results on farmers' intentions to continue applying CEP in agriculture in Hanoi, along with an analysis of influencing factors, including demographic characteristics, perceived barriers, and adoption goals.

Both awareness and attitudes of farmers were found to have statistically significant effects in this study. Awareness of the concept of CE in agriculture positively influenced the intention to continue practicing (Coef. = 0.44, 95% CI = 0.33 to 0.55, $p < 0.01$) and to promote the practice to others (Coef. = 0.28, 95% CI = 0.15 to 0.42, $p < 0.01$). In contrast, awareness of legal and policy-related barriers had a negative impact on the intention to continue practicing (Coef. = -0.05, 95% CI = -0.23 to 0.12, $p < 0.01$) but resulted not statistically significant in encouraging others. Farmers with a positive attitude were more likely to continue practicing (Coef. = 0.11, 95% CI = -0.03 to 0.26, $p < 0.01$), participate in training programs (Coef. = 0.15, 95% CI = 0.27 to 0.04, $p < 0.05$), and encourage others to adopt similar practices (Coef. = 0.18, 95% CI = 0.26 to 0.09, $p < 0.01$).

The analysis reveals that older farmers are generally less inclined to continue practicing circular agriculture (Coef. = -0.32, 95% CI = -0.51 to -0.13, $p < 0.01$) and are also less likely to promote it to others (Coef. = -0.24, 95% CI = -0.34 to -0.14, $p < 0.05$). Male farmers are more likely than female farmers to intend to continue practicing circular agriculture (Coef. = 0.05, 95% CI = -0.15 to 0.25, $p < 0.05$) and to participate in training programs (Coef. = 0.31, 95% CI = 0.09 to 0.53, $p < 0.01$).

Conversely, farmers with larger agricultural landholdings showed less intention to continue implementing CEP (Coef. = -0.03, 95% CI = -0.02 to 0.11, $p < 0.01$).

Farmers with 5 to 10 years of experience demonstrated a stronger intention to continue practicing circular agriculture (Coef. = 0.04, 95% CI = 0.00 to 0.08, $p < 0.01$) and were also more likely to encourage others to adopt the practice (Coef. = 0.11, 95% CI = 0.06 to 0.16, $p < 0.01$).

Table 5 – Factors Influencing Farmers' Adoption of Circular Economy Practices in Agriculture

Characteristics	Continue applying		Participate in training courses		Encourage others	
	OR	95% CI	OR	95% CI	OR	95% CI
Farmers' awareness						
Conceptual awareness	0.44***	0.33; 0.55	0.09	-0.03; 0.21	0.28***	0.15; 0.42
Legal policies awareness	0.18**	0.01; 0.36	0.00	-0.19; 0.19	-0.05	-0.27; 0.17
Awareness of barriers arising from legal policies	-0.05***	-0.23; 0.12	-0.00	-0.13; 0.13	0.00	-0.15; 0.15
Farmers' attitude	0.11***	-0.03; 0.26	0.15**	0.27; 0.04	0.18***	0.26; 0.09
Demographic						
Age	-0.32***	-0.13; -0.51	-0.01	-0.18; 0.17	-0.24**	-0.34; -0.14
Gender (vs. Female)						
Male	0.05**	-0.15; 0.25	0.31***	0.09; 0.53	0.05	-0.19; 0.30
Agricultural Experience (vs. No more than 5 years)						
5–10 years	0.04***	0.00; 0.08	0.04*	-0.00; 0.09	0.11***	0.06; 0.16
11–15 years	0.2	0.28; 0.12	-0.03	-0.25; 0.19	-0.02	-0.27; 0.22
More than 16 years	-0.03	-0.41; 0.34	0.09	-0.22; 0.39	0.42	0.08; 0.76
Type of cultivation						
Crop cultivation	0.06	-0.21; 0.34	0.09	-0.22; 0.39	0.42**	0.08; 0.76
Livestock farming	-0.08	-0.28; 0.12	-0.03	-0.25; 0.19	-0.02	-0.27; 0.22
Mixed	0.11*	-0.13; 0.34	0.14	-0.12; 0.40	0.02	-0.27; 0.31
Size of cultivated land (vs. < 3500 m^2)						
3600 - 6000 m^2	-0.03	-0.10; 0.05	0.02	-0.06; 0.10	-0.13	-0.22; -0.04
> 6000 m^2	-0.03***	-0.02; 0.11	0.00	-0.07; 0.07	0.04	-0.04; 0.12

*** p<0.01, ** p<0.05, * p<0.1

Source: Author's analysis of survey data using Stata

4.2. Discussion

Our study's primary objective was to elucidate the influence of farmers' awareness and attitudes on their adoption of circular economy practices. Consistent with the KAP framework, our results confirm that cognitive (awareness) and affective (attitude) factors are the strongest drivers of adoption. Therefore, Hypotheses H1 and H2 are confirmed. This aligns with established behavioral theories and corroborates previous studies emphasizing the pivotal role of psychological readiness in agricultural transitions (de Lauwere et al., 2022; Herrera et al., 2023; Lombardi et al., 2025). Specifically, farmers' conceptual awareness significantly promotes the continued adoption of circular practices (OR=0.44). However, the analysis reveals a critical nuance: while general conceptual awareness acts as a facilitator, awareness of legal policies exerts a more complex influence. Although awareness of supportive policies positively correlates with adoption, the depth of this knowledge remains limited. Most farmers recognize CE terms through mass media but lack a comprehensive understanding of specific incentives, such as those in the 2020 Environmental Protection Law or green credit mechanisms. This superficial understanding may explain why the magnitude of the impact of policy awareness (OR=0.18) is lower than that of conceptual awareness. It suggests that without clear, accessible guidance on *how* to access support, policy awareness alone is insufficient to drive widespread behavioral change. This knowledge gap presents a significant opportunity for policy intervention. Existing literature demonstrates that when farmers are clearly informed about tangible economic benefits – such as transition subsidies, tax incentives, and preferential pricing mechanisms – their willingness to adopt sustainable practices increases substantially (Alfano et al., 2023; Edler et al., 2024). Economic instruments act not only as financial enablers but also as strong signals of governmental commitment, thereby reducing perceived risks and enhancing the perceived value of adoption (Trujillo-Barrera et al., 2016).

Attitude emerged as a pivotal determinant across all three behavioral dimensions: continued adoption, participation in training, and encouraging others. A positive attitude acts as an intrinsic motivation that transforms passive awareness into active practice and social advocacy. This finding aligns with recent international research, such as Lombardi et al. (2025), who studied Italian olive growers and similarly concluded that cognitive factors and positive attitudes towards eco-innovations are essential precursors to adoption. Both studies highlight that regardless of the geographical context (Vietnam or Italy), the internal psychological state of the farmer – driven by perceived benefits and environmental values – is fundamental to the transition towards circular agriculture. Furthermore, this corroborates Ajzen (1991), indicating that positive attitudes significantly increase the likelihood of performing sustainable behaviors.

Conversely, awareness of policy-related barriers was found to have a negative impact on adoption behaviors. Farmers who acutely perceive legal hurdles – such as the lack of specific technical standards, unclear land-use regulations for circular models, or complex administrative procedures for accessing support – are less likely to sustain CE practices. So that, hypothesis H3 is confirmed. This finding is particularly significant as it highlights the "double-edged sword" of legal frameworks: while intended to support, an incomplete or fragmented legal environment can create perceived risks that deter farmers. This empirically supports the need for a unified and transparent legal corridor, moving beyond general encouragement to specific, enforceable technical guidelines. As Hungerford and Volk (1990) emphasized, knowledge and skills are essential for driving behavioral change.

Younger farmers tend to adopt circular agriculture practices more readily. This finding aligns with previous studies that have highlighted older farmers' reluctance to transition their farming systems (May, 2019) and that sustainable farmers are generally younger than their conventional counterparts (Comer et al., 1999).

Farmers with moderate experience (5-10 years) are more likely to continue implementing circular economy practices in agriculture. This may be attributed to their relatively flexible habits, as they are less entrenched in traditional practices and thus more open to adopting new, more efficient methods (Rizzo et al., 2024). Additionally, smaller-scale farmers tend to be more agile in experimenting with new techniques and technologies (Cohen, 2010; Rizzo et al., 2024; Rosenbusch et al., 2011). In contrast, those managing larger landholdings often face greater investment demands – financial, temporal, and labor-related – and are more likely to approach innovation with caution due to the higher perceived risks (Beus & Dunlap, 1990). Smaller-scale operations, on the other hand, facilitate easier transitions to circular practices and technologies. While economic considerations remain important, these farmers also show greater concern for sustainability and community well-being.

The findings of this study corroborate previous research indicating that positive individual practices can enhance collective behaviors (Bandura, 1977; Steyaert & Jiggins, 2007). Furthermore, Naziri et al. (2014) highlight the significant role of cultural norms and beliefs in shaping agricultural behaviors in Vietnam. Specifically, smallholder farmers often engage in collective action not primarily due to market incentives, but rather driven by concerns over food safety, aiming to ensure the production of safer vegetables.

5. Policy gaps and analysis

The study reveals key policy gaps hindering the adoption of circular economy practices in Vietnam's agriculture, rooted in demographic disparities, limited knowledge transfer, and insufficient use of behavioral incentives. Addressing these requires targeted, inclusive, and multifaceted interventions.

A major gap lies in policies insufficiently tailored to farmer demographics. Younger and moderately experienced farmers are more receptive, while older and large-scale operators remain resistant due to entrenched practices and higher risk perceptions. This reflects a lack of age- and scale-specific mechanisms – such as subsidized training or risk-mitigation tools – which risks inequitable benefits and slows sectoral transformation.

Knowledge dissemination is also shallow. While farmers recognize basic concepts through media and cooperatives, their understanding of legal frameworks and technical instruments is superficial. Current communication strategies emphasize broad outreach rather than detailed education, limiting informed adoption. Multilevel training platforms and culturally attuned messaging could strengthen comprehension and align policies with prevailing community-oriented values.

Finally, attitudes strongly shape behavioral outcomes, yet psychosocial levers remain underutilized. Favorable attitudes enhance adoption, training, and peer influence, but policies focus narrowly on economic or regulatory measures. Integrating social marketing and community-based programs could amplify collective engagement and spillover effects.

In sum, demographic misalignment, superficial knowledge, and weak attitudinal strategies constrain Vietnam's circular agriculture transition. Bridging these gaps requires holistic reforms that combine demographic targeting, enhanced education, and behavioral insights, alongside empirical monitoring to adapt to evolving needs.

6. Limitation and recommendation

6.1. Limitations

This study, while providing valuable insights into the adoption of CE practices among Vietnamese farmers, is subject to several limitations that warrant consideration. First, the sample may not fully represent the diversity of Vietnam's agricultural landscape, as it primarily draws from respondents in specific regions (northern provinces of Vietnam), potentially overlooking variations in agroecological zones, ethnic groups, or socioeconomic contexts. This geographic and demographic constraint could limit the generalizability of findings, particularly regarding cultural norms and collective behaviors emphasized in prior research (Naziri et al., 2014:2). Second, reliance on self-reported data through surveys and interviews introduces potential biases, such as social desirability or recall inaccuracies, which may inflate reported attitudes and intentions toward circular practices (Ajzen, 1991:3). Third, the cross-sectional design captures behaviors at a single point in time, precluding causal inferences about long-term adoption dynamics or the evolution of knowledge gaps over time (Rizzo et al., 2024:3). Moreover, while attitudes were assessed as influential, the study did not deeply explore external factors like market fluctuations or climate variability, which could interact with demographic variables (Beus & Dunlap, 1990:2; May, 2019:2). Finally, legal awareness was measured within a fragmented regulatory landscape lacking unified technical standards, and broader institutional or market factors were not deeply examined. This fragmentation might have affected the precision of assessing farmers' true understanding of legal obligations and benefits.

6.2. Recommendations

To address the identified gaps and limitations, several recommendations are proposed for policymakers, practitioners, and researchers. For policy enhancement, governments should prioritize demographic-targeted interventions, such as subsidized training and risk-sharing programs for older and large-scale farmers, to overcome resistance rooted in experience and scale. Additionally, knowledge dissemination efforts must be deepened through accessible, culturally sensitive platforms – including community workshops and digital apps – that align with local priorities like food safety and sustainability. Leveraging psychosocial factors, policies could incorporate social marketing campaigns to foster positive attitudes and collective action, drawing on social learning principles. Especially, Policy reforms should prioritize a coherent legal framework with mandatory technical standards, robust enforcement, clear policy communication, and complementary economic incentives (e.g., green credit, tax benefits, market support) to foster widespread CE adoption in agriculture and advance Vietnam's sustainability goals. For practitioners, smallholder cooperatives should facilitate peer-mentoring networks to encourage innovation among diverse farmer groups, emphasizing scalable circular techniques suited to smaller operations. Finally, future research should adopt longitudinal designs with larger, more representative samples to track behavioral changes over time and examine external influences. Mixed methods approaches, integrating quantitative metrics with qualitative insights, would further enrich understanding of circular agriculture transitions in Vietnam.

7. Conclusion

This research provides new evidence on the role of legal awareness in shaping farmers' adoption of CE practices in agriculture in northern Vietnam. While farmers demonstrate favorable attitudes and a general conceptual understanding of CE, their limited knowledge of specific legal provisions and their perception of policy-related barriers continue to hinder widespread adoption. These findings highlight a persistent disconnection between supportive attitudes and the ability to act on them within an enabling and coherent regulatory environment.

The analysis also shows that demographic characteristics condition the likelihood of adoption: younger and moderately experienced farmers are more responsive to CA practices, while older and larger-scale farmers remain more cautious. These differences underscore the need for differentiated and targeted policy instruments rather than a uniform approach, particularly when designing incentives or training programs.

The most important insight concerns the inadequacy of the current legal and policy framework. The fragmentation of CE-related regulations across multiple laws prevents effective communication, weakens enforcement, and reduces accessibility for farmers. As a result, farmers face difficulties in identifying applicable rules, available incentives, and compliance requirements. Without a clear and targeted legal instrument, farmers cannot fully understand their rights, obligations, or the benefits available to them.

The implications are clear. Vietnam urgently needs an integrated and agriculture-specific CE policy framework, anchored in binding technical standards and complemented by robust monitoring and enforcement. Legal reforms must be supported by practical communication strategies that translate complex provisions into accessible guidance. At the same time, market-based instruments – such as preferential public procurement, green credit, and tax incentives – should be mobilized to create tangible economic motivations for farmers to transition to circular practices.

Beyond Vietnam, this study contributes to international debates by demonstrating how legal awareness and policy design critically mediate the translation of positive attitudes into actual behavior. By applying the KAP model at the farmer level, the study highlights the importance of integrating legal and institutional dimensions into empirical analyses of CA transitions. This perspective draws attention to the often-overlooked role of regulatory frameworks in shaping behavioral outcomes.

These findings are consistent with recent empirical evidence indicating that farmers' cognitive characteristics and policy-related incentives play a decisive role in translating positive attitudes into actual adoption of circular practices. Recent studies on circular eco-innovations in agriculture show that environmental risk awareness and regulatory support mechanisms, such as subsidies, are among the strongest predictors of farmers' willingness to adopt circular practices, often outweighing purely structural or technological factors (Lombardi et al., 2025). This reinforces the argument that legal and policy frameworks should not only promote CE principles in abstract terms, but also actively enhance farmers' understanding of regulatory instruments and reduce perceived legal and institutional uncertainty

Future research should expand beyond northern provinces, employ longitudinal designs to capture change over time, and integrate qualitative insights to deepen understanding of institutional and market dynamics. Such efforts would allow for a more comprehensive assessment of how evolving policy environments influence farmers' adoption trajectories. By doing so, scholars and policymakers alike will be better equipped to design policies that close the gap between conceptual awareness and practical adoption.

In sum, the findings underscore both the potential and the challenges of CA in Vietnam. Harnessing this potential requires coherent legislation, tailored support for diverse farmer groups, and the alignment of legal reforms with economic incentives. If pursued in an integrated and context-sensitive manner, these measures will not only accelerate CE adoption domestically but also strengthen Vietnam's position in global markets increasingly shaped by sustainability standards.

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Special issue – The circular economy as a lever for decarbonization

Circular economy and decarbonization in construction: Evidence from life cycle costing in Italy

Federica Carla Carollo[*], *Francesca Ceruti*[**], *Lucia Rigamonti*[***]

Abstract

Purpose. The purpose of this work is to answer whether selective demolition is economically viable, as well as to highlight the limitations of the construction and demolition (C&D) waste management chain in Italy and make recommendations to overcome them.
Methods. An environmental Life Cycle Costing analysis is conducted to assess the costs of selective demolition and manufacturing recycled aggregates in the Lombardy Region (Northern Italy). The investigated system encompasses all management phases of inert waste originating from demolition activities, from its generation at the building end-of-life to the treatment phase in a recycling plant, till the market replacement as recycled aggregate.
Results and discussion. The economic inventory relating to 7 case studies shows that the average cost for demolition and C&D waste management is € 7.04 per m^3 of a demolished building. When a considerable proportion of metal waste stream is sold, this cost is minimised.
Conclusion. Following the results, it is possible to identify the criticalities of the C&D waste management chain and how to overcome them to close the loop in the construction sector. Future research should focus on expanding the market for high-quality recycled aggregates by encouraging their sale and usage in new buildings.

Keywords: Life Cycle Costing (LCC), selective demolition, construction and demolition waste, recycled aggregates, economic impact.

JEL classification: D15, L52, M11

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1. Introduction

Construction and demolition (C&D) waste represent 45.5% of the total production of special waste in Italy, according to the most recent ISPRA report (2021). Although the recovery rate is 78.1% (ISPRA, 2021), various regulatory, economic, technical, and cultural barriers (Cutaia et al., 2022) prevent the widespread use of recycled aggregates (RAs) produced by C&D waste recycling activities. Backfilling and excavated soil are not included in this proportion, which only refers to the preparation for reuse, recycling, and other types of material recovery (ISPRA, 2021). The intended usage of RAs might vary depending on their quality and performance characteristics. The Ministry of the Environment's Circular 15/07/2005 No. 5205 indicates the most appropriate uses for RAs according to specific properties. Therefore, respecting the characteristics described by the standard, embankments, road foundations, environmental restorations, fillers and bridges, additional layers with antifreeze, capillary, draining function, and finally concretes with resistance class Rck <15 Mpa, may consist of RAs. Among the limitations, market acceptance of products made using secondary resources as input material will only be ensured when production costs are lower than virgin materials (Cutaia et al., 2022). Nevertheless, even more critical, the presence of impurities in the RAs and the difficulty in guaranteeing their consistent production (Borghi et al., 2018; ICESP, 2020) preclude their use in structural concrete (Dhir et al., 2019). To produce high-quality RAs, the waste entering the recycling plant must be as homogeneous as possible. This requires that the materials be carefully sorted throughout the structure's demolition phase, a practice currently uncommon in Italy (Cárcel-Carrasco et al., 2021; Pantini & Rigamonti, 2020). For this reason, selective demolition should be encouraged along with expanding the market for RAs, which are currently not economically competitive with natural aggregates. In this context, Life Cycle Thinking methodologies (Life Cycle Assessment (LCA), Environmental Life Cycle Costing (eLCC), and Social Life Cycle Assessment (sLCA)) (Toniolo et al., 2020) can be valuable tools for investigating the economic, environmental, and social aspects of a product or process throughout its life (Jacob-Lopes et al., 2021). Recent studies highlight that circular economy strategies not only reduce waste and resource extraction but also represent an effective pathway towards decarbonization, with potential reductions of up to 39% of global emissions through material efficiency (Circle Economy, 2023). In this sense, the construction sector, as one of the largest consumers of energy-intensive materials, is crucial for aligning circular practices with climate neutrality targets (Pauliuk et al., 2021). In particular, The eLCC is currently seen as a "driver" for construction improvement (Manewa et al., 2021) since it allows better financial decisions to be made by taking into account all the relevant costs of an asset (Kelly and Hunter, 2009; Martinez-Sanchez et al., 2015).

2. eLCC overview and previous studies

Rebitzer et al. (2003) are among the first to define the eLCC as the evaluation of all costs associated with a product life cycle directly borne by more cycle stakeholders (e.g., supplier, manufacturer, user/consumer). The literature, however, shows that its application to building end-of-life is seemingly very limited, probably due to a lack of data access and reliability, standards and guidance documents, and unawareness among construction operators (Manewa et al., 2021). Indeed, the eLCC methodology, unlike the LCA, lacks regulation, expertise, and direction and is now only acknowledged (but not deeply described) in some current standards, like ISO 15663:2021, ISO 15686-5:2017, ISO 15643-4 and IEC 60300-3-3. To develop a general agreement for an international standard that parallels the ISO 14040 standard for LCA, the Society of Environmental Toxicology and Chemistry (SETAC) published, in 2011, a code of practice for eLCC (Swarr et al., 2011), which provides a framework for evaluating decisions with consistent, but flexible system boundaries as part of product sustainability assessment. To encourage further case studies and peer-reviewed research, the code of practice aims to provide readers with a firm knowledge of implementing eLCC in conjunction with LCA. The code offers recommendations that expand on the ISO 14040 standards' four-phase framework to make it easier to define and apply uniform system boundaries for LCC and LCA studies that complement one another on a particular product's system. As another example of methodology conjunction, Hoogmartens et al. (2014), in their research, describe the full environmental LCC (feLCC), which extends eLCC by incorporating monetised, non-internalised environmental costs that may be discovered using environmental assessment approaches such as LCA, to demonstrate explicitly that eLCC is not an equivalent of LCA or cost-benefit analysis. There are various examples in the literature of LCA and LCC being used together to thoroughly examine the environmental and financial sustainability of the C&D waste management chain. However, the two techniques have never been paired with the monetisation of environmental impacts, as the feLCC implies. Some analysed studies consider environmental and economic factors, while others examine only one. Hu et al. (2017), for example, employ LCC and LCA in a case study in the Netherlands for demolition, recycling, and new construction to identify the environmental and financial hotspots in selective demolition and waste management in the Dutch context. The findings indicate that integrating new construction with demolition projects to maximise reuse potentials, particularly metals, is essential for improving demolition's environmental and economic profiles and related material treatment. This best practice can save life cycle costs by 23%. The metal fraction is a key parameter since it has the highest economic value (despite representing 6% of total recovered material by weight). The use of RAs in new construction is environmentally favourable owing to the avoidance of raw material extraction and the reduction of aggregate supply transportation. The research by Mah et al. (2018) examines the quantity of concrete waste created throughout the construction and demolition stages of some structures in Malaysia, as well as the incorrect management of it, which frequently has a significant environmental effect. The primary goal of this research is to discover the most environmentally friendly scenario for concrete waste handling. The LCA modelling is used to assess the environmental impact and GHG (Greenhouse gases) emissions, whereas the LCC is used as an extension of LCA in terms of economic dimension. According to the findings, recycling concrete waste to replace natural aggregates in concrete production has the best eco-efficiency (reduced environmental and cost implications), whereas landfilling has the lowest. This analysis also shows that transportation distances and mining activities are the two most significant factors of GHG emissions and cost impact. To optimise environmental and financial savings, they suggest that mobile material recovery facilities should be built as close to the waste producer and recycled material demand point as feasible to offset the distance between the building site and the landfill. Furthermore, Di Maria et al. (2018) show that combining LCA and LCC data can highlight the environmental and economic drivers in C&D waste management in the Region of Flanders in Belgium. The integrated research findings can assist policymakers in promoting all the options contributing to sustainability and limiting those that create barriers. The results suggest that increasing high-quality C&D waste recycling can greatly lower the system's total environmental effect. A similar approach is used in Dahlbo et al. (2015) work, where the Finnish C&D waste management is evaluated holistically using LCA, LCC, and other methods. The findings show that the metal treatment performed well in all the assessments; thus, improving it would not significantly impact the system. Mixed C&D waste is the worst fraction regarding climate change impacts, prices, and material recycling. Other economic assessment approaches are employed in addition to the LCC approach. For example, Coelho and de Brito (2010) conduct a "global cost" study comparing selective demolition versus conventional demolition in Portugal. According to this study, selective demolition is more expensive than conventional demolition since labour expenses are about six times higher due to the increased time required to complete the operation and the limited usage of mechanical equipment. It is suggested that landfill prices in the Lisbon Region should be raised from 90% to 1500% to make most selective demolition operations economically like conventional demolitions. Also, in the Portuguese context, Coelho and de Brito (2013) conduct a cost-benefit analysis on inert recycling operations, demonstrating that the material input gate fee is the largest share, providing around 86% of all benefits. Table 1 summarises the scientific articles described above.

Table 1 – Summary of the studies analysed

Article	**Geographic location**	**Methodologies applied**	**System Boundaries**	**Costs investigated**	**Data collection method**	**Key economic findings & numerical benchmarks (standardized in €)**
Hu et al. (2017)	Netherlands	LCA LCC	Demolition, recycling, and new construction	Internal costs	Case study analysis	Integrating new construction with demolition projects to maximise reuse potentials, particularly metals, can reduce total life cycle costs by **23%**. Additionally, the implementation of traceability reduces management costs by **50%** through better waste sorting and lower treatment fees
Mah et al. (2018)	Malaysia	LCA LCC	Demolition, recycling, and new construction	Internal costs	Case study analysis, direct interviews	Recycling concrete waste to replace natural aggregates archieves the highest eco-efficiency (reduced environmental and cost implications), while landfilling has the lowest. Specifically, on-site mobile recycling (**3.35 €/t**) leads to a **68.1% cost reduction** compared to tratidional landfill disposal (**10.50 €/t**) by eliminating transport logistics.
Di Maria et al. (2018)	Belgium	LCA LCC	C&D waste end-of-life: Landfilling and Recycling	Internal costs	Sectorial reports, literature reviews and direct interviews	Increasing high-quality C&D waste recycling can significantly lower the system's total environmental effect.From an economic perspective, high landfill taxes in Flanders (**55 €/t**) act as the primary driver for recycling, making it more competitive than disposal despite high labor costs of **39.20 €/h**.
Dahlbo et al. (2015)	Finland	LCA LCC BAT (best available technology)	C&D waste end-of-life: Landfilling and Recycling	Internal costs	Analysis of market price data and general estimations	Metal treatment performs optimally across all environmental and economic assessments, where mixed waste was selected as the worst fraction in terms of climate change impacts, prices, and recycling potential. Material purity is the primary profit driver: while wood recovery involves a net cost of **~25€/t,** metal recovery generates substantial economic credits up to **450 €/t**

Article	Geographic location	Methodologies applied	System Boundaries	Costs investigated	Data collection method	Key economic findings & numerical benchmarks (standardized in €)
Coelho and de Brito (2010)	Lisbon	Global cost	Demolition	Internal costs	Case study analysis	Selective demolition is significantly more expensive (**~6x**) than conventional methods because it is **5.7 times more labor-intensive**. This is due to the increased time required for manual operations and the limited use of heavy machinery. Consequentely, selective demolition profitability relies heavily on the recovery of high-value materials, such as steel (**150 €/t**), to offset these higher personnel costs.
Coelho and de Brito (2013)	Lisbon	Cost-benefit analysis	C&D waste recycling	Internal costs	Case study analysis	Recycling plants are economically viable with a **2.1 year payback period**. The material input gate fee represents the largest share of revenue, providing around **86%** of all cost benefits. However, the system's efficiency is sensitive to disposal costs, as **79.5%** of operational expenses are linked to managing non-recyclable residuals (**7.50 €/t**).

Despite the increasing application of Life Cycle Costing (LCC) in construction and demolition contexts, existing studies exhibit considerable methodological heterogeneity and limited standardisation. Recent reviews highlight that LCC applications in this field vary widely in terms of system boundaries, cost categories included, and integration with circular economy principles, thereby limiting cross-study comparability (Vella et al., 2026; Shen et al., 2021). Although some studies integrate LCC with environmental life cycle assessment (LCA), they are often based on project-specific case studies with limited generalisability and do not systematically identify the key economic cost drivers of selective demolition practices (Cerchione et al., 2025). These limitations are further compounded by the intrinsic challenges of cost data collection: data are typically drawn from heterogeneous sources, may be business sensitive, and are often expressed using sector-specific cost models and terminology that require reconciliation within a unified inventory. In addition, cost data tend to be more volatile than physical flows, and results are strongly influenced by geographical location due to market fluctuations and regulatory differences (Islam et al., 2015; Di Maria et al., 2018; Swarr et al., 2011). Despite these challenges, a substantial share of the existing LCC literature relies on international datasets that may not adequately reflect the regulatory and economic specificities of the Italian construction sector. This study responds to these gaps by providing detailed, empirically grounded LCC data for both conventional and selective demolition, based on primary data collection and standardised cost categories with transparent assumptions, within the underrepresented Italian context. The originality of the work lies in its granular cost breakdown, which explicitly differentiates between selective and conventional demolition practices – a level of detail that is often missing in the current literature – and in the establishment of a realistic and updated economic benchmark for demolition and C&D waste management in Italy. As a first step towards a potential alignment with environmental life cycle assessment and the future application of the full environmental LCC (feLCC) framework proposed by Hoogmartens et al. (2014), the eLCC methodology is applied to multiple Italian case studies. In line with the objectives of European stakeholders aiming to promote circularity in the construction sector (ECESP, 2021), this work ultimately contributes to the development of context-specific scenarios to foster circular demolition practices from an Italian perspective, which has so far received limited attention in the academic literature.

3. The Italian context

3.1. C&D waste

C&D waste is codified in Chapter 17 of the European Waste Catalog (EWC) as "Waste from construction and demolition operations (including land reclamation)", where a related code (EWC code) is assigned to each waste flow (Eurostat 2010). Secondary raw materials (SRMs) in the form of RAs can be created by proper treatment of this specific type of waste (DGRV no. 1773/2012). SRMs offer several benefits, including greater supply security, reduced virgin material and energy usage, reduced climatic and environmental consequences, and lower production prices (European Parliament 2016). However, the quality of the RAs produced is strictly connected to the type and the homogeneity of waste generated during demolition and to the type and age of the building. As a result, it is critical to carry out a proper demolition procedure, including planning for waste sorting operations. By reducing the demand for virgin aggregates and the associated energy-intensive production processes, secondary raw materials contribute directly to lowering life-cycle carbon emissions, strengthening the nexus between resource efficiency and climate mitigation (Businge & Mazzoleni, 2023).

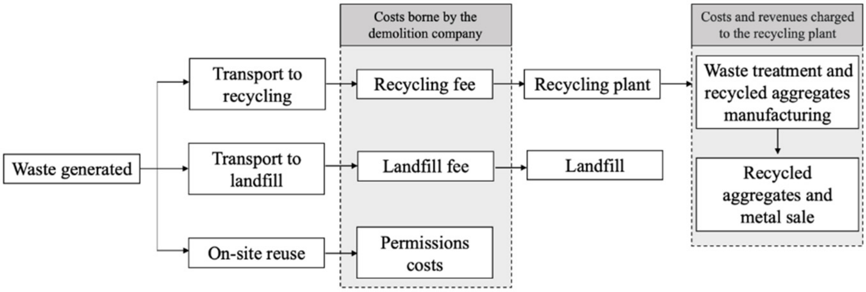
3.2. Selective demolition

At the beginning of 2020, the UNI website published the new voluntary code of practice UNI/PdR 75:2020, "Selective deconstruction - Methodology for selective deconstruction and waste recovery from a circular economy perspective". The standard defines selective demolition as "a series of sorting operations into homogeneous fractions, using machinery and equipment, with the primary goal of maximisation of reuse and recycling of the C&D waste" (UNI/PDR no.75/2020, p. 12). Conventional demolition operations should be replaced by selective disassembly and deconstruction operations aimed at obtaining mono-material fractions (e.g., concrete, bricks, cement, wood) suitable for treatment in recycling plants to get high-quality SRMs. According to UNI/PDR 75:2020, selective demolition is divided into three stages: planning, operational, and database implementation. The preliminary assessment and the executive project are part of the planning stage. The operative step includes preparing the areas on the construction site for temporary waste storage, deconstruction, and the selective demolition itself. Finally, the company must compile the documentation on the building materials database, which includes all flow-related information. The goal is to simplify the design phase in the case of an eventual new demolition, increasing the recycling and reuse rate. The presence of extraneous and dangerous substances and other materials that could reduce the recyclability of the C&D waste is checked during the preliminary assessment. The selective disassembly phase, which occurs before demolition, is designed to remove parts of the structure that can be reused immediately. A critical aspect of these activities is that all disassembled demolition materials must be put separately on the site for effective waste recovery and recycling (D.Lgs no.152/2006). Selective demolition necessitates reorganising the construction site to prepare for the dismantling and deconstruction operations aimed at obtaining homogeneous fractions and providing additional space for storing the separate scraps. Deconstruction also necessitates a significant increase in trained personnel. As a result, the cost of this type of demolition is estimated to be higher than conventional demolition techniques (Coelho and de Brito 2011; Mondini 2019). Therefore, industry operators still prefer to use conventional demolition methods.

3.3. C&D waste management chain

In Italy, sustainable C&D waste management is still in its early stages, and landfilling is the most common end-of-life destination for C&D waste (Di Maria et al. 2018) even if the situation is different in the different regions (see for example Pantini & Rigamonti 2020 for Lombardy region). Figure 1 schematises the typical path of inert waste from its generation to the destination with the costs that must be borne and to whom they compete. The C&D waste can be disposed of in a landfill, recycled, or reused on-site. In the first two cases, the demolition company must pay for transporting the waste to the appropriate treatment plant or sanitary landfill (transportation + gate fee). In the third case, however, the company is responsible for the costs of on-site waste treatment. The recycling plants bear the costs of treating the waste that enters the plants and manufacturing the SRMs, but they earn three incomes from the gate fee paid by demolition companies, the sale of the RAs and the sale of the metal fractions.

Figure 1 – Tracing scheme of waste flows and related costs to be borne



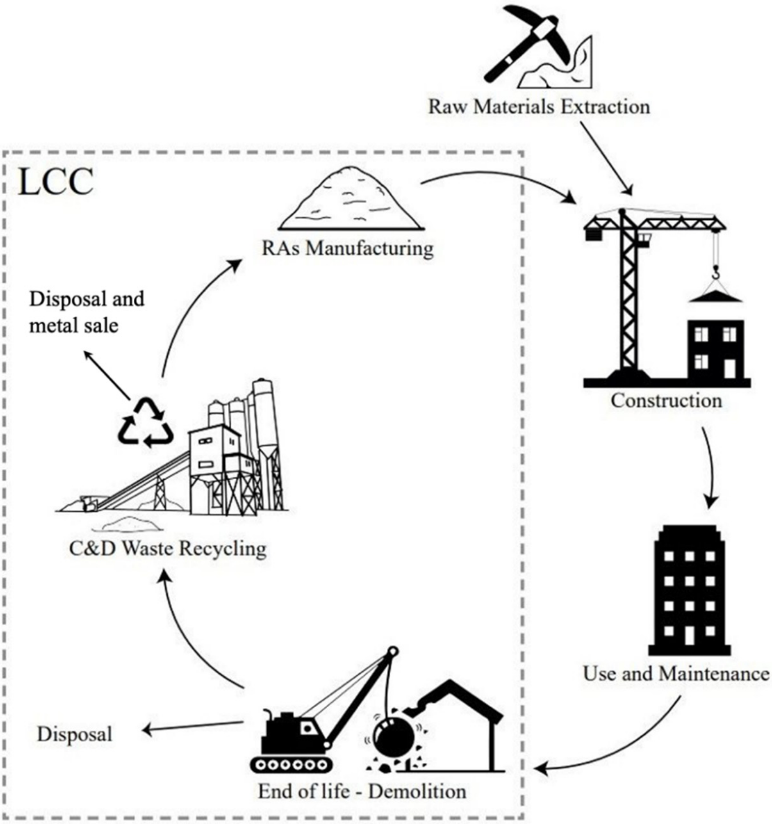
4. Material and methods

This research phase aimed to apply an eLCC, which draws on conventional LCC data, expanding it to include life cycle costs incurred by more than one actor (Hoogmartens et al., 2014), to the C&D waste management chain in Lombardy (Northern Italy). It will be described in the following paragraphs. In this case, the demolition companies and recycling plants were considered actors in the analysed system.

4.1. Goal and scope

As previously stated, this work aims to evaluate the internal costs of the C&D waste management chain in Italy. In this context, it is crucial to clarify the terminology and system boundaries used, as nomenclature in the LCC field is not yet fully homogeneous and the methodology is not highly standardized. Specifically, this study focuses exclusively on evaluating the internal costs directly borne by the actors involved int the C&D waste management chain (i.e., demolition companies and recycling plants). Consequently, external costs, such as monetized environmental or social externalities that are not internalized in current market prices, are excluded from this assessment to ensure a clear focus on the immediate economic viability for industry operators under current market conditions. To archieve this, the functional unit chosen for the system is the demolition of a cubic meter (m^3) building. The investigated system includes all management phases of inert waste originating from demolition activities, from its generation at the building end-of-life, during an ordinary or selective demolition, to the treatment phase in a recycling plant, till the market replacing as RAs (Figure 2). Any phase prior to the building's demolition is excluded. The reference year is 2019.

Figure 2 - The system boundaries represented by the hatching area



4.2. Data collection

The inventory is implemented for each process in the management chain, with the construction of two surveys, one for demolition businesses and the other for C&D recycling facilities. During the eight-month data-collecting period, 66 demolition companies and 27 recycling firms were contacted. It was feasible to obtain complete data for seven case studies on the demolition phase (with a response rate of 10.61%) and two mineral waste recycling facilities (with a response rate of 7.41%). The response rate demonstrates the high level of confidentiality of the information needed. The commercial building typology predominates among the collected demolition cases, with just one case belonging to the residential category and one to the school building type. Even though the questionnaire was sent to firms throughout Italy, all case studies were from the Lombardy region (Northern Italy). The cost per volume of demolished buildings (€/m^3) is calculated by adding the entire cost of demolition to the total cost of disposal (resulting from the questionnaires for demolition companies) and recycling (resulting from the questionnaires for recycling plants).

4.2.1 Setting up the questionnaire for demolition companies

The demolition case study survey is split into five macro-sections, including the general information and all the preliminary costs, machinery acquisition costs, operative costs, disposal, and recycling costs. Specific local taxes and potential financial incentives were excluded from the inventory to ensure the results reflect the intrinsic operational costs of the processes, making the findings more generalizable. Furthermore, overhead costs (e.g. administrative management, marketing, and office utilities) were omitted as they are highly dependant on the specific organizational structure and size of individual companies rather than the technical characteristics of the demolition method itself. By focusing on direct operational costs, the study provides a more standardized and transparent benchmark for comparing selective and conventional demolition techniques.

The questionnaire sections are detailed below, and Table 2 illustrates the survey structure with all the needed data.

Section 1: General information

The first section contains general information such as the demolition company name, the typology of demolished structure, the volume empty to full [m^3], the technique of demolition carried out, and the demolition duration [h].

Section 2: Preliminary costs

Depending on the type of building, the preparatory phase can be more or less expensive. In any case, the companies must bear the costs of the demolition project [€], the planning and preparation [€], the eventual reclamation of the building [€], the safety charges [€], and the cost of the environmental due diligence [€], which is the process of assessing the property for any potential risk of environmental contamination (Polidoro 2020).

Section 3: Machinery acquisition costs

The expected lifespan [h], purchase price [€], and hours of use [h] (referred to a specific demolition) is required for each piece of machinery used during the demolition activity. The total cost of the equipment, referred to as the single intervention, was determined by multiplying the hourly cost (purchase cost/lifespan) by the number of hours of usage during the demolition.

Section 4: Operative costs

This section includes the machinery maintenance costs [€/y], the annual salary for personnel [€/y], the insurance costs [€], as well as the use of electricity, fuel, and water with matching billing prices [€]. The reported annual costs were divided by the average number of working hours per year (2024 h) to convert machine maintenance and personnel wages to euros.

Section 5: Disposal and Recycling costs

The final section of the survey is separated into destination tabs based on whether the generated flow is directed to a landfill, for disposal with energy recovery, for recycling, reused on-site (after adequate treatment with crusher and mobile screen), or third-party managed. Each module requires the type of waste (using the EWC code) and the relative quantity, as well as the gate fee [€/t] and the relative transport costs [€/t].

Table 2 – Demolition company survey: Data required (the self-calculated values are in italics)

Section	Data requested	Detailed requests and calculations	Unit
1. General Information	Company name		
	Building typology	o Commercial o Residential o Services	
	Volume (empty to full)		m^3
	Type of demolition executed	o Selective o Conventional o Total o Partial	
	Demolition time		hours
2. Preliminary costs	Demolition project		€
	Setting of the demolition site		€
	Building reclamation		€
	Security wages		€
	Environmental due diligence		€
3. Machinery Acquisition costs	Typology	o Excavator o Tower crane etc.	
	Expected lifespan		years
	Acquisition cost o *Hourly cost*	*acquisition cost/lifespan*	€ €/hour
	Usage time		hours
	Total intervention cost	*hourly cost x usage time*	€
4. Operative costs	Machine maintenance o *Hourly cost* o *Total*	*annual cost / 2024* *hourly cost x demolition time*	€/year €/h €
	Personnel wages o *Hourly cost* o *Total*	*annual cost / 2024* *hourly cost x demolition time*	€/year €/h €
	Insurance		€
	Consumption	Energy o Bill cost o *Total*	kWh €/kWh €
		Fuel o Bill cost o *Total*	Litres €/litre €
		Water o Bill cost o *Total*	Litres €/litre €
5. Disposal and Recycling costs	Typology of waste	EWC code	-
	Destiny	o Landfill o On-site reuse o Recycling o Third-party management	
	Quantity		tonnes
	Gate fee		€/tonne
	Transport cost		€/tonne
	Total cost	*quantity x gate fee + quantity x transport cost*	€

4.2.2 Setting up the questionnaire for recycling facilities

The questionnaire for recycling plants is subdivided into six macro-sections. The six parts collect general information on the facility and all expenses related to preliminary costs, machinery investment costs, operating costs, and incoming and outgoing flows (such as RAs). The questionnaire sections are described in detail below, and Table 3 depicts the survey structure, including all relevant data.

Section 1: General information

The plant name, location, site area [m^2], plant type (moving, self-propelled, or fixed), expected lifespan [y], and treatment capacity [t/y] are all included in the general information. The actual tonnes treated in the reference year are computed by summing the tonnes of incoming waste declared by the plant.

Section 2: Preliminary costs

These are the costs borne for the acquisition of the plant site [€], insurance [€], and end-of-life machinery [€]. These expenses are incurred at the beginning of the year or on a one-time basis (as in the case of the machinery end-of-life). Therefore, the yearly cost is calculated by dividing them by the plant's expected lifespan.

Section 3: Machinery acquisition costs

The requests for each machinery in the inventory (e.g., jaw crushers, rotating or vibrating screens, iron and plastic removers, and other mechanical accessories) are the expected lifespan [y], the cost of purchasing [€], and the duration of usage during the year [h/y]. The total cost regarding the reference year (2019) is calculated by multiplying the cost of acquisition (previously divided by the lifespan) by the number of hours of usage during the year.

Section 4: Operative costs

The costs of machinery maintenance [€/y], annual personnel wages [€/y], security wages [€/y], and energy, fuel, and water consumption stand for the operative costs of a waste treatment facility. Furthermore, EU Regulation 305/11 on construction products placed on the market and the recent Legislative Decree 106/17 for construction products (including recycled ones) require the CE certification level of the aggregates produced. The survey requests the level of CE certification, which can be system 2+, which requires an initial inspection of the recycling plant as well as ongoing surveillance, assessment, and verification, and system 4, which requires the manufacturer's self-certification (EU Regulation 305/11), as well as the relative annual cost (€/y). The cost per tonne treated is determined by dividing the annual fee by the number of tonnes treated that year.

Section 5: Input flows

The incoming quantity [t] and the cost charged for admittance [€/t] (the so-called gate fee) are required for each incoming flow identified by the EWC code. The total revenue due to incoming flows is calculated by multiplying the incoming quantity by the relative gate fee.

Section 6: Output flows

This last section includes all streams separated from inert mineral waste that cannot be handled at the plant and thus have a different fate, as well as the production and sale of RAs. For these outflows, the type, destination, quantity [t] and landfill cost [€] or selling price (in the case of metal streams) are listed. The second part of this section is dedicated to RAs products, which include the type and particle size class d/D (ratio between the size of the lower and upper diameter), the typology, i.e., RAs mixed in a single fraction, of different granulometric size, from concrete or bituminous origin, the quantity produced [t], the selling price [€/t], and the selling rate.

Table 3 – Recycling facilities survey: data required (the self-calculated values are in italics)

Section	Data requested	Detailed requests and calculations	Unit
1. General Information	Plant name Localisation		
	Site area		m^2
	Treatment capacity		tonnes
	Tonnes treated per year		tonnes/year
	Expected lifespan		years
	Plant type	○ Mobile ○ Self-propelled ○ Fixed	
2. Preliminary costs	Purchase of the plant site ○ *Annual cost*	*purchase cost/plant lifespan*	€ €/year
	Insurance ○ *Annual cost*	*insurance cost/plant lifespan*	€ €/year
	Machinery end-of-life ○ *Annual cost*	*End-of-life cost/plant lifespan*	€ €/year
3.Machinery Acquisition costs	Typology	○ Jaw crusher ○ Vibrating screen ○ etc.	
	Expected lifespan		hours
	Acquisition cost ○ *Hourly cost*	*purchase cost/lifespan*	€ €/hour
	Usage time		hours
	Total intervention cost	*hourly cost x usage time*	€
4. Operative costs	Machine maintenance		€/year
	Personnel wages		€/year
	Security wages		€/year
	CE certification	○ Level 2+	€/year

Section	Data requested	Detailed requests and calculations	Unit
		○ Level 4	
	Consumption	Energy ○ Bill cost ○ *Total*	kWh €/kWh €
		Fuel ○ Bill cost ○ *Total*	Litres €/litre €
		Water ○ Bill cost ○ *Total*	Litres €/litre €
5. Input flows	Typology of waste	EWC code	-
	Quantity treated		tonnes
	Gate fee		€/t
	Total revenue	*Quantity treated x gate fee*	€
6a. Output flows	Typology of waste	EWC code	-
	Destiny	○ Landfill ○ Recycling	
	Quantity		tonnes
	Disposal cost/revenue		€/t
		Quantity x disposal cost/revenue ○ Landfill ○ Metal sale	€
6b. RAs	Typology and granulometric class	○ Mixed RAs in a single fraction ○ RAs of different grain sizes ○ RAs from concrete ○ Bituminous RAs	
	Quantity produced		tonnes
	Selling price		€/t
	Selling rate	quantity sold/quantity produced x 100	%

5. Results

The results of the arithmetic mean for each cost item of the seven cases are displayed in Tables 4 and 5. Regarding the demolition phase, the values in €/m^3 (Table 4) are determined by dividing each cost by the empty to full volume of the demolished structure. The values in €/t for the recycled plants (Table 5) are derived by dividing the costs incurred by the tonnes treated during the reference year, 2019. Starting from the demolition phase, with the data acquired, it is possible to calculate the costs of the macro-categories of preliminary costs, machinery acquisition, operation, and disposal costs. The highest costs, within the preliminary ones, are those borne for safety charges and removing hazardous materials from the building (particularly materials containing asbestos). Among all the machinery employed, the data shows that the excavator (including all the attachments) competes for 89% of the overall acquisition expenses. Instead, employee salary is the most significant regarding operative costs, more than fuel and electricity consumption. The average cost of demolition activities (excluding waste disposal costs) is 5.53 €/m^3. As previously stated, the costs borne by recycling plants are expressed in euros per tonne of waste processed at the facility during the reference year (2019). Based on the data, it emerges that the plant earnings are nearly entirely derived from the payment for the delivery of the waste to be treated (-12.28 €/t). The profit from the sale of RAs is -2.06 €/t, while the revenue from the sale of metals is -0.83 €/t, and these profits are insufficient to cover the treatment expenses (6.09 €/t).

To calculate the average cost of the entire supply chain (demolition and treatment of generated waste), all costs have been reported in €/m^3 demolished (FU). The calculation is done by multiplying the cost of recycling (including the revenue deriving from the sale of metal waste) and the sale of RAs expressed in €/t for the tonnes of inert waste sent for recycling that are present in a demolished cubic meter [t/m^3] (data extracted from the demolition companies' questionnaire). The gate fee of the recycling plant is excluded from the calculation to combine the two LCC analyses on demolition and recycling. The average overall cost of the whole chain is 7.04 €/m^3. It is also shown that correctly executed selective demolition results in higher total supply chain costs (the average value of the selective demolition cases is 8.81 €/m^3) compared to conventional demolition cases (the average value of the conventional demolition cases is 2.69 €/m^3). Figure 3 compares the average cost values between cases in which a correct selective demolition is performed and the cases closest to a conventional demolition (Cases 5 and 6). The figure shows that the most critical cost items across the management chain are those connected to the acquisition of demolition equipment and employee wages. Comparing the costs of the two demolition techniques shows that the costs of machinery acquisition, safety (which relates to personnel), and building reclamation are substantially higher in selective demolition.

Table 4 – Demolition company: Average costs

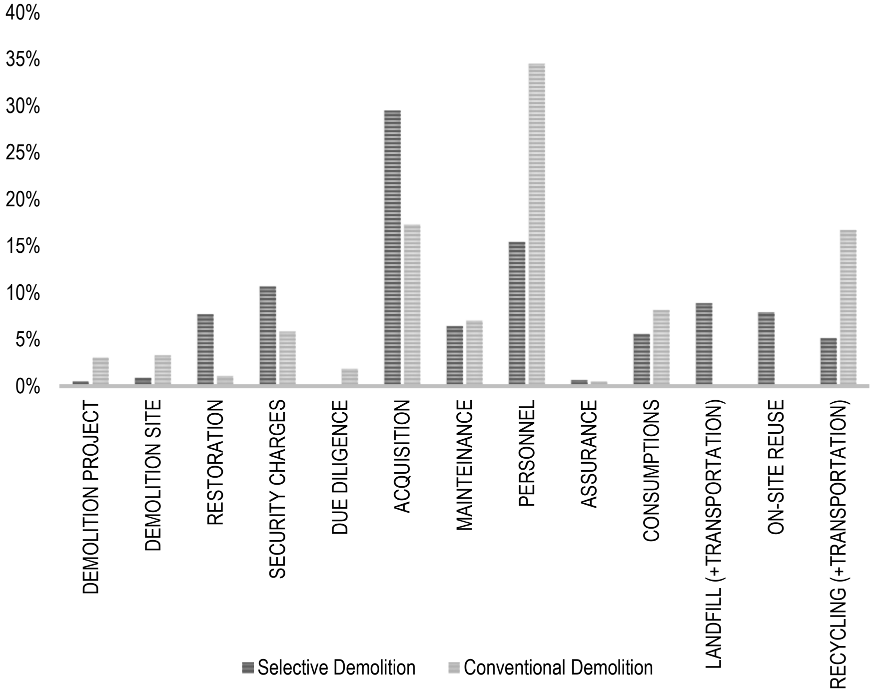
Section	Cost item	Average cost per m³ demolished
Preliminary costs	Demolition project Setting of the demolition site Building reclamation Security wages Environmental due diligence	0.06 €/m³ 0.08 €/m³ 0.50 €/m³ 0.72 €/m³ 0.02 €/m³
Machinery acquisition costs	Machinery acquisition	1.99 €/m³
Operative costs	Machine maintenance Personnel wages Insurance Consumptions	0.46 €/m³ 1.23 €/m³ 0.05 €/m³ 0,42 €/m³
Disposal and recycling costs	Landfill fee Transportation On-site reuse Recycling	0.52 €/m³ 0.25 €/m³ 0.50 €/m³ 0.24 €/m³
TOTAL	***eLCC (Demolition + Recycling)***	***7.04 €/m³***

Table 5 – Recycling facilities: Average costs

Section	Cost item	Average cost per tonne treated
Preliminary costs	Purchase of the plant site Insurance Machinery end-of-life	0.51 €/t 0 €/t* 0.26 €/t
Machinery acquisition costs	Machinery acquisition	0.83 €/t
Operative costs	Machine maintenance Personnel wages Security wages CE certification Consumptions	0.73 €/t 2.53 €/t 0.01 €/t 0.15 €/t 1.06 €/t
Input flows	Gate fee	-12.28 €/t
Output flows	Landfill Metals sale	0.01 €/t -0.83 €/t
RAs	Selling price	-2.06 €/t
TOTAL	***Treatment operations*** ***Revenues***	***6.09 €/t*** ***15.17 €/t***

* The value is insignificant.

Figure 3 – The contribution of individual expenditures on overall costs (in percentage) for selective and conventional demolition



5.1. Sensitivity analyses

Table 6 shows the range of variation between the minimum and maximum values for each cost item relating to the entire supply chain. Given that some of these have a significant variation, it was decided to proceed with a sensitivity analysis to see how the total cost of the supply chain would vary as costs vary within the ranges defined below. For simplicity, the chosen cost items have a difference between maximum and minimum greater than 2.00 €/m^3. Accordingly, the parameters with the most significant variability are the building reclamation, security wages, acquisition costs of machinery and personnel costs. Among these, the machinery acquisition cost and personnel reach a difference greater than 4.00 €/m^3.

Table 6 – eLCC – total range (min-max) and average value (wide range values are in italics)

	Cost item	**Min**	**Max**	**Average**
Demolition	Demolition project	0.03 €/m^3	0.13 €/m^3	0.06 €/m^3
	Setting of the demolition site	0.00 €/m^3	0.21 €/m^3	0.08 €/m^3
	Building reclamation	*0.00 €/m^3*	*2.86 €/m^3*	0.50 €/m^3
	Security wages	*0.12 €/m^3*	*2.51 €/m^3*	0.72 €/m^3
	Environmental due diligence	0.00 €/m^3	0.10 €/m^3	0.02 €/m^3
	Machinery acquisition	*0.27 €/m^3*	*4.90 €/m^3*	1.99 €/m^3
	Machine maintenance	0.00 €/m^3	1.31 €/m^3	0.46 €/m^3
	Personnel wages	*0.14 €/m^3*	*3.29 €/m^3*	1.23 €/m^3
	Insurance	0.00 €/m^3	0.21 €/m^3	0.05 €/m^3
	Consumptions	0.05 €/m^3	0.93 €/m^3	0.42 €/m^3
	Landfill fee	0.00 €/m^3	1.35 €/m^3	0.52 €/m^3
	Transportations	0.00 €/m^3	1.90 €/m^3	0.25 €/m^3
	On-site reuse	0.00 €/m^3	1.21 €/m^3	0.50 €/m^3
	Recycling (excluding inert waste)	0.00 €/m^3	0.32 €/m^3	0.08 €/m^3
	Recycling inert waste*	0.00 €/m^3	0.78 €/m^3	0.16 €/m^3
TOTAL	***Base-case scenario***			***7.04 €/m^3***
	Best-case scenario			***4.85 €/m^3***
	Worst-case scenario			***13.24 €/m^3***

* Data obtained from the LCC on recycling plants

The starting scenario is the one with the average costs resulting in the value chain cost of 7.04 €/m^3. The sensitivity analysis aims to compare the costs of the best- and worst-case scenarios. In the best-case scenario, the cost with the most significant variability margin is replaced with the minimums defined in table 6. The total cost of the supply chain in this way would be reduced by 31%, reaching the final cost of 4.85 €/m^3. On the contrary, in the worst-case scenario, the five cost items are replaced with the maximum values, resulting in an increase of 88% of the total cost up to 13.24 €/m^3.

Another sensitivity analysis is run to show the economic impact of separating metals at the demolition site. The metal is often transported for recycling and benefiting from scrap metal is a common activity. If the metal flows are substantial, the revenues from their sale can be sufficient to cover the demolition costs. By including metal scrap sales (-1.63 €/m^3), the whole cost is reduced by more than 20% on average (5.41€/m^3).

6. Discussion

One of the most significant criticalities of the management chain discovered after the analysis is that the average result of the seven demolition cases shows that the most significant proportion of all production (95%) is inert mineral waste (EWC 170904). Metal waste is 4% of overall waste, whereas organic materials (such as paper and wood) and hazardous waste (collected after building reclamation) constitute 1%. Table 7 illustrates the average percentage compositions of inert mineral waste, metals, and other materials. According to the waste composition obtained, inert mineral waste is almost entirely composed of a mixed stream of C&D waste (EWC 170904), with just 4% referring to a distinct cement stream (EWC 170101). Metals account for 96% of the flux of iron and steel (EWC 170405), with aluminium (EWC 170502) and cables accounting for the remainder (EWC 170411). The "other" category, which constitutes a tiny fraction of the total, is mainly composed of mixed packaging (EWC 150106) and insulating materials (EWC 170600). On the other hand, no organic material, such as wood, was identified (EWC 170201).

Table 7 – Percentage composition of the categories of inert mineral, metallic and other waste

	Total mass fraction %	Materials division (EWC code)	Mass fraction %
Inert waste	95%	170904 – Mixed C&D waste	96%
		170802 – Gypsum materials	0.1%
		170101 – Cement	3.9%
Metals	4%	170405 – Iron and steel	96%
		170502 – Aluminium	3%
		170411 – Cables	1%
Other	1%	150106 – Mixed packaging	56%
		170600 – Insulating materials	20%
		170302 – Bituminous Materials	8%
		170605* and 180603* - Hazardous materials (asbestos)	16%
		170201 – Wood	0%

Furthermore, although respondents stated selective demolition operations in all seven demolition cases, an assessment of the machinery used, demolition timeframes, and waste flow generated on-site revealed that only five cases out of seven were carried out appropriately. The fifth and sixth cases present a noticeable lack of material sorting and screening, as more than 90% of the flows generated refer only to the mixed C&D fraction (EWC 170904). A proper selective demolition would have involved a subdivision into distinct flows of concrete, bricks, metals, and organic substances (e.g., wood). In the first three cases, the inert fraction (EWC 170904) is reused on-site after adequate treatment with a small mobile plant owned by the firm, a procedure currently used in medium-large demolition activities in Italy. The remaining flows concern inert waste sorted and sent to treatment plants (nearly 0.4%) or landfills (about 1-2%). In the fourth case, 33% of the fluxes (all metal flows) are recycled. The remaining part, particularly hazardous waste, is disposed of in landfills or transferred to third-party disposal companies. The mixed C&D flow is isolated from the cement, iron, and steel in the last case, and the bituminous mixtures, representing 1% of total waste production, are disposed of in landfills.

The results above confirm the outcomes obtained from previous LCC studies on the C&D waste management chain, demonstrating that the studies are related even though the geographical context is different. Similar to the findings of Coelho and de Brito's (2010) study, it is shown that selective demolition is more expensive than conventional demolition, with the longer time required to complete the operation and the limited use of mechanical equipment. It is also confirmed that recycling plants' material input gate fee makes up the largest share (Coelho and de Brito (2013)). The metal fraction is a key parameter for Hu et al. (2017), Mah et al. (2018) and Dahlbo et al. (2015) because it has the highest economic value. This is supported by the sensitivity analysis on metal waste flows, which reveals that even though metal waste represents 4% of the total average waste, their selling can lower the cost of the full chain by nearly 20%. These findings confirm that circular strategies such as metal recovery and the replacement of virgin aggregates can deliver dual outcomes: economic value creation and substantial carbon savings. This dual benefit has been increasingly recognized in modelling studies and sectoral analyses across manufacturing and residential contexts (Bressanelli & Saccani, 2025; Businge & Mazzoleni, 2023; Pauliuk et al., 2021). Building on these findings and considering that the results of this study identify machinery acquisition, safety-related personnel costs, and building reclamation as the primary contributors to the higher cost of selective demolition, specific strategies must be implemented to enhance its economic competitiveness. For instance, the significant impact of machinery costs could be mitigated through the development of equipment sharing platforms or specialized rental markets for advanced sorting tools, reducing the initial capital expenditure for smaller firms. Additionally, streamlining the building reclamation phase through the integration of Building Information Modelling (BIM) - based pre-demolition audits (European Commission, 2018; Volk et al., 2014) could significantly reduce the time required for hazardous material identification. While the analysed buildings are often dated, the integration of modern Scan-to-BIM technologies allow for the creation of digital inventories of existing structures, enabling precise mapping of material volumes even in the absence of original digital documentation (Volk et al., 2014). This would, in turn, lower safety-related personnel costs and improve the overall efficiency of the selective process, making it a more viable alternative to conventional methods.

7. Conclusions

Enhancing selective demolition practices and fostering a stronger market for recycled aggregates are not only significant measures to close material loops in the construction sector, but also strategic levers for decarbonization, in line with international evidence on material efficiency and climate neutrality (Circle Economy, 2023). Expanding the market for high-quality recycled aggregates would not only improve the economic viability of recycling plants but also avoid the carbon-intensive production of cement and steel, thus generating co-benefits for both circularity and decarbonization (Oladapo et al., 2024; Santos et al., 2025).

During this study, several obstacles were encountered in acquiring data suitable for modelling the eLCC, owing to firms' unwillingness to share sensitive data such as their expenses or revenues. However, utilising the available data, it was possible to give a first estimation of the demolition chain costs in the Lombardy Region. According to the research, the average cost for demolition and C&D waste management is 7.04 € for each m^3 of a demolished building. When a considerable proportion of metal waste stream is sold, this cost is minimised. However, when a proper selective demolition is executed, the overall supply chain costs are higher (approximately 8.81 €/m^3) than when the demolition does not include selective disassembly and material sorting (around 2.69 €/m^3). It should be noted that selective demolition involves more manual effort and, as a result, a higher cost of security wages and equipment use. According to the interviews with demolition companies, the absence of material sorting is determined by the fact that it is difficult to have sufficient spaces accessible inside the demolition sites to keep the waste separate while waiting for transportation. As a result, sector operators prefer to deliver mixed waste in a single heterogeneous stream (EWC 170904). To mitigate these economic and logistical barriers, this study suggests a two-fold strategy. First, at a technological level, the integration of digital tools such as BIM for pre-demolition audits could optimize the identification of hazardous materials, thereby reducing reclamation type and safety related personnel costs. Second, the impact of high initial investments could be balanced by promoting equipment-sharing platforms should lower the capital barriers for smaller firms to access in advanced sorting tools, making selective practices more accessible for small and medium-size firms. Complementary to these measures, a possible solution for construction sites that cannot host individual flows of concrete, bricks, ceramics, and so on could be to classify the waste as EWC 170107 – mixtures of concrete, bricks, tiles, and ceramics, which collect most of the inert waste but, unlike EWC 170904 – mixed C&D waste, reduce the need to separate the various streams. By reducing the need to differentiate the multiple flows, recyclability and subsequent manufacturing of high-quality aggregates might be facilitated without demanding too personnel. The sensitivity analysis allows to determine which cost items had the most fluctuation and hence those on which it would be suitable to act using incentive mechanisms to obtain the best-case scenario. Future research breakthroughs include investigating the environmental implications of demolition using the LCA approach and then the monetisation of these impacts to implement the feLCC (according to Hoogmartens et al., 2014), which, hence, include other than the internal costs, some external costs that can be internalised in the short term (De Menna et al., 2016; Swarr et al., 2011). Future research should also be aimed at closing the loop in the C&D waste management chain by stimulating the market for high-quality RAs, promoting their sale and use in new buildings, proposing a solid financial incentive system and providing data and recommendations helpful to contracting authorities to include the correct disposal of demolition waste in public procurement.

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Data availability statements

All data generated or analysed during this study refer to aggregate and anonymous results and are included in this published article.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Special issue – The circular economy as a lever for decarbonization

Aquaculture vs decarbonization through industrial symbiosis: The role of bivalve shell recycling

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Abstract

Recycling mussel shells offers environmental and industrial benefits. As a by-product of aquaculture and food processing, shells are often discarded, contributing to waste management challenges and costs. Recent studies highlight their potential as a sustainable source of high-purity calcium carbonate ($CaCO_3$), which can be extracted through processes involving washing, grinding, and calcination. This valorization reduces waste volumes, lowers disposal expenses for producers and introduces low-cost raw material to the $CaCO_3$ market. Notably, calcium derived from mussel shells can be utilized in emerging technologies such as calcium looping (CaL) for CO_2 capture, where calcium oxide (CaO) acts as a regenerable sorbent. Using shell-derived calcium in such applications supports circular economy principles and enhances the environmental performance of carbon capture. The MATSHELL project explores the potential of recycling bivalve shells to produce biogenic $CaCO_3$ and reuse for high-value applications. Findings show that biologically sourced precipitated $CaCO_3$ offers a competitive alternative to conventional sources, with rising market demand in high-value sectors. However, key barriers exist, including supply chain integration, regulatory complexity, and limited industrial adoption. The results of our analysis, conducted by interviewing a panel of experts, identified potential actions to address the challenges in accordance with industrial symbiosis models. The potential of the developed model was enhanced by integrating appropriate activities to optimize its implementation.

Keywords: aquaculture, waste reduction, circular economy, calcium carbonate.

JEL classification: Q22, Q00, Q5, Q53, Q57

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1. Introduction

In recent decades, the aquaculture industry has experienced significant growth across different regions, driven by the growing interest in healthier products and more health-conscious dietary patterns (FAO, 2024). However, production within the European Union has stagnated, despite political support, investments, and research efforts (FAO, 2024; Guillen et al., 2025). Historically, several EU countries were leaders in aquaculture, particularly in the production of low trophic level species such as mussels and oysters. However, the mussel industry has faced environmental constraints, economic challenges, and regulatory complexities that have impeded its growth (Avdelas et al., 2021).

The EU's mussel production, which peaked in the late 1990s at over 600,000 tons, declined by 20% by 2016 (FAO, 2024). This reduction represents a significant portion of the stagnation in EU aquaculture. Several factors contribute to this decline, including climate change, harmful algal blooms, increased sea temperatures, ocean acidification, and extreme weather events. These environmental stressors impact mussel growth rates, reproduction cycles, and overall productivity. Additionally, the presence of pollutants such as heavy metals and microplastics in coastal waters raises concerns about food safety and marketability (Quintáns-Fondo et al., 2016).

Also, the entry of cheaper and increasingly dominant importers into the EU market (Garlock et al., 2020) has undermined the profitability of domestic producers, many of whom operate small-scale family businesses with limited economies of scale due to the fragmentation of producers, a lack of coordinated marketing strategies, and difficulties in obtaining new licenses for expansion (Soliño & Figueras, 2025). Focusing on the production side, a promising approach to revitalize the molluscs sector lies in the adoption of industrial symbiosis, where different industries collaborate to create mutually beneficial exchanges of resources, waste, and by-products with the idea of creating profitable circular economy models (Masi et al., 2025; Zhan et al., 2022; Jović et al., 2019; Silva et al., 2019).

Traditionally considered as waste, the shells of molluscs are often discarded during aquaculture and food processing, generating significant disposal costs and environmental burdens for producers. However, recent research has revealed that mussel shells contain up to 95% calcium carbonate ($CaCO_3$) (Azarian & Sutapun, 2022), a valuable material with wide-ranging industrial applications (Hamester et al., 2012).

Several practical experiences across Europe have demonstrated both the potential and the limitations of reusing bivalve shells as secondary raw materials (e.g. Barros et al., 2009). In the Algarve region of Portugal, surveys among shellfish producers revealed that around 67% of bivalve shells are still disposed of as common waste, while only a limited share is dried, crushed, and reused (Magalhães et al., 2024). The main challenges identified include the absence of standardized collection systems, insufficient logistical infrastructure, and a lack of awareness regarding the economic and environmental value of these materials, despite consistent literature on the topic (e.g. Francis, 2025; Morris et al., 2016, 2019; Summa et al., 2022; Yao et al., 2014; Zhan et al., 2022). The shells are often mixed with organic residues, increasing the costs of storage, transportation, and treatment (Medina Uzcátegui et al., 2022). Furthermore, the regulatory framework does not clearly classify shells as by-products, which discourages industries from investing in reuse strategies (Magalhães et al., 2024).

An emerging case of circular valorisation is represented by Wast3D Shells[1], created in 2024 in Taranto (Italy), which focuses on sustainable materials for building and infrastructure industry[2]. While it is too early to evaluate the long term viability of the initiative, this example shows that when technical innovation is combined with local resource management, shell recycling can create new value chains and reduce dependence on virgin mineral extraction, and it validates former scientific suggestions (e.g, Fu et al., 2022; Her et al., 2021). A review of other applications of shell derived $CaCo_3$ can be found in Hart (2020). Beyond the immediate economic and environmental benefits, the calcium extracted from mussel shells holds potential for integration into advanced technologies, particularly in the field of carbon capture (Namikawa & Suzuki, 2024). In processes such as calcium looping (CaL), calcium oxide (CaO) derived from shell calcination serves as a regenerable sorbent for CO_2 removal (De Lena et al., 2022).

Nevertheless, the scalability of these processes is constrained by the heterogeneity of shell composition (Schiopu et al., 2025), contamination from marine biofilms, and the energy intensity of calcination (He et al., 2023). Moreover, the absence of cooperative networks linking aquaculture, waste management, and manufacturing sectors represents a structural barrier to the large-scale adoption of shell-derived materials. So, these initiatives remain isolated and highly dependent on regional support, lacking integration with broader industrial ecosystems.

Despite these obstacles, the valorisation of bivalve shells offers a compelling opportunity to align business and industrial strategies with fundamental circular economy principles (Zorpas, 2024; Uvarova et al., 2023; Veleva & Bodkin, 2018), as well as with carbon mitigation imperatives. The transformation of shells into calcium carbonate could serve dual purposes: reducing the environmental burden of shell waste and providing a renewable source of carbon capture material for industries with high CO_2 emissions, such as cement, lime, and steel production. Integrating this process within an industrial symbiosis framework could create localized loops where shell waste from coastal areas is redirected toward nearby emission-intensive industries.

Industrial symbiosis (IS) is commonly acknowledged as a sub-field of Industrial Ecology, and it represents a collaborative approach where traditionally separate industries engage in the physical exchange of materials, energy, water, and by-products, in order to achieve competitive advantage and reduce environmental impact (Chertow, 2000; Lombardi & Laybourn, 2012). IS processes are designed to enhance sustainability and economic performance by reducing costs, minimizing waste, and optimizing resource use. Consequently, IS strategies are considered from some scholars as expression of circular economy oriented business behaviour (Uvarova et al., 2023; Zorpas, 2024). As highlighted by Scafà et al. (2018), three main models of IS are identified by literature. First model recovers the principles of industrial districts, its paradigm being the pioneering and long lasting experience of Kalundborg Symbiosis (Cheshmehzangi, 2025; Ehrenfeld & Gertler, 1997). A second model is the Eco-Industrial Parks. The main difference in respect of districts, is that former mainly emerge from bottom-up processes and coopetitive behaviours among agents

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[1] https://wast3dshells.com/.

[2] https://circulareconomyforfood.eu/en/wast3d-shells-circular-innovation-from-mussels-to-concrete.

(Aviso et al., 2022) which are linked by a symbiotic supply chain (Brandao et al., 2025), while the latter are the outcome of a conscient, top-down, deliberate strategy (Mintzberg & Waters, 1985). Third model aligns with the idea of designing networks and providing platforms for enabling IS. National Industrial Symbiosis Programme (NISP) in the UK (Jensen et al., 2011) is a well-known example of tool provider, from the CRISP software to its successors (Yeo et al., 2019). These platforms leverage intelligent systems and algorithms (Zhao et al., 2025) to identify and recommend potential synergies for waste and resource reuse (Silva et al., 2022). However, IS platforms face significant challenges, linked to limited sustainability commitment, poor cooperation, and technical as well as economic barriers (Krom et al., 2022). Challenges are confirmed across literature. For instance, review from Grant et al. (2010) found that nine of 17 ICT tools for IS reviewed in the paper were no more in use. In addition, focusing on past experiences in IS, scholars highlight the existence of various drivers and barriers that influence the pursuit of eco-sustainable economic development through the creation of symbiotic networks (Boom-Cárcamo & Peñabaena-Niebles, 2022). The study by Henriques et al. (2021) emphasizes that the impact of these factors varies across different industries, presenting a complex intervention landscape that requires tailored measures to effectively address sector-specific needs. Regulation, intermediation, spatial proximity, and economic returns appear to be the main incentives for companies to invest in symbiosis projects, while social, technological and economic aspects tend to be more significant obstacles to establishing exchange networks (Neves et al., 2019). Another relevant aspect is the lack of proximity between the two ends of the symbiotic chain (Chrysikopoulos et al., 2024). The presence of industrial areas capable of attracting multiple businesses and creating dense networks of relationships establishes reference hubs that can drive industrial symbiosis (Yadav & Majumdar, 2024).

Several studies, also, have identified critical bottlenecks in the implementation of industrial symbiosis, particularly during its final stages, where firms must rigorously evaluate the trade-offs between costs and benefits within competitive market environments (Boom-Cárcamo & Peñabaena-Niebles, 2022; Chrysikopoulos et al., 2024; Henriques et al., 2021; Neves et al., 2019; Sellitto et al., 2025). Enterprises often exhibit a reluctance to adopt innovative solutions when operating under frameworks that do not facilitate risk-sharing, thereby impeding the uptake of new technologies and processes (Diaz et al., 2024; Henriques et al., 2022; Ventura et al., 2025). This cautious approach can significantly constrain the full utilization of research outputs and delay the integration of scientific advancements into industrial symbiosis systems.

Building on these experiences, the following research question emerges:

Can the recycling of bivalve shell waste, when integrated into industrial symbiosis networks, provide a sustainable pathway for calcium carbonate production that enhances CO_2 *capture in high-emission sectors?*

In this context, the recently launched "Development of Advanced Materials for Industry and Cosmetics Derived from Waste Bivalve Shells from Fishing and Aquaculture" (MATSHELL) project has brought together multiple research institutions and production facilities in Italy to experiment the latest advancements in processing and extraction techniques aimed at obtaining valuable products and raw materials from mussel shells. Specifically, it aimed to repurpose waste bivalve shells from aquaculture to develop advanced materials for high value industries. As a model of the circular economy, MATSHELL demonstrated the ecological, economic, and social benefits of utilizing shells, which contributed to biodiversity conservation, economic gains for farmers, and sustainability in human activities. The project expanded the potential applications of calcium carbonate, ensuring its environmental and commercial viability.

In the following, we highlight the perspectives in terms of industrial symbiosis that reflect the activities and research findings conducted in the field within the framework of MATSHELL project, supported by a SWOT analysis that provided insights into strengths, weaknesses, opportunities, and threats of the proposed symbiotic approach.

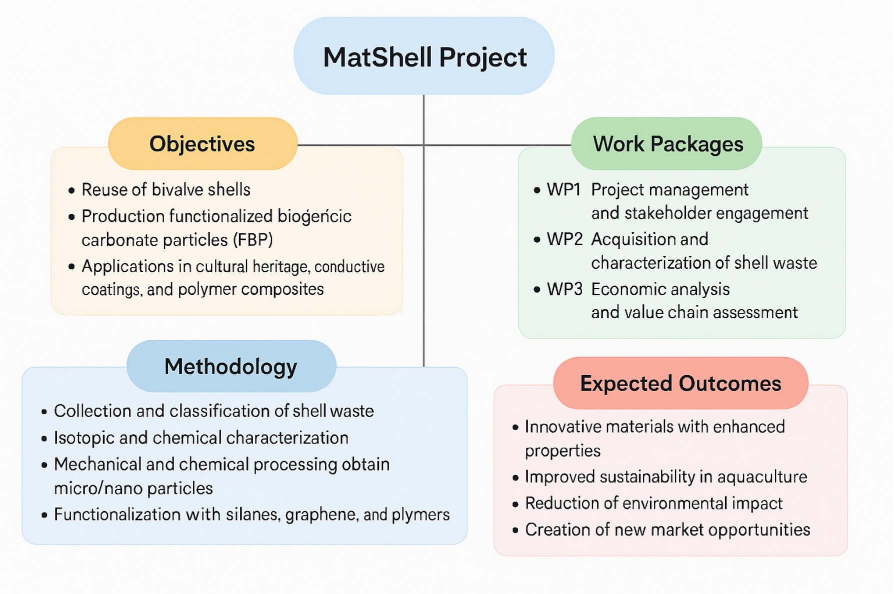
2. MATSHELL project overview and proposition

MATSHELL project aimed to repurpose discarded shells resulting from farmed mollusc production. Given the high level of innovation in the processes involved, the project also sought to develop and experimentally scale up ground particles of biogenic calcium carbonate. MATSHELL exemplified circular economy principles, particularly because shells are a valuable biomaterial. The initiative not only enhanced the sustainability of the aquaculture sector but also provided several benefits, including ecological advantages by contributing to biodiversity conservation and ecosystem functionality, secondary economic gains for mollusc farmers and processors, and social benefits linked to human well-being through the increased sustainability of anthropogenic activities involved in transformation processes. The scientific and technological advancements developed within MATSHELL enabled the production of fine biogenic particles (FBP) with customized functional groups, expanding its potential applications beyond conventional uses of calcium carbonate.

The project was designed considering the unique compositional, structural, and mechanical properties of shells as well as their widespread availability. These composite materials consisted of calcium carbonate and a small fraction (2-5% by weight) of an organic bio-macromolecular matrix, which provided the shells with mechanical properties that could not be synthetically replicated in laboratory settings.

The methodology involved collecting and classifying shell waste, performing isotopic and chemical characterization, and processing shells into micro- and nano-sized particles through mechanical and chemical techniques. The project was structured into three work packages: project management and stakeholder engagement, acquisition and characterization of shell waste, and economic analysis with value chain assessment. Expected outcomes included innovative materials with superior mechanical and chemical properties, improved sustainability in aquaculture, reduced environmental impact, and the creation of new market opportunities within a circular economy framework. In Figure 1 we report a detailed infographic summarizing the MatShell Project, with color-coded sections for Objectives, Methodology, Work Packages, and Expected Outcomes.

Figure 1 – Detailed infographic summarizing the MatShell Project, with color-coded sections for Objectives, Methodology, Work Packages, and Expected Outcomes



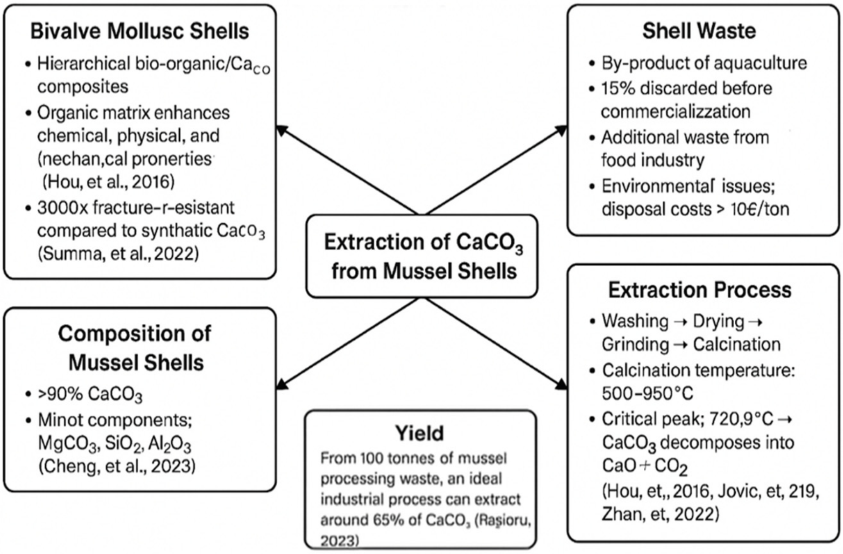
a. MATSHELL's scientific foundations: Literature Review of Bivalve Shell Waste Recycling Techniques

As attested by consolidated literature, bivalve mollusc shells are sophisticated hierarchical composites composed of calcium carbonate and organic materials, exhibiting remarkable advanced functional properties through their intricate nanostructural design (Hamester et al., 2012; Taylor & Layman, 1972). Their unique structure arises from the incorporation of a small organic matrix within the calcium carbonate crystal lattice (Hou et al., 2016). Although this organic matrix constitutes only 2-5% by weight, it significantly enhances the chemical, physical, optical, and mechanical properties of the material, making it 3000 times more fracture-resistant than synthetic or geogenic $CaCO_3$ (Summa et al., 2022).

These shells are by-products of bivalve mollusc aquaculture. A case study from Central Java production estimates that green mussel shells accounts for 70% of the total production (Ismail et al., 2022) which, given a world mussel production of around 2 million metric tons (Gosling, 2021), equals to around 1.35 million metric tons of $CaCo_3$ stored in mussel shell yearly. Data from MATSHELL reveals that approximately 15% of the molluscs' weight is discarded as unwanted waste before commercialization (e.g., for mortality), not accounting for the additional source of shell waste originated from food processing industries and consumption. Most of this waste is either sent to landfills or dumped into the sea, causing several environmental issues (Magalhães et al., 2024). This part of the processing chain is unsustainable, and disposal costs may be significant, according to applicable regulation framework.

As highlighted in Figure 2, the extraction of calcium carbonate $CaCO_3$ from mussel shells follows a well-established process that involves washing, drying, grinding and calcination. The calcination of the shells is essential to obtain CaO, which is used in numerous industrial applications (Hou et al., 2016; Jović et al., 2019; Zhan et al., 2022). Mussel shells are mainly composed of $CaCO_3$, and small amounts of other minerals such as $MgCO_3$, SiO_2 and Al_2O_3 (Cheng et al., 2023). According to a general consensus in the literature relating experimental data from different geographic areas, from 100 tonnes of mussel processing waste, an ideal industrial process can extract around 65% of $CaCO_3$ (e.g., Alonso et al., 2021; Ismail et al., 2022; Roșioru, 2023). Pioneering industrial experience which started in 2003 in Galicia (Spain), showed both low level of efficiency and emissions problems. However, the learning curve was rapid, despite a plant oversized in respect of actual waste supply (Barros et al., 2009).

Figure 2 – Calcium carbonate ($CaCO_3$) extraction from mussel shell



Source: Author's own elaboration

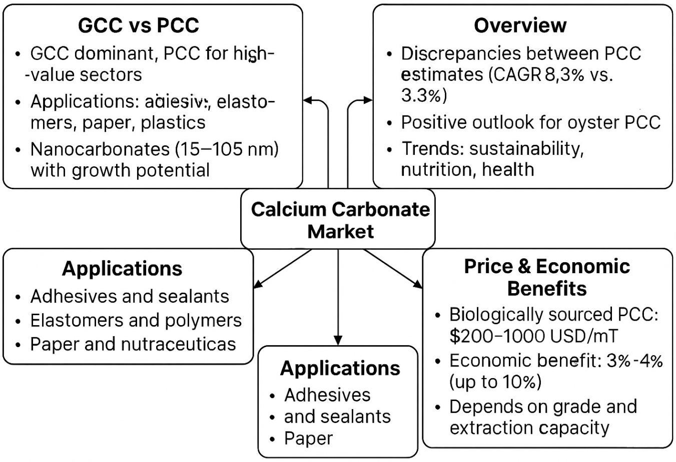
A recent study focusing on proxy products, tried estimating the economic and environmental viability of the industrialized process, concluding for an expected Internal Return Ratio of 12.7% and a yield in $CaCo_3$ of around 83% in respect of waste treated (He et al., 2023). The expected return is aligned with the market of investments in chemical industry, according to McKinsey sources (Lorbeer & Ezekoye, 2024).

b. Industrial Symbiosis Perspectives

Within the scope of MATSHELL, the waste primarily consists of mussels that, during the growth and finishing process, are deemed unsuitable for consumption and commercialization, such as specimens affected by mortality. This type of waste typically represents a significant proportion relative to the volume effectively marketed and imposes a specific disposal cost on producers' financial accounts. According to empirical data collected by MATSHELL, the incidence of waste in volume rises up to around 16% of production. Consequently, it is worthwhile to explore the potential for recycling this waste to obtain valuable raw materials for downstream production processes, in an IS perspective. Indeed, while acknowledging the growing debate about the under-conceptualization of circular economy (e.g. Nosková, 2025; Hirsch & Levin, 1999), we agree with industrial ecologists (e.g., Stahel, 2016; Blomsma & Brennan, 2017; Kirchherr et al., 2025) upon the strict linkage between IS and circularity. From our standpoint, Industrial Ecology can be considered as a precursor of circular economy frameworks, and Industrial Symbiosis represents the organizational effort provided by industries in order to achieve circular and sustainable goals (Corsini et al., 2024; Ramírez-Rodríguez et al., 2024; Veleva & Bodkin, 2018) while improving value production (Stahel, 2016).

For evaluating the potential for value creation, MATSHELL team integrated the scientific literature with research on $CaCo_3$ market available information. Converging sources from various commodity market analysts (ChemAnalist, Fact, …) indicate that the calcium carbonate market is expected to grow significantly in the coming years, both in the segment derived from rock fragmentation (Ground or GCC) and in the segment obtained through alternative extraction and synthesis processes (Precipitated or PCC) (See Figure 3 for a summary). Specifically, while GCC has been and will continue to be the dominant market component, PCC is of particular interest to high-value-added sectors, including adhesives, sealants, elastomeric materials, plastics, printing paper, nutraceutical products, and more. This is consistent with information available in the scientific literature (e.g. Francis, 2025; Summa et al., 2022; Zhan et al., 2022; Morris et al., 2016, 2019; Yao et al., 2014). In addition, PCC-generating processes appear to be capable of producing, at least in part, ultra-fine particles (15-105 nm, known as "nanocarbonate"), which have strong growth potential (Barros et al., 2009; Ismail et al., 2022). These nanoparticles can (or they could in the future) serve as specialized antibacterial agents, components of anticancer drugs, and dietary supplements (Cai et al., 2025), as well as being used in the more traditional construction sector, a major consumer of bulk materials (see Fu et al., 2022).

Figure 3 – Calcium Carbonate market overview



Source: Future Market Insight, Straits Research, Coherent Market Insights, IMARC Group PW Consulting

To the best of our knowledge, no specific market data on mussel-derived PCC are available, but related information exists for PCC obtained from oyster shell processing. This market niche is driven by demand from high-value-added industrial sectors (dietary supplements, pharmaceutical products, personal care, animal nutrition), and, according to various analysts, it benefits from favourable regulatory developments as well as increased consumer environmental awareness.

Based on available data, the price of biologically sourced PCC varies significantly, according to the regional market[3] (North America, Europe, APAC) and CaCo$_3$ grade. He et al. (2023), estimated relevant prices for biological sourced PCC ranging between 200 and 1000 USD/mT, referring to bulk prices found on Alibaba.com. Our researches on commercial sites (IndiaMart, MadeInChina) yield similar results. After combining all the context elements with empirical data, we consider that extracting and selling biologically sourced PCC might provide mussel producers a gross economic benefit between 3% and 4% of production value, which is a conservative estimation. If we introduce more optimistic price estimations, the gross benefit could be estimated at 10% or more, according to the capacity of the extraction process to maximize high-end products, in line with He et al. (2023) estimations.

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[3] Source: chemanalyst.com

c. From Shell Waste to CO_2 Capture: The Potential of Calcium Looping

Aside from standard economic considerations about the market-value of shell derived $CaCo_3$, the recycling of mussel shells offers an interesting opportunity to support carbon capture technologies, particularly through the calcium looping process (Alonso et al., 2021). Calcium looping (CaL), also referred to as the regenerative calcium cycle (RCC), is a second-generation carbon capture technology that has gained significant attention for its potential to mitigate CO_2 emissions from industrial sources such as cement plants, power stations, and waste-to-energy facilities. The process is based on two reversible chemical reactions: carbonation and calcination, which enable the cyclic capture and release of CO_2 using CaO as a solid sorbent (Hanak et al., 2015).

In particular, CaL is a thermochemical process that captures CO_2 from flue gases using calcium oxide (CaO)-based sorbents, which react with CO_2 to form $CaCO_3$. The sorbents are regenerated through calcination, releasing concentrated CO_2 for sequestration or utilization, and restoring CaO for reuse. This closed-loop system offers multiple environmental and economic benefits.

One of the key advantages of CaL is its compatibility with high-temperature industrial processes, allowing for integration without significant infrastructure modifications. Unlike liquid absorbents used in amine scrubbing, CaL avoids issues such as corrosion and solvent degradation, offering a more robust and scalable solution for CO_2 capture.

Pilot-scale implementations of CaL have demonstrated promising results. A notable example is the TRL7 CFB-CaL pilot at La Pereda (Arias et al., 2024), which achieved CO_2 capture efficiencies exceeding 99% using circulating fluidized bed technology and biomass-fired calcination. The system was able to treat over 2000 Nm^3/h of flue gases, showcasing the scalability and retrofitting potential of CaL in existing industrial setups. According to recent studies, calcined mollusc shells often display enhanced carbonation reactivity compared to natural limestone. This improved performance is linked to the residual porosity of shell-derived CaO, which facilitates gas diffusion and accelerates the chemical reactions (Hart & Onyeaka, 2020). By substituting conventional mineral resources with shell waste, the environmental impact of quarrying is also reduced, adding further benefits in terms of the circular economy and sustainability. Thus, shell recycling represents a promising pathway in decarbonization strategies (Adjei et al., 2025), and CaL process adds value to the waste treated (Anthony, 2011).

d. Proposal for an industrial symbiosis model

MATSHELL project has provided significant evidence that new extraction and processing techniques can yield high-purity calcium carbonate products from bivalve shell waste, confirming previous studies about the feasibility of transforming this biological residue into a valuable industrial resource (Francis, 2025; Schiopu et al., 2025; Cheng et al., 2023; Ismail et al., 2022; Zhan et al., 2022; Summa et al., 2022; Morris et al., 2019). Through an integrated experimental approach combining material characterization, process optimization, and environmental assessment, the research has demonstrated that controlled calcination and precipitation routes can produce calcium carbonate of exceptional purity and crystalline stability. These characteristics make the resulting material suitable for a wide range of applications, spanning from pharmaceutical and nutraceutical formulations to advanced industrial processes such as calcium looping for CO_2 capture and reuse (Adjei et al., 2025; Alonso et al., 2021; Hart & Onyeaka, 2020; Hanak et al., 2015; Anthony, 2011).

One of the central findings of the project concerns the intraspecies variability of outcomes based on both geographical and operational parameters, aside interspecies considerations (Piras et al., 2024). The mineral composition and microstructure of the shells were found to depend strongly on the local marine environment, aquaculture practices, and seasonal factors influencing shell growth. Such geographical differentiation affects the reactivity, whiteness index, and particle morphology of the extracted carbonates. In addition, MATSHELL team identified that the degree of pre-treatment, as cleaning, classification, and granulometric control of the shell waste, plays a decisive role in determining the final product quality. When the discarded shells are adequately sorted, washed, and mechanically refined prior to calcination, the extracted calcium carbonate exhibits superior physicochemical properties and higher market value. As illustrated in previous pages, these results confirm that the proper management of shell residues can lead not only to waste reduction but also to the creation of high-value materials.

However, some caveats apply. To the best of our knowledge, the first structured trial to industrialize $CaCo_3$ extraction from mussel shells was the Calizas Marinas experience (Barros et al., 2009). Calizas was a Galician company that actively operated in this market from 1999 to 2010 and, despite some achievements, it officially ceased its administrative existence in 2017. This happened despite a strong capitalisation (over €5 million in share capital), the involvement of many regional producers of mussels (43 companies), and the active support of the Autonomous Community of Galicia as a facilitator[4]. From our standpoint, two reasons clearly emerge for their failure: an extraction process that was not sufficiently mature, and the oversizing of the plant. This second point is crucial from the Industrial Symbiosis perspective, because it highlights deficiencies in the design and in the governance system, as mussel producers did not fully comply their engagement about waste drop-off. Following Chrysikopoulos et al. (2024), we can detect a vicious circle between scarce short term economic viability and the commitment of the network. In these conditions, the availability of financial means was not a sufficient anticipator of future returns, so it did not play the role acknowledged in the literature (e.g. Corsini et al., 2024). In addition, other biogenic $CaCo_3$ extraction research projects, highlight relevant challenges, in particular for oyster sourced biomaterial, as: high initial investment, competition with similar replacement products in the market, cost of research on high-quality product development, a thorough comparison of market product prices and production costs, a year-round supply of oyster shell processing waste, and maintaining the processing plant to guarantee a steady performance (Chowdhury & Ehimen, 2022). Finally, as reminded in introduction, the experience of Wast3d Shell in Taranto is still too new to be scrutinized.

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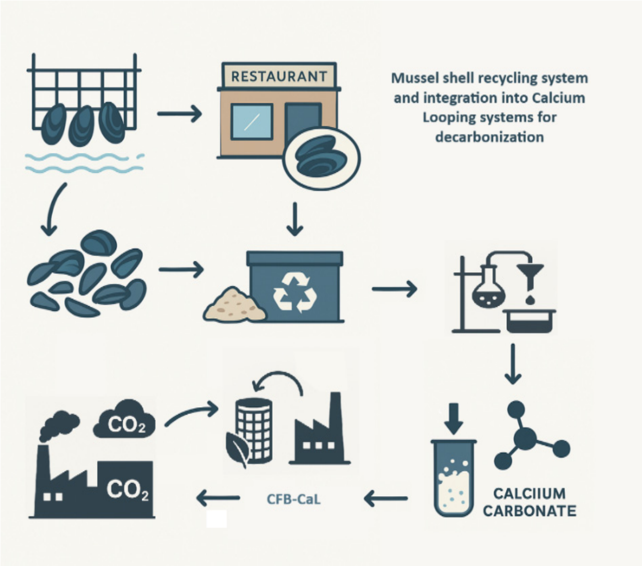
[4] Source: www.interfishmarket.com.

These experiences alert about some criticalities. First, the existence of a valuable disposal is not sufficient for sustain industrial symbiosis. Second, the existence of a clear demand for disposal derived products is not sufficient for sustain industrial symbiosis. Third, the existence of incentives is not sufficient for sustain industrial symbiosis. As supported by broad literature, Industrial Symbiosis requires a well-established ecosystem (Morales & Diemer, 2019) marked by shared values, cooperation, and coordination (Marian R. Chertow & Ehrenfeld, 2012), where appropriated metrics allow for full account of net benefits (Mirata et al., 2024; de Araujo et al., 2011).

Figure 4 – Mussel shell recycling system



Source: Author's own elaboration

In response to these insights, MATSHELL project developed a proposal for an industrial symbiosis model that integrates shell waste valorisation with carbon-intensive sectors. The model leverage on the optimal plant sizing by He et al. (2023), which is around 1/8 of Calizas' size, on high TRL in specific pilot plant (Arias et al., 2024), and on high performances of biogenic $CaCo_3$ for CaL (Adjei et al., 2025; Arias et al., 2024). This niche design avoids most of the criticalities raised by Chowdhury and Ehimen (2022). The small sizing of the projected plant allows for localized networks (Chertow, 2000) where shell residues are collected from coastal regions, processed into refined calcium carbonate, and supplied to industries involved in cement, lime, or steel production, sectors with substantial CO_2 emissions and high demand for carbonate materials. This reduces the need for complex symbiotic upstream networks, allowing for simpler models based on the design of diffused eco-parks (Scafà et al., 2018). Downstream networks will complement the monitoring for outlet markets and revenue securing.

The overall system architecture and process integration developed within MATSHELL are summarized in Figure 4, which schematically represents the proposed industrial symbiosis pathway from shell collection to calcium carbonate production and its downstream applications. The proposed system begins with the collection of mussel shells from seafood processing facilities and foodservice establishments. These shells undergo pre-treatment processes including washing, drying, and grinding, followed by chemical purification to isolate $CaCO_3$. The extracted calcium carbonate is then utilized in the production of solid sorbents for calcium looping systems (Hanak et al., 2015).

This configuration aligns theoretical perspectives on industrial ecology with practical applications of circular economy as discussed before, aiming to close both material and carbon loops through regional cooperation and resource optimization.

To assess the feasibility and strategic positioning of the proposed integrated system, the research team adopted a qualitative methodology based on semi-structured interviews with scientific experts and sector stakeholders. This approach involved presenting the developed industrial symbiosis model, eliciting expert perceptions, and systematically identifying the factors they considered as supporting or opposing its implementation. The results of the analysis are presented below in a SWOT analysis format.

3. Data and method

The empirical component of this research was conducted on a purposive sample composed of thirteen university-based researchers and six stakeholders from the production sector, reflecting the interdisciplinary and multi-actor approach adopted within the MATSHELL project. The academic sample included ten chemists and three marine ecologists, each contributing specific expertise related to the characterization and environmental assessment of bivalve shell waste. The group of chemists was primarily responsible for the classification and compositional analysis of mussel shells, focusing on variations in their physical and chemical properties as a function of geographical origin and the production chain from which the waste was derived. Their activities encompassed both the laboratory-based examination of mineral content, crystalline structure, and impurity profiles, and the comparative assessment of samples collected from different coastal and aquaculture sites. The aim was to identify how local environmental conditions, water chemistry, and processing practices influence the quality and potential recyclability of shell residues. In parallel, the three marine ecologists within the research team investigated the biological and environmental aspects of the production sites, with particular attention to the ecological footprint associated with shellfish cultivation and shell waste management. Their work involved evaluating the potential impacts of shell disposal on benthic ecosystems, assessing nutrient cycling, and identifying opportunities for mitigation and restoration. This ecological perspective complemented the chemical and material analysis by situating shell recycling within a broader environmental sustainability framework. To extend the analytical perspective beyond the academic domain, the sample was expanded to include six participants representing the entrepreneurial and organizational dimensions of the sector. These comprised four shellfish producers directly involved in the MATSHELL project and two representatives from the Italian Association of Shellfish Producers. Their inclusion allowed for the exploration of the practical feasibility, economic constraints, and institutional attitudes toward shell recycling and industrial symbiosis models.

The following table summarizes the panel of experts from the MATSTHELL project used in this study:

Table 1 – Different categories of experts involved in MATSHELL project, their characterization and main tasks

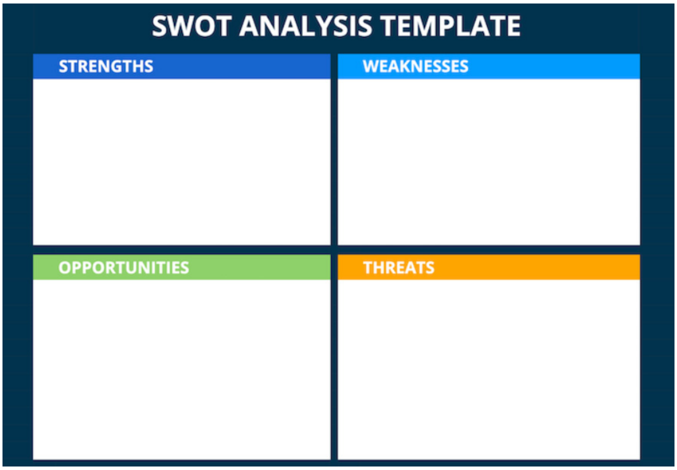
Expert Characterization	Expert Type	Main Tasks in the Project
Chemist	• Academic • 10 experts	• Classification and compositional analysis of mussel shells • Study of physical and chemical properties based on geographical origin and production chain • Laboratory analysis of mineral content, crystalline structure, and impurity profiles • Comparative assessment of samples from coastal and aquaculture sites
Marine Ecologist	• Academic • 3 experts	• Analysis of biological and environmental aspects of production sites • Assessment of the impact of shell disposal on benthic ecosystems • Study of nutrient cycling and identification of mitigation and restoration opportunities • Integration of ecological perspective into the environmental sustainability framework
Mussel Producer	• Private • 4 experts	• Providing operational data and waste management practice • Evaluation of technical feasibility of shell recycling • Contribution to defining economic and practical constraints
Representative of the Italian Association of Shellfish Producers	• Private • 2 experts	• Analysis of institutional and regulatory dynamics • Support for promoting industrial symbiosis models • Discussion of economic and organizational implications

All participants were presented with the proposed industrial symbiosis framework (see Figure 4). Feedback was collected using a SWOT analytical framework, assessing strengths, weaknesses, opportunities, and threats, in order to capture both disciplinary insights.

4. SWOT analytical framework

The SWOT analysis framework has its roots in 1950s, with the seminal works of Stewart about strategy and long-range planning (Puyt et al., 2020) Several practitioners and scholars contributed to its development (Helms & Nixon, 2010; Palazzo, 2024), and today it is acknowledged as a foundational methodology for strategic planning across diverse organizational contexts (Freyn & Hoffman, 2023), despite some issues (King et al., 2023). Its analytical strength lies in its ability to distinguish between internal factors, which fall within an organization's control, and external factors, which are influenced by broader environmental dynamics (Benzaghta et al., 2021). Strengths and weaknesses denote internal attributes that respectively facilitate or hinder the achievement of organizational objectives, whereas opportunities and threats represent external conditions that either support or challenge strategic goals. Although methodologically simple, SWOT's analytical potential has been substantially enhanced through its integration with complementary models and decision-making tools (Yavuz & Baycan, 2013). Its adaptability has allowed it to be embedded within broader strategic frameworks, thereby expanding its analytical scope.

Figure 5 – SWOT Template used in this study.



In applied settings, SWOT is commonly operationalized through matrices that guide the formulation of strategic alternatives (see Figure 5), namely: SO (strengths–opportunities), ST (strengths–threats), WO (weaknesses–opportunities), and WT (weaknesses–threats).

In our study, we strengthened the analytical robustness of the SWOT framework by incorporating expert opinions from the various research units involved in MATSHELL project, as well as insights from private stakeholders as showed in Table 1. As suggested in literature (Helms & Nixon, 2010; Yavuz & Baycan, 2013; Bull et al., 2016), by systematically incorporating expert assessments and stakeholder contributions, this framework generates multidimensional perspectives and enables the quantification of qualitative SWOT factors, thereby strengthening the reliability and precision of strategic evaluations.

5. Results and discussion

The analysis of expert interviews provided a rich set of insights that proved fundamental for advancing the study's analytical framework. The initial phase involved gathering qualitative data and perceptions from a diverse group of stakeholders, each offering nuanced perspectives on the dynamics, challenges, and opportunities characterizing the symbiotic system under investigation. This exploratory stage was essential not only for identifying recurring themes but also for capturing the heterogeneity of viewpoints that typically emerges when consulting experts with varied backgrounds and professional experiences.

Following this first round of data collection, a systematic reclassification process was undertaken to organize the information within the structure of a cumulative SWOT analysis. The raw insights derived from the interviews were reorganized and mapped onto the four quadrants of the SWOT framework. This step allowed for the transformation of individual observations into more coherent and analytically meaningful categories. The reclassification aimed to identify emerging patterns, reduce redundancy, and group related factors in a way that facilitated the recognition of broader macro-areas of strategic relevance.

Once these macro-areas were delineated, an additional effort was made to anchor each thematic cluster in the existing academic literature. This step served a dual purpose: it validated the empirical findings emerging from the expert interviews, and it reinforced the analytical robustness of the SWOT categorization through established theoretical references. For each macro-area, a relevant theoretical framework or scholarly contribution was identified to substantiate the interpretation of the qualitative evidence. This alignment ensured that the empirical insights were not only grounded in expert experience but also situated within a broader conceptual and methodological context. The integrated results of this process are presented below, offering a comprehensive overview of how interview-based insights were translated into structured analytical categories supported by theoretical foundations. The synthesis illuminates the main strategic orientations that emerged for each quadrant and provides a clear depiction.

Subsequently, a holistic verification of the overall strategic model was conducted. This phase entailed revisiting the SWOT-derived macro-areas and examining their interconnections to ensure internal consistency and strategic coherence. In doing so, specific actions were formulated in relation to each area of the SWOT analysis. These actions were designed to leverage strengths, mitigate weaknesses, seize opportunities, and address threats through targeted interventions. The resulting strategic proposals offer actionable guidelines that can inform decision-making processes and support long-term planning efforts.

6. SWOT Analysis Results

Strengths

- **Technological Maturity**: Calcium looping has reached a Technology Readiness Level (TRL) above 7, indicating that the process has been demonstrated in operational environments and is ready for industrial deployment (Arias et al., 2024).

The maturity of CaL systems ensures that integration with existing industrial infrastructure is technically feasible and economically viable. Furthermore, the chemical extraction of $CaCO_3$ from mussel shells is based on well-established purification protocols, allowing for consistent quality and scalability (Schiopu et al., 2025; Magalhães et al., 2024; He et al., 2023; Ismail et al., 2022; Hou et al., 2016; Barros et al., 2009). Building on this foundation, MATSHELL project has played a pivotal role in consolidating and systematizing the various extraction methodologies proposed in the scientific literature. Through extensive experimental validation, MATSHELL has codified a series of efficient protocols tailored to the specific characteristics of mussel shells, depending on their origin, whether from aquaculture, industrial processing, or post-consumption waste. This differentiation enables the selection of the most suitable process in each context, optimizing both yield and product quality while mitigating the impact of potential contaminants. As a result, the project has laid the groundwork for a flexible and adaptive processing framework. This advancement is particularly valuable for industrial implementation, where variability (Piras et al., 2024) in raw material composition can pose significant challenges to standardization and performance consistency in downstream carbon capture applications.

- **Process Compatibility**: The modular architecture of CaL systems enables flexible integration across a wide range of industrial emitters, including cement plants, steel mills, and power generation facilities (Adjei et al., 2025; De Lena et al., 2022; Hanak et al., 2015; Anthony, 2011). This diversity significantly enhances the potential for identifying suitable symbiotic partners for decarbonization initiatives. In particular, regions with established mussel farming operations can strategically align with nearby industrial emitters to optimize material flows and minimize logistical burdens. Beyond technical efficiency, such localized systems offer significant social and territorial benefits (Cheshmehzangi, 2025; Sellitto et al., 2025; de Araujo et al., 2011). By embedding decarbonization practices within existing regional structures, such as aquaculture, food processing, and industrial manufacturing, these initiatives can foster greater civic engagement and public appreciation for sustainable industrial transformation (Chertow, 2000). The visible reduction of waste and the creation of symbiotic relationships between sectors enhance the perceived value of these infrastructures. This is especially relevant in coastal urban areas, where industrial facilities often face growing public opposition due to environmental concerns. Integrating carbon capture with circular resource use, such as mussel shell recycling, can shift public perception, positioning these facilities as contributors to ecological regeneration rather than sources of degradation. As a result, strategic localization not only improves logistics but also strengthens the social license to operate in sensitive urban and coastal contexts (de Araujo et al., 2011).

Weaknesses

- **Complexity of Symbiotic Linkages**: Establishing a robust supply chain that connects seafood waste producers, chemical processors, and CO_2 capture facilities requires significant coordination to manage the interdependence of parts (Aviso et al., 2022). This interdependence is binding, especially for the part of the mussel farms that have difficulty imagining a second outlet market (that of shells and production waste) in addition to the primary one familiar to them (the food products market). This double market challenge is difficult to manage also because of a clear imbalance of entrepreneurial skills towards their first and historical market, rather than in a completely different market with little or even totally unknown dynamics of competition and exchanges. The hesitation for the mussel farms stems also from the difficulty of integrating such a market internally, given the required technical expertise and the vastly different technologies compared to those used in their respective areas of operation (Summa et al., 2022). This hesitation manifests itself in a fear of establishing a relationship of interdependence between the parties, which is often seen as a threat and a constraint on the freedom of future choices of companies (Ventura et al., 2025). This paradoxically turns out to be more surmountable if one looks at it from the point of view of scientific collaborations with engineering systems that can facilitate the structuring of extraction production processes in an efficient manner, thanks to synergies with research centres and with the provision of high and specific technical skills (Aviso et al., 2022). In this case, the strong scientific collaboration that could be triggered following experimental pilot projects turns out to act as a driving force rather than as a barrier to action. Furthermore, the development of projects turns out to be an opportunity for the creation of those collaborative relationships that can take root and allow the positive evolution of an effective industrial symbiosis system.

- **Variability** in shell composition and contamination levels can introduce quality control challenges in the $CaCO_3$ extraction phase. Factors such as environmental exposure and residual organic matter can affect the purity and consistency of the extracted material. Contaminants like heavy metals, biofilms, and food residues may interfere with chemical purification steps, requiring additional processing stages that increase operational complexity and cost. Ensuring uniform quality of $CaCO_3$ is critical for its application in calcium looping systems, where sorbent performance depends on precise chemical properties (Arias et al., 2024; Anthony, 2011; De Lena et al., 2022). Therefore, robust quality control protocols and standardized input streams are essential for industrial scalability.
- **Capital Intensity**: While the core technologies involved, waste collection, chemical processing, and carbon capture, are mature, their integration into a cohesive industrial ecosystem demands substantial upfront investment (Chowdhury & Ehimen, 2022; He et al., 2023). To overcome financial barriers, especially in smaller municipalities or decentralized regions, a structured collaboration between public authorities and the banking sector is essential. Facilitating access to capital through green financing instruments or public-private partnerships can accelerate deployment. Moreover, investment can be framed as environmental remuneration (Anthony, 2011), where decarbonization outcomes are monetized and accounted for as carbon credits or avoided emissions, thus creating measurable value and incentivizing participation across institutional and financial stakeholders.

Opportunities

- **Expanding Decarbonization Market**: The global push for decarbonization, driven by regulatory frameworks such as the EU Green Deal and national carbon neutrality targets, is accelerating the adoption of CO_2 capture technologies. CaL is gaining traction due to its cost-effectiveness and compatibility with high-temperature industrial processes. The demand for sustainable sorbents is expected to rise, creating a favorable market for bio-derived $CaCO_3$ (Summa et al., 2022). As for market prices of carbon carbonate, European prices have fluctuated between 300 USD/mT and 410 USD/mT since 2022. However, these prices are for the entire market regardless of source (GCC or PCC), and they are strongly influenced by the construction sector dynamics, which is not the main target for biologically sourced CC. Also, it is worth noticing that some supply chain disruptions happened, especially in the US during 2024[5], which is one of the risks that make industrial symbiosis of strategic interest. With regard to the specific pricing of biologically sourced calcium carbonate, market analysis proved to be challenging due to its niche nature and the confidentiality maintained by most producers regarding price listings.

- **Policy Incentives and Circular Economy Mandates**: Governments are increasingly supporting circular economy initiatives through subsidies, tax incentives, and research funding. The integration of mussel shell recycling into carbon capture aligns with these policy trends, potentially unlocking financial and regulatory support. Moreover, the system contributes to multiple Sustainable Development Goals (SDGs), including responsible consumption, climate action, and industry innovation (Masi et al., 2025; Ramírez-Rodríguez et al., 2024; Summa et al., 2022). Financial instruments, including green bonds and innovation grants, may be leveraged to support infrastructure development and stakeholder coordination. Additionally, the system's alignment with SDGs enhances its appeal to public and private actors seeking to meet ESG (Environmental, Social, and Governance) targets (Francis, 2025; de Araujo et al., 2011).
- **Regional Development and Job Creation**: The establishment of localized processing hubs for shell waste and $CaCO_3$ production can stimulate regional economies, particularly in coastal areas with strong aquaculture sectors. This model promotes green job creation and supports the transition to low-carbon industrial ecosystems (Ventura et al., 2025). When strategically positioned near coastal industrial zones, these hubs can serve as catalysts for socio-economic revitalization. Many of these areas face progressive decline due to the environmental incompatibility of traditional manufacturing activities with current sustainability standards. By repurposing existing infrastructure and retraining local workforces, the development of mussel shell recycling and carbon capture facilities offers a pathway to industrial renewal. These hubs can absorb displaced labour from declining sectors, fostering inclusive employment and technological upskilling. Moreover, their proximity to both waste sources and emission-intensive industries enhances logistical efficiency and symbiotic integration (Jensen et al., 2011). This spatial strategy not only supports environmental goals but also reinforces regional resilience (Morales & Diemer, 2019) through sustainable industrial diversification.

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[5] Source: www.chemanalyst.com.

Threats

- **Geographical Dispersion** of Symbiotic Nodes: The effectiveness of the integrated system relies heavily on the spatial proximity between mussel shell waste sources, $CaCO_3$ processing facilities, and CO_2 capture sites (Cheshmehzangi, 2025; Morales & Diemer, 2019; Scafà et al., 2018). When these nodes are geographically dispersed, transportation costs and associated emissions can significantly reduce the environmental and economic benefits of the system. Logistical bottlenecks may also disrupt material flows, undermining operational reliability. Therefore, it becomes strategically essential to map and to identify coastal industrial zones and mussel production regions where these symbiotic-nodes naturally converge. Targeting such areas for the development of pilot systems can optimize logistics, reduce infrastructure costs, and accelerate deployment. These geographically concentrated and integrated hubs allow for streamlined material handling and foster industrial symbiosis by also implementing digital traceability systems (Zhao et al., 2025). This spatial planning approach enhances both the feasibility and sustainability of the mussel shell-to-carbon capture value chain.
- **Regulatory Uncertainty and Market Volatility**: While the decarbonization market is expanding, it remains sensitive to policy shifts and economic fluctuations. Changes in carbon pricing, environmental regulations, or public funding priorities could impact the viability of the system. For example, when regulations lack clear definitions and fail to introduce real disincentives for waste and pollution, companies perceive industrial symbiosis as excessively risky and refrain from committing resources (Chrysikopoulos et al., 2024). The absence of public financial support or easy access to funding, in fact, discourages symbiotic initiatives, given the high initial costs associated with infrastructure development, the adoption of new technologies, and research and development activities (Sellitto et al., 2025). The involvement of facilitators and public authorities in facilitating the exchange of industrial residues provides additional support by mitigating risk through research and development funding, tax incentives, and knowledge dissemination (Henriques et al., 2022; Ventura et al., 2025).

7. Proposed strategic actions for advancing mussel shell-based carbon capture initiatives

The proposed actions aim to operationalize an industrial symbiosis model that leverages mussel shell waste as a feedstock for calcium looping (CaL) processes, thereby contributing to carbon capture and circular economy objectives. These actions are structured across four dimensions: leveraging strengths, addressing weaknesses, capturing opportunities, and mitigating threats.

Actions leveraging strengths

The maturity of CaL technology (Arias et al., 2024) and the availability of validated extraction protocols provide a strong foundation for early implementation. To capitalize on these strengths, regional pilot hubs should be established in high-potential coastal zones where mussel farming and industrial CO_2 emissions are geographically concentrated. Such hubs would serve as integrated platforms for shell collection, pre-processing, and CaL operations, reducing logistical complexity and enabling economies of scale. In parallel, technology demonstration campaigns are essential to build confidence among industrial emitters. By showcasing the performance stability of bio-derived $CaCO_3$ sorbents under real operational conditions, these campaigns can accelerate adoption and foster partnerships. Demonstrations should emphasize comparative advantages over conventional sorbents, including cost-effectiveness and sustainability credentials. Finally, community-facing communication programs must be developed to strengthen social acceptance. Public perception often represents a critical barrier to industrial projects; therefore, transparent communication highlighting waste reduction, carbon capture benefits, and local economic gains can counteract opposition and enhance legitimacy.

Actions to address weaknesses

Current weaknesses relate primarily to governance complexity, quality variability, and financial constraints. To overcome these, a Symbiosis Facilitation Initiative (de Araujo et al., 2011; Sellitto et al., 2025) should be created. This initiative would operate under a joint governance model involving mussel farms, industrial actors, research institutions, and public authorities. Its functions would include mediating contracts, establishing risk-sharing arrangements, and providing legal and managerial expertise to less-experienced stakeholders, under the strategic design of diffused eco-park (Scafà et al., 2018). By institutionalizing coordination, the initiative can reduce transaction costs and enhance trust.

Quality control represents another critical weakness. The introduction of standardized protocols for sampling, testing, and contamination removal is imperative. Harmonization will ensure consistent feedstock quality and operational reliability. Digital tracking systems should be implemented to record shell origin and composition, enabling full traceability. Additionally, pre-processing stations can homogenize shell material before CaL application, mitigating variability and contamination risks. Financial barriers can be addressed through green financing instruments. Blended finance models, combining public-private partnerships, green bonds, and ESG investment funds, can mobilize capital for infrastructure development. Carbon capture benefits should be monetized via carbon credit schemes, while credit guarantees can incentivize SME participation in the value chain.

Actions to capture opportunities

The initiative aligns closely with global sustainability agendas, creating opportunities for resource mobilization and stakeholder engagement. Explicitly linking outcomes to SDGs and ESG frameworks will enhance attractiveness to investors and public agencies, positioning the project within broader climate and circularity narratives. Accessing EU innovation grants and regional cohesion funds represents another opportunity, as demonstrated by recent programmes (e.g., Chowdhury & Ehimen, 2022). Programs targeting industrial decarbonization, blue economy development, and circular value chains are particularly relevant. Proactive engagement with funding bodies can secure financial support for pilot projects and scale-up phases. Finally, workforce development is essential to sustain long-term operations. Local retraining programs, in collaboration with vocational institutes, can reskill workers from declining industrial sectors for roles in shell processing, quality control, and CaL operation. This approach not only addresses labour shortages but also reinforces the socio-economic legitimacy of the initiative.

Actions to mitigate threats

External threats include spatial mismatches, regulatory uncertainty, and market volatility. To mitigate these, spatial mapping and prioritization should identify symbiosis hotspots where mussel farms, shell waste streams, and CO_2 emitters converge. Early deployment in these areas will maximize efficiency and minimize logistical costs. Regulatory risk can be reduced through policy engagement. Advocacy efforts should aim to secure long-term stability by clarifying industrial symbiosis definitions in legislation, promoting stable carbon pricing mechanisms, and requesting subsidies for circular feedstock-based carbon capture. Finally, market volatility necessitates flexible business models. Long-term supply contracts for $CaCO_3$ can stabilize revenue streams, while diversification into alternative applications beyond CaL, such as construction materials or specialty chemicals (Hart, 2020) can buffer demand fluctuations. Further refining of $CaCo_3$ is also an option (Roșioru, 2023). Risk-sharing mechanisms should be incorporated to protect SMEs from price shocks, ensuring resilience across the value chain.

8. Conclusion and future research trajectories

As we demonstrated in previous pages, the integration of mussel shell waste into calcium looping (CaL) systems represents a novel circular economy approach with significant environmental and industrial potential. Mussel shells, rich in calcium carbonate ($CaCO_3$), are generated in large volumes from aquaculture and foodservice sectors. Through pre-treatment and chemical purification, high-purity $CaCO_3$ can be extracted and used to produce solid sorbents for CaL systems, which capture CO_2 from industrial flue gases. This closed-loop model not only mitigates waste disposal issues, but also contributes to scalable decarbonization. Calcium looping has reached a Technology Readiness Level (TRL) above 7, enabling integration with cement, steel, and energy sectors. MATSHELL project has advanced purification protocols tailored to shell origin, enhancing process adaptability and product consistency.

However, challenges persist. First, variability in shell composition and contamination complicates $CaCO_3$ standardization, requiring robust quality control. Second, mussel producers often lack familiarity with secondary markets, creating hesitancy in forming interdependent supply chains, with potentially disruptive effect on the symbiotic network, as in the Galician experience. Third, implementing the symbiosis initiative demands significant capital investments. Public-private collaboration, particularly with banking institutions, is essential to unlock green financing and environmental remuneration mechanisms, such as carbon credits.

On the other hand, geographic proximity between mussel farms and industrial emitters facilitates symbiotic partnerships, improving logistics and public acceptance, especially in coastal urban areas. In this regard, the public sector can play a highly significant role by establishing eco-industrial parks or by managing industrial areas in an integrated manner, thereby fostering the co-location of firms and enabling resource exchanges. Such exchanges should be appropriately identified and supported through the definition of a clear regulatory framework, particularly with respect to the distinction between by-products and waste. This regulatory differentiation is fundamental, as it allows a residual stream to be classified as a "by-product" rather than as "waste" (e.g. Article 184-bis of Legislative Decree 152/06 in Italy), thus facilitating its direct reuse without the need for complex and burdensome bureaucratic procedures. From this perspective, the primary role of public authorities lies in removing existing barriers ("barrier busting") and in creating the infrastructural and regulatory conditions ("market creating") that make industrial symbiosis a viable and scalable practice within a more agile overall organizational framework. At the same time, beyond facilitating and promoting the development of eco-industrial parks to ensure a more coherent and integrated supply structure, it is equally important to simultaneously activate market dynamics through policy measures capable of stimulating demand for outputs and derivatives generated by symbiotic processes. In this sense, the advantage offered by this case study is particularly relevant, as the products envisaged as outcomes of the symbiotic process would directly support green practices and public policies. This creates the opportunity to identify and mobilize dedicated funding streams specifically targeted at initiatives of this kind.

Building on the limitations we recognise in this work, several avenues for future research emerge, which, in our opinion, could appeal to a wider audience of researchers and practitioners interested in developing the proposed model. First, the interaction between the proposed symbiotic model and real market dynamics requires a period of adaptation and gradual penetration. Early-stage pilot hubs may face operational inefficiencies, unstable supply chains, or limited producer engagement, potentially jeopardizing the short-term profitability and long-term viability of the system. This calls for deeper investigation into the evolutionary pathways of new entrants within industrial symbiosis contexts. Second, the geography of the symbiotic system introduces constraints linked to local cultural, administrative, and infrastructural barriers. These may prevent the emergence of optimal hubs, instead favoring only those regions where institutional or bureaucratic conditions happen to be more permissive, even if sub-optimal in terms of logistics or industrial proximity. Future research should therefore include a systematic analysis of geographic and institutional barriers specific to mussel shell–based CaL systems. Finally, the symbiotic initiative may clash with the generational and organizational dynamics of mussel-producing firms, many of which are family-run and characterized by path dependency, risk aversion, and intra-firm decision-making norms. These internal dynamics can hinder innovation adoption, delay collaboration agreements, or create asymmetric participation among producers. A dedicated research stream examining family business behavior within circular economy and industrial symbiosis frameworks would therefore be highly beneficial.

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Organizational and external influences on circular economy adoption in oil and gas: A MENA perspective

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Abstract

This study employs quantitative methods to develop a Circular Economy (CE) adoption scale in the MENA oil and gas sector. Using Exploratory Factor Analysis, Confirmatory Factor Analysis, and Structural Equation Modeling, it validates theoretical constructs derived from Literature review. A comprehensive literature review of 110 articles combined with data from 230 industry workers in various Middle East and North Africa (MENA) countries were analyzed to explore antecedents to CE adoption specifically in Oil and Gas sector. Findings reveal that innovation mediates the relationship between organizational drivers and external pressures, enhancing CE practices. While organizational inclination and external pressures positively affect innovation, moderation analysis shows that external pressures do not significantly amplify the impact on CE adoption. This research contributes to academic and practical discussions on integrating sustainability in the oil and gas sector, emphasizing innovation. Future studies should expand geographic scope, diversify sampling, and assess technological impacts on CE, providing crucial insights for policymakers and strategists in resource-heavy industries.

Keywords: circular economy, adoption, innovation, external pressure, organization, quantitative.

JEL classification: O33, L10, O35

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1. Introduction

The conventional linear economic paradigm, distinguished by extraction, utilization, and disposal processes, has historically served as the fundamental basis for contemporary industrial economies as depicted in Figure 1a, including the oil and gas (O&G) industry. This paradigm has resulted in notable environmental and energy security issues, namely in the oil and gas industry, which includes numerous subindustries such as manufacturing, processing, transportation, and commercial sales

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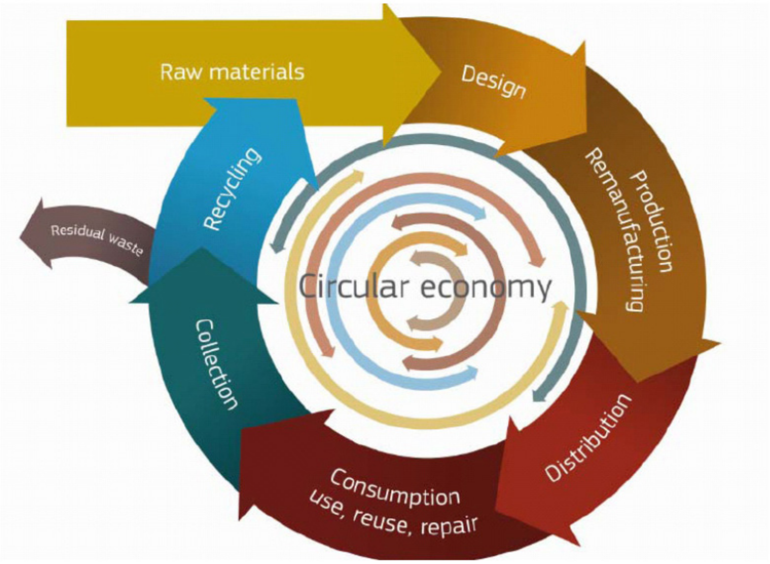
(Mandegari et al., 2017; Kirchherr et al., 2017; Macini & Mesini, 2008). Petroleum refineries, which manufacture more than 2,500 products from crude oil, are significant contributors to worldwide pollution because of the hazardous chemicals they release, leading to severe threats to human health, aquatic ecosystems, and the economy (Cholakov, 2009; Thorat & Sonwani, 2022). The inherent lack of sustainability in the linear model has led to a transition towards a Circular Economy (CE) in the oil and gas industry. The primary objective of CE is to minimize waste while safeguarding valuable materials and products to optimize their utilization, so tackling environmental issues and resource scarcity (Hagelüken et al., 2016; MacArthur, 2013) as depicted in Figure 1b. The fundamentals of the CE model are intrinsically connected to sustainability; these include zero-waste design, a product-service system, and the restoration of the planet's ecosystems. This strategy is particularly relevant when the oil and extracting industry emissions represent approximately 42% of global emissions while the industry is experiencing mounting demands to reduce emissions while maintaining production. (Malik & Askari, 2022).

Figure 1a – Linear economy flow diagram

Source: Upadhayay & Alqassimi, 2018

Circular Economy (CE) has received interest regionally and globally, mainly due to the rising levels of waste produced by industrialization and the COVID-19 pandemic. In the MENA oil and gas industry context, CE profoundly reduces the seismic environmental and social impacts of landfilling and the sector's massive reliance on extractive industries (Felix et al., 2022; Jain et al., 2020). CE promotes sustainable product design, material management, and provision of markets for related products, imperatives that are vital for sustainable economic development (Hysa et al., 2020). Changing to a Circular Economy in the Oil and Gas sector requires overcoming barriers like geographical scope, material complexity, and a long-established linear operating model (Hazen et al., 2017). Despite these obstacles, the implementation of circular economy principles is gaining momentum, as the notion of a "circular carbon economy" is emerging as a strategic method to tackle resource shortage and environmental contamination in the petrochemical and oil and gas sectors. The described methodology uses innovative technology and business solutions to progress in closing material and energy loops (Esposito et al., 2018; Palm et al., 2024; Lau et al., 2022).

Figure 1b – Circular economy



Source: Bonciu, 2014

This increased demand is mainly accounted for by oil and gas products, which implies that the industry has to come up with ways through which it can be able to meet this demand while at the same time minimizing the advancement of adverse environmental impacts (Newell et al., 2016). If implemented, the CE model can save up to $ 1 trillion annually by 2025 and support the achievement of net-zero emission goals by 2050 as pointed out by Esposito et al. (2018) and Heo et al (2022). Also, Circular Economy(CE) aims at a sustainable balance between nature conservation and economic development, making it become a vital part of the oil and gas industry's transformation toward sustainability (Wang, 2018). The Circular Economy offers substantial prospects for the Oil and Gas industry to improve its environmental performance, conform to worldwide climate objectives, and promote sustainable development, especially in the MENA region. The oil and gas industry can make a significant contribution to global sustainability through the implementation of environmentally responsible production methods and integrating a comprehensive value chain approach to product life cycles (Ibn-Mohammed et al., 2021; Zaleski & Chawla, 2020). Further section 2 outlines the research aim, motivation, and questions. A comprehensive literature review (Section 3) identifies three key antecedents – Organizational Inclination, Innovation, and External Pressure – supported by theoretical underpinnings. Section 4 presents the research methodology, detailing research design, data collection, sampling, and analysis techniques. Empirical validation using EFA, CFA, and SEM is discussed in Section 5. Section 6 presents hypothesis testing results, followed by implications in Section 7. Limitations and directions for future research are addressed in Section 8, while Section 9 concludes the paper, emphasizing innovation's pivotal role in CE adoption.

2. Research aim and motivation

The time has come for practical sustainable industrial solutions, especially within the oil and gas industry, which is now under pressure to demonstrate its environmental footprint and sustainability performance (Malik & Askari, 2022; Lau et al., 2022). About eight MENA countries offer more than 30% of the global oil supply, implying that integrating the energy sector into international sustainability goals is crucially important (Jain et al., 2022). This paper builds on the analysis of identified themes based on literature review using Exploratory factor analysis (EFA), Confirmatory Factor Analysis (CFA), and Structural Equation Modeling (SEM). These methods provide a mathematical and coherent model, making the purported relationships and constructs in previous researches more accurate and statistically audited (Hazen et al., 2017; Bressanelli et al., 2019).

The broad purposes of this research is to offer practical recommendations to the relevant policymakers and strategic managers. Thus, this paper provides academic value by offering a methodologically sound and empirically tested study that enhances the academic literature on sustainable practices in the oil and gas industry while supplying tangible global strategies through industry counselors and policymakers about the circular economy (Esposito et al., 2018; Ibn-Mohammed et al., 2021). This approach highlights the emerging awareness of sustainability and environmental conservation in the MENA oil and gas industry through a quantitative model that may create a foundation for future works in this important field (Wang, 2018; Zaleski & Chawla, 2020). The following research questions (RQ) were identified.

RQ1. How effectively does the literature review represent the theoretical constructs influencing circular economy adoption in the MENA oil and gas sector?

This research question focuses on the extent to which previous researches captured the various theoretical models and, in the process, establishes the validity of the tool in measuring the proposed constructs.

RQ2. What is the objective reality of the conceptual map tested with methods of significance, such as Confirmatory Factor Analysis (CFA) and Structural Equation Modeling (SEM)?

This question seeks to validate the constructs and relationships quantitatively, determining their statistical robustness and relevance.

RQ3. To what extent does the empirically developed rational-actor model imply changes to the theoretical framework outlined in the conceptual map?

This question seeks to answer the following question: Does the empirical evidence suggest that method adjustments should be made to match the theoretical components, thereby increasing the model's usefulness

3. Literature review

A plan was developed to find pertinent material in order to do a comprehensive literature study on the adoption of the circular economy. Given the nature of the research topic, it was determined that a keyword search would be the most efficient method of obtaining pertinent results. To find the relevant studies, Scopus was searched using the following keywords in two stages in first stage "circular economy" AND "adoption." keywords were used to get a broad spectrum of literature. In second stage, to better align the review with the energy and resource-intensive nature of the oil and gas sector, the Scopus database was again searched using an expanded set of keywords: ("circular economy" AND "adoption") AND ("oil" OR "gas" OR "energy" OR "decarbonization" OR "carbon reduction" OR "energy efficiency" OR "MENA").

Since the database's creation, only English-language journal articles, review papers, and conference papers were included in searches. A search for a scholarly research was conducted in January 2025. Meeting papers, editorials, books, chapters, proceedings, and other resources were not included in the databases. The selection criterion was based on PRISMA (Figure 1). The first search yielded a total of 2549 items. After narrowing the search to only include peer-reviewed, open-access publications with full-text accessibility, 175 papers in all were gathered, and 110 of them underwent full-text reviews for a thorough literature assessment. Summary of comprehensive Literature review is provided in Appendix A, based on literature review three main antecedents were identified which comes out to be Organizational Inclination, Innovation and External pressure. Table 1 provide the summarized literature review leading to constructs. In second stage of search 31 documents were identified separately focusing on Circular economy adoption in oil and gas.

Although the circular economy (CE) literature is extensive across manufacturing, SMEs, and consumer goods sectors, relatively fewer studies explicitly address energy-intensive and carbon-intensive industries such as oil and gas, particularly within the MENA region (Blomsma & Brennan, 2017). Existing research suggests that, where applied to the oil and gas sector, circular economy strategies are increasingly framed around decarbonization pathways, energy-efficiency improvements, carbon circularity, waste-to-energy processes, and the extended utilization of hydrocarbon assets and infrastructure (Cherepovitsyn, A., & Rutenko, E. (2022); Dua & Jain, 2024; Jain et al., 2020). However, empirical and region-specific evidence remains fragmented, particularly for fossil-fuel-dependent economies in the MENA region, where circular economy adoption is closely intertwined with national energy-transition and net-zero objectives (Al Hosni et al., 2020; Munodawafa & Johl, 2022). Therefore, this review narrows its analytical focus toward studies that explicitly link circular economy adoption with energy systems, fossil fuel industries, and decarbonization objectives, while retaining broader organizational and institutional insights relevant to CE implementation.

Complete Literature review table is provided in Table A1 in Appendix.

Figure 1 – PRISMA statement

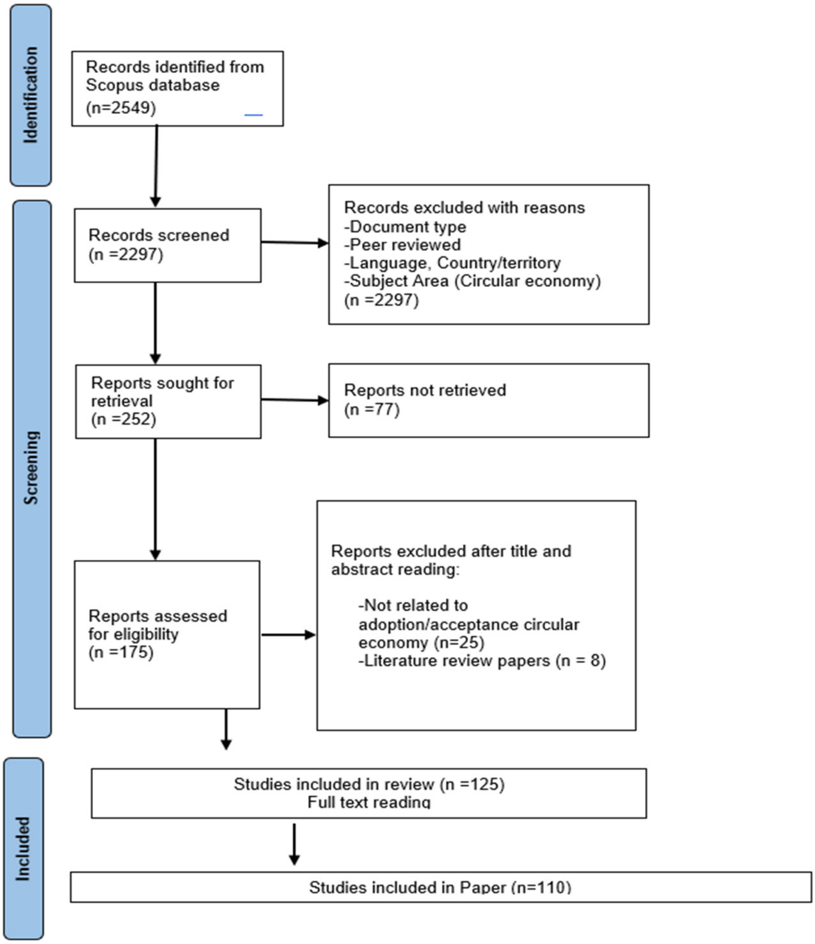


Table 1 – Summarized literature review

S.No	Extracted Construct	Relevant Literature
1	Organizational Inclination	Faisal et al., 2024; Al Rawashdeh et al., 2024; Kirchherr et al, 2018; Agyemang et al., 2019; Tura et al., 2019; Liu & Bai, 2014; Mura et al., 2020; Akinwale, 2024; Ormazabal et al., 2018; Al Rawashdeh et al., 2024; Soni et al., 2023; Castro-Lopez et al., 2023; Assmann et al., 2023; Govindan & Hasanagic, 2018; Al Rawashdeh et al., 2024; Sohal et al., 2022; Kwarteng et al., 2022; Ali et al., 2024; Barros et al., 2021; Barboza et al., 2022; Teixeira, 2025; Sivula, 2021; Bocken et al., 2018.
2	External Pressure	Segarra-Blasco et al., 2024; Castro-Lopez et al., 2023; Ranta et al., 2018; Calzolari et al., 2023; De Jesus & Mendonça, 2018; Jain et al., 2020; Melati et al., 2022; Jakhar et al., 2019; Ting et al., 2024; Moktadir et al., 2018; Schmidt et al., 2021; Nassani et al., 2023; Agyabeng-Mensah et al., 2024; Wang et al., 2022; Rizos et al., 2016.
3	Innovation	Sanchez-Garcia et al., 2024; Matarneh et al., 2024; Laskurain-Iturbe et al., 2021; Despoudi et al., 2023; Luthra et al., 2021; Perotti et al., 2025; Dorrego-Viera et al., 2025; Yin et al., 2025; Jesus et al., 2025; Ai et al., 2024; Linder & Williander, 2017; Geissdoerfer et al., 2023; Pieroni et al., 2021; Lüdeke-Freund et al., 2019; Frishammar & Parida, 2019; de Padua Pieroni et al., 2019; Franco, 2017.

3.1. Organizational Inclination to circular economy adoption

Research is investigating the diverse aspects, including motivators, obstacles, and organizational facilitators, that affect the implementation of Circular Economy practices in SMEs and manufacturing sectors worldwide. Faisal et al. (2024) investigate the impact of individual and organizational factors on CE practices among SMEs in Bangladesh. Analyzing responses from 280 participants, the study highlights a strong correlation between CE adoption and elements such as environmental consciousness, innovation propensity, leadership commitment, and training programs—underscoring the significance of sustainability in SMEs. In a similar context, Akinwale (2024) explores CE adoption among 301 Saudi Arabian MSMEs, revealing high awareness but low actual implementation. Key enabling factors include employee training, financial resources, digital technology, top management commitment, and customer pressure.

Al Rawashdeh et al. (2024) repeatedly emphasize the influence of top management commitment and organizational motivation on CE adoption in the UAE, providing consistent insights for policymakers and stakeholders. Soni et al. (2023) expand this perspective by highlighting the role of distributed leadership in emerging markets. Their study emphasizes power-sharing, delegation, collaborative decision-making, and authority-sharing as trust-building mechanisms that facilitate CE integration and strengthen employee engagement. Barriers to CE adoption remain a recurrent theme. Kirchherr et al. (2018) conducted a large-N study across the EU and identified cultural barriers, consumer interest, and internal company culture as primary obstacles – more influential than technological barriers – indicating a niche discourse among sustainability professionals. This gap between awareness and practice is also addressed by Liu and Bai (2014), who find a significant discrepancy between firms' declared awareness and their actual behavior, recommending strategies to bridge this gap.

From a sector-specific perspective, Agyemang et al. (2019) analyze Pakistan's automobile manufacturing industry and find that profitability, cost reduction, and environmental concerns are major drivers of CE, while ignorance, cost constraints, and lack of expertise function as critical barriers. Tura et al. (2019) provide a broad analytical framework encompassing environmental, economic, social, political, technological, supply chain, and organizational factors to systematically evaluate CE drivers and barriers across industries. In terms of operational practices, Mura et al. (2020) examine how SMEs implement CE principles, focusing on waste management, packaging, supply chain, and product design. Waste management emerged as the most widely adopted practice, reflecting its practicality and accessibility for smaller firms. Ormazabal et al. (2018) add a Spanish perspective, exploring CE potential in SMEs and identifying compliance, corporate image, and cost-saving as prominent motivators, alongside resource reutilization and financial advantages.

Institutional factors and agility are also essential. Castro-Lopez et al. (2023) explore how institutional pressures and organizational agility influence CE strategies and specific circular practices in manufacturing firms, revealing varying effects depending on context. Complementing this, Assmann et al. (2023) identify 54 determinants of circular business model adoption, categorizing them into themes such as culture, regulation, market orientation, strategy, business cases, collaboration, operations, and knowledge – providing granular insights for decision-makers. Policy influence plays a critical enabling role in CE adoption. Govindan and Hasanagic (2018) examine CE implementation in supply chains and argue that governmental tools – laws, risk reduction strategies, and strict governance – offer the most significant positive impacts. Similarly, Ali et al. (2024) assess how government support and organizational culture impact sustainable performance in manufacturing industries, emphasizing the importance of eco-innovation, adherence to policy, and a supportive organizational culture in driving CE and economic growth.

In the Indian context, Sohal et al. (2022) explore challenges and enablers for SMEs transitioning toward a circular economy. Applying socio-technical systems theory, the study underscores practices such as reducing waste, recycling, repurposing, and repairing as central to the shift. Kwarteng et al. (2022) analyze CE business models in Ghana and reveal a positive correlation with improved financial performance, moderated by organizational culture, thus linking circularity with economic value creation. Barros et al. (2021) delve into how CE practices influence diverse business areas, including strategic planning, cost management, supply chain, quality and environmental management, logistics, service operations, and R&D. Their findings advocate internalizing circularity principles across all operational domains for maximum impact. Barboza et al. (2022) focus on the cultural dimensions of CE, identifying 29 organizational values essential to fostering a circular economy culture and stressing the importance of soft factors and human resource management. Sivula (2021) investigates circular business model innovation (CBMI) in Finland's forest industry using empirical case studies from both SMEs and MNCs. The study identifies key enablers and barriers in CBMI processes and provides insights into types and design approaches for circular models. Similarly, Bocken et al. (2018) propose a CE experimentation framework emphasizing iterative processes, collaboration, and continuous learning. Their study highlights how low-risk experimentation can support sustainable transitions in business.

A macro-level comparison by Teixeira (2025) between Portugal and Sweden's CE progress, based on Eurostat data, reveals that Sweden has outperformed Portugal in areas such as workforce training, circular material usage, and consistent green job growth. This supports the alignment of national CE efforts with Sustainable Development Goals (SDGs). Collectively, this body of literature converges on the recognition that CE adoption is shaped by a confluence of individual, organizational, institutional, and policy-related factors. While drivers such as leadership, training, financial incentives, and eco-innovation are repeatedly emphasized, substantial barriers – including cultural inertia, cost concerns, and knowledge gaps – continue to impede progress. Regional and sectoral variances further underline the need for localized, flexible strategies. This comprehensive understanding offers vital direction for stakeholders aiming to accelerate the shift toward circularity, especially within SMEs and manufacturing ecosystems. In energy-intensive industries such as oil and gas, organizational inclination toward circular economy adoption is increasingly shaped by decarbonization commitments, energy-efficiency targets, and net-zero strategies (Jain et al., 2020; Munodawafa & Johl, 2022).

3.2. External pressure for circular economy adoption

Institutional frameworks and External Pressure play a pivotal role in the transition to a circular economy (CE), influencing adoption strategies, performance, and innovation across regions and sectors. Several studies highlight that the regulatory environment, stakeholder expectations, knowledge dissemination, and organizational agility significantly impact the CE trajectory. Segarra-Blasco et al. (2024) emphasize the importance of institutional frameworks in advancing CE, noting that knowledge and environmental spillovers positively influence adoption. They argue that policymakers should account for these factors to enhance CE implementation. In alignment, Castro-Lopez et al. (2023) examine the role of institutional pressures and organizational agility on CE strategies and practices within manufacturing firms. Their findings reveal that such pressures result in varying outcomes depending on organizational context, pointing to the complexity of institutional influence.

Expanding on institutional influence, Ranta et al. (2018) assert that the CE represents a sustainable alternative to the linear model. Their study reveals that recycling is the predominant CE action, often propelled by regulatory measures. However, they stress that diversified institutional support remains essential for comprehensive CE implementation. Similarly, Calzolari et al. (2023) explore the hierarchy of institutional pressures and supply chain integration in driving CE adoption. Their findings suggest that coercive market and regulatory pressures exert a stronger influence compared to other forms of pressure. Jain et al. (2020) delve into the Indian oil and gas sector, investigating how institutional pressures affect CE performance. They find that organizations with higher flexibility are more adept at responding to coercive pressures, demonstrating the moderating role of organizational characteristics. Melati et al. (2022) further contextualize these barriers, reporting that while companies are aware of the long-term economic and environmental benefits of CE, they often lack the necessary technical, financial, knowledge-based, regulatory, and institutional support. Adoption is thus primarily driven by access to information, peer networks, and regulatory incentives.

The role of innovation is central to overcoming institutional and technical obstacles. De Jesus and Mendonça (2018) analyze eco-innovation pathways and propose transformative innovation as a strategy to overcome sustainability-related challenges. They offer practical insights for shaping policy and organizational strategies in favor of CE. Jakhar et al. (2019) also investigate innovation dynamics, finding that stakeholder pressures on Indian manufacturing firms significantly affect CE efforts. Their results show that exploratory innovation supports CE adoption, while exploitative innovation has an inhibitory effect. Agyabeng-Mensah et al. (2024) expand on stakeholder engagement and innovation, exploring the impact of supply chain stakeholder pressure, circular innovation orientation, and environmental information exchange capability in Ghanaian SMEs. Using institutional and resource orchestration perspectives, they reveal that these pressures and capabilities jointly enhance CE supply chain adoption. Ting et al. (2024) present complementary insights from Malaysia's manufacturing sector, identifying motivators such as regulatory frameworks and internal drivers that positively influence CE business model adoption. Conversely, barriers inhibit sustainable production, even when adoption is achieved.

In the context of sustainable manufacturing in developing economies, Moktadir et al. (2018) focus on Bangladesh's leather industries. Their findings highlight the importance of CE-related knowledge in reducing waste and improving resource utilization. This complements findings by Nassani et al. (2023), who analyze the link between circular economy principles (CETP) and zero waste practices (IP), discovering that IP significantly influences CETP and acts as a mediator in shaping sustainable practices. Schmidt et al. (2021) analyze market orientation in relation to CE practices in German SMEs, particularly closed-loop strategies. They find that closed-loop orientation mediates the relationship between market orientation and only two types of CE practices, indicating limited but specific pathways for CE integration. On a broader policy level, Wang et al. (2022) highlight the global shortfall in meeting Paris climate targets, stressing that CE strategies must be accelerated to reduce emissions in key sectors including built environment, transportation, food, and clean energy. Rizos et al. (2016) contribute an early but still-relevant perspective by exploring barriers faced by SMEs in adopting CE models. Their study identifies financial limitations and lack of technical skills as primary constraints. They advocate for policy reforms aimed at fostering consumer preference for green products and enhancing support for SME transitions toward CE. For oil and gas firms, external pressures extend beyond generic regulatory compliance and increasingly stem from climate policies, decarbonization mandates, national energy-transition strategies, and international commitments such as net-zero targets (Dua,2024). These pressures intensify the role of circular economy practices as mechanisms for improving energy efficiency, reducing carbon intensity, and maintaining sectoral legitimacy in fossil-fuel-dependent economies (Al Hosni et al., 2020).

3.3. Innovation in circular economy

The integration of technological innovation and novel business models has emerged as a critical enabler of circular economy (CE) transitions across sectors and geographies. Research highlights that technologies such as artificial intelligence, robotics, additive manufacturing, blockchain, and digital platforms, coupled with innovative circular business models (CBMs) and open innovation strategies, are instrumental in addressing sustainability challenges and operationalizing CE principles. Sanchez-Garcia et al. (2024) explore the role of emerging technologies, specifically blockchain and artificial intelligence, in enhancing CE outcomes. They identify challenges related to supply chain transparency, skill gaps, and regulatory adaptation, and emphasize the need for further research to address these barriers. Extending this line of inquiry, Matarneh et al. (2024) examine how Industry 4.0 capabilities, green supply chain integration, and CE capabilities jointly influence corporate sustainability performance. Their findings underscore the transformative role of such technologies in enhancing CE capabilities and promoting long-term sustainable development.

Similarly, Laskurain-Iturbe et al. (2021) analyze the influence of key technologies – additive manufacturing, AI, and robotics – on core CE strategies such as reducing input consumption, reusing materials, recovery, recycling, and waste reduction. Additive manufacturing and robotics showed the most significant positive impacts, reinforcing the role of technology in facilitating CE goals. However, technology alone is insufficient without adaptive business models that enable CE implementation. Geissdoerfer et al. (2023) focus on business model innovation, comparing start-ups, diversification, transformation, and acquisition pathways. They identify 25 barriers and 10 drivers to CE adoption, particularly noting the influence of market and financial factors on start-ups and diversification models. Lüdeke-Freund et al. (2019) contribute to this domain by analyzing 26 CE business models through a morphological lens, identifying six dominant patterns – repair, maintenance, reuse, refurbishment, recycling, and cascading – that support resource flow closure.

Supporting this, Pieroni et al. (2021) propose sectorial CBM patterns to help manufacturers navigate the complexity and uncertainty associated with CE transitions. Their work provides insights into how pattern variations can guide sector-specific innovation. To facilitate structured transformation, Frishammar and Parida (2019) propose a roadmap for CBM transformation, offering a step-by-step approach to align companies with CE principles for economic, environmental, and social benefits. A complementary tool, the Circular Economy Business Model Configurator, introduced by de Padua Pieroni et al. (2019), is designed to help manufacturers develop tailored CBMs by addressing gaps in existing approaches. Open innovation (OI) is increasingly recognized as a catalyst in translating CE goals into practice. Perotti et al. (2025) examine two inter-organisational collaborative approaches that leverage OI strategies to promote circular business practices across supply chains and ecosystems. Dorrego-Viera et al. (2025) further explore how companies can overcome barriers to developing circular products through OI, emphasizing the importance of sourcing external knowledge, addressing technical issues, and involving consumers and academic institutions in co-creation.

In the Chinese context, Yin et al. (2025) show that OI significantly boosts CE practices, including trade credit provision, green patent accumulation, and enhanced information exchange. Their findings highlight regional disparities, with stronger effects observed in eastern China. Jesus et al. (2025) find that OI practices, particularly collaboration with external actors and co-creation, positively affect CE implementation. They also demonstrate that Industry 4.0 technologies mediate this relationship, although absorptive capacity does not moderate it. Reinforcing the role of national policy, Ai et al. (2024) assess the impact of China's Circular Economy Pilot Policy (CEPP) and find it significantly boosts green patent applications, especially in developed and educated cities with lower resource dependency. Beyond the manufacturing sector, CE has found emerging applications in the food industry. Despoudi et al. (2023) examine CE implementation in Indian SMEs operating in the fruit and vegetable sector. Despite resource scarcity and food waste concerns, adoption remains limited. The study highlights both enablers and barriers, emphasizing the need for tailored strategies in emerging economies.

Franco (2017) analyzes the implementation challenges of CE within the European textile industry. Through case studies, the research identifies crucial factors influencing firms' transition to circular products, including product design and innovation in supplier-buyer relationships. Linder and Williander (2017) explore the uncertainties entrepreneurs face in adopting CBMs, noting that variants like Xerox's remanufactured photocopier model can, in some cases, exacerbate uncertainty rather than mitigate it. However, longitudinal action research provides useful counterexamples of successful transitions. Luthra et al. (2021) synthesize conceptual, theoretical, and empirical insights in their editorial on "Industry 4.0, Cleaner Production and Circular Economy". They emphasize synergies between decision-based tools, policy-guided research, and procedural innovations, contributing valuable knowledge for academia, industry, and society on ethical CE transitions. Within the oil and gas context, innovation-driven circular economy practices increasingly support decarbonization through technologies such as carbon capture and utilization, waste-heat recovery, process optimization, digital energy management, and circular carbon value chains (Cherepovitsyn et al., 2018). These innovations link circular economy adoption directly to measurable improvements in energy efficiency and emissions reduction, reinforcing the role of technological and digital capabilities in enabling circular energy transitions (Munodawafa & Johl, 2022).

3.4. Circular economy adoption in the oil and gas industry

In the oil and gas industry, the circular economy is increasingly conceptualized as a decarbonization-oriented framework that integrates resource efficiency, energy optimization, emissions reduction, and extended asset lifecycles (Cherepovitsyn et al., 2018; Hees et al., 2019; Jain et al., 2020).The context of the oil and gas sector has started to appreciate the importance of the circular economy (CE) principles in minimizing the adverse effects on the environment. This natural transformation will be caused by the scarcity of limited and depleting sources like fossil fuels and the increasing pressure to practice sustainability within this sector. Hees et al. (2019) have predicted that with more catalyst and processing technologies development, it is becoming possible to design and produce more complex, reusable, and value-added petroleum products to address CE and sustainable development objectives. This innovation shows that the industry can innovate and look for efficient ways of saving and reusing resources, as seen here. Additional evidence from Jain et al. (2020) has supported how EMS moderates the relationship between organizational flexibility and institutional concerns for improving CE efforts. Thus, Cherepovitsyn et al. (2018) have pointed to the following analytical and managerial implications for extended underutilized oil and gas resources as one of the sustainable development paths for the sector. They all suggest that the need for change in the industry, which is dictated by reducing hydrocarbon reserves, must be addressed.

Also, other possibilities for implementing CE principles can be observed during the decommissioning or the conversion of the offshore platforms, as indicated by Basile et al. (2021). These processes provide new insights, shift values, and modify behaviors to align with sustainable corporate goals, thus fostering the creation of sustainable business models. This approach addresses environmental concerns and considers the relationships with all stakeholders, proposing a multi-criteria decision-making methodology to evaluate and compare potential decommissioning options. Continued research into and the creation of different technologies for handling waste is also rooted in requiring the enhancement of CE in the oil and gas industry. Paukov et al. (2019) described the low-temperature, environmentally friendly technology for utilizing municipal solid waste to produce liquid products. This process works hand in hand with the other conventional refining processes, does not require an additional and expensive supply of energy, and does not emit any polluting materials; hence, it is a clear example of how CE principles have been implemented.

In Oman, it is widely believed that the adaptation of CE has been deemed necessary because the country needs to diversify its economy beyond the Oil and gas sectors. More recently, Al Hosni et al. (2020) discussed the barriers and found that governmental restrictions and insufficient facilitating legislation are the major hurdles to CE advancement. This study also underscored a strategy to give research the much-needed boost of governmental support by eliminating technical obstacles with adequate and proper regulations supported by trained experts. Munodawafa and Johl (2022) further explained how eco-innovations are necessary to counter the effects of environmental decay, energy vulnerability, and poor air quality. Their research developed an Eco-innovation Capabilities Scale specifically for oil and gas firms, emphasizing the necessity for such innovations to sustain the industry's competitiveness and environmental stewardship. In summary, the integration of circular economy principles in the oil and gas sector is increasingly recognized as essential for sustainable development. Overall, the literature suggests that the contribution of circular economy adoption in oil and gas lies not only in material circularity but also in measurable energy-efficiency gains, reduced carbon intensity, and alignment with national energy-transition and decarbonization agendas, particularly in hydrocarbon-dependent regions such as the MENA region (Al Hosni et al., 2020; Munodawafa & Johl, 2022; Nassani et al., 2023).

4. Theoretical underpinnings

A summarized content available literature of circular economy adoption across various industry with relevant theoretical underpinnings is presented in Table 2. According to Theory of planned behavior by Ajzen (1991), organizational Comprehensive plan for engaging in CE practices depends on their attitudes, perceived control, and subjective norms. This theory is useful in explaining Organization's Behavioral Intention towards CE Adoption, this postulates that organizational intentions are largely influenced by Organizational perceived Behavioral Control toward environmental stewardship (Ajzen, 1991). Moreover, Organizational Culture Theory by Schein (1992) sheds the light on the way Culture become so rooted and endorses or contradicts new practices like CE, which is important for Organization's Work Culture Inclination to CE Adoption as mentioned by Schein (1992). Further, the resources-based view on the beginning of Barney (1991) underlines that only those capabilities in the organization organism, as, for example, then into the waved given organizational capability like managerial support, can be ideally suitable for the realization of sustainable competitive advantages beginning with the CE adoption in line with Organisation's Managerial Inclination to CE Adoption as on principle of forming-near Barney (1991).

It is therefore the innovations in CE that are central to change towards becoming more sustainable. The Diffusion of Innovations Theory (Rogers, 1962) is relevant to Technical Innovations for CE Adoption Some technologies are adopted when they have relative advantage over the older technologies, and are compatible with the existing operations (Rogers, 1962). Another theory that underpins Economical Innovations for CE Adoption includes the Economic Theory of Innovation as envisaged by Schumpeter in 1942 where it pointed out that economical innovations are capable of displacing current business patterns or developing new ones in the circulation of innovations (Schumpeter, 1942). Based on Transaction Cost Economics (TCE) developed by Williamson (1979), a model known as Outsourced Innovations for CE Adoption is used to identify the costs relating to a certain transaction and decide whether to outsource or internalize the practices of CE.

A key factor for influencing CE adoption is often exerted from outside. The Institutional Theory as proposed by DiMaggio and Powell (1983), connects to Government's Pressure for CE Adoption where organizational guidelines and policies, as well as government requirements force organisations to adopt CE practices (DiMaggio & Powell, 1983). Competitive Dynamics Theory which is encompassed in Competitive Forces for CE Adoption whereby competitive forces compel organizations to adopt CE to strengthen or defend their positions in the market (Porter 1985). Closingly, the last theory affecting the analysed factors is Globalization Theory (Giddens, 1990), explaining that global pressures cause organisations to adopt CE practices across borders (Giddens, 1990). Resume of the above discussion is given in Table 3.

5. Empirical validation through quantitative methods

It is the transition from a general idea or speculation to producing evidence to support the idea theory under the developmental process. In the case of quantitative research, Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) contain the statistical tools required for assessing the soundness of measurement of constructs that are included in conceptual maps (Bressanelli et al., 2019).

Another quantitative research technique used in validating the conceptual maps is Structural Equation Modeling (SEM). This method enables the researcher to establish a connection between the latent variables and provides a holistic framework for the factors (Esposito et al., 2018). Combined with these quantitative measures, they enhanced the quality of the research by backing theoretical claims with empirical data, which produced deeper insights into policy and strategic decisions. Moreover, because quantitative research is based on the accumulation of numerical data and computations, such research also allows the creation of models of prediction that, in turn, are quite helpful when it comes to understanding possible impacts of certain factors and being rational when choosing. Qualitative and quantitative methods in social sciences or environmental disciplines can assess the size of a particular phenomenon and the effectiveness of various approaches to a large extent (Creswell & Clark, 2017).

Table 2 – Relevant literature for theoretical underpinning of Circular Economy Adoption

S.No.	Title	Authors	Industry Focus	Theoretical Framework(s)	Key Insights
1	Implementation of Circular Economy in a Developing Economy's Mining Industry Using Institutional Theory: The Case of Namibia	Kahupi et al., 2024	Mining	Institutional Theory	Analyzes adoption of circular economy practices in the mining sector of Namibia through the lens of institutional theory.
2	Circular economy–From review of theories and practices to development of implementation tools	Kalmykova et al., 2018	Various sectors	General Theoretical Review	Provides an extensive review of existing theories and practices related to the circular economy, offering insights into the development of practical implementation tools.
3	Adoption of circular economy practices in small and medium-sized enterprises: Evidence from Europe	Dey et al., 2022	Small and Medium Enterprises (SMEs)	Multiple Theories	Explores the adoption of circular economy practices in European SMEs and identifies key barriers and drivers.
4	Barriers to the adoption of circular economy practices in micro, small and medium enterprises: Instrument development, measurement and validation	Mishra et al., 2022	Micro, Small, and Medium Enterprises (MSMEs)	Barrier Theory	Develops and validates an instrument to measure barriers to circular economy adoption, highlighting the theoretical underpinnings of these barriers.
5	Evaluating the barriers and drivers of adopting circular economy for improving sustainability in the mining industry	Osei et al., 2023	Mining	Sustainability Theories	Identifies and evaluates the barriers and drivers of circular economy adoption in the mining industry, integrating sustainability theories into the analysis.
6	Circular economy applications in the construction industry: A global scan of trends and opportunities	Guerra et al., 2021	Construction	Industry-specific Theoretical Review	Provides a global scan of circular economy adoption in the construction industry, discussing the gap between theory and practice.
7	Barriers to the adoption of digital technologies in a functional circular economy network	Kandasamy et al., 2023	Industry 4.0 & Circular Economy	Technology Adoption Theories	Discusses the barriers to adopting digital technologies in Industry 4.0 and circular economy networks, offering a theoretical perspective on technology adoption.
8	How does circular economy work in industry? Strategies, opportunities, and trends in scholarly literature	Silvério et al., 2023	Various Industries	Conceptual Reference Model	Analyzes strategies and opportunities for circular economy adoption across different industries, providing a conceptual model for industry adoption.
9	Adoption of additive manufacturing for sustainable operations in the era of circular economy: Self-assessment framework with case illustration	Priyadarshini et al., 2022	Additive Manufacturing	Graph Theory Matrix	Studies the challenges of adopting additive manufacturing for circular economy goals using the Graph Theory Matrix approach.

S.No.	Title	Authors	Industry Focus	Theoretical Framework(s)	Key Insights
10	An extended institutional theory perspective on the adoption of circular economy practices: Insights from the seafood industry	Do et al., 2022	Seafood	Institutional Theory	Offers an extended perspective on how institutional theory can explain circular economy adoption in the seafood industry.
11	Circular economy adoption by SMEs in emerging markets: Towards a multilevel conceptual framework	Malik et al., 2022	Small and Medium Enterprises (SMEs)	Multilevel Conceptual Framework	Proposes a multilevel conceptual framework for understanding circular economy adoption in SMEs in emerging markets.
12	How can open innovation contribute to circular economy adoption? Insights from a literature review	Jesus & Jugend, 2023	Various Industries	Actor Network Theory, Industrial Network Theory	Explores the role of open innovation in circular economy adoption, with a focus on network theories.
13	Research gaps and future directions on social value stemming from circular economy practices in agri-food industrial parks: Insights from a systematic literature review	Atanasovska et al., 2022	Agri-food	Social Value Theories	Identifies research gaps in the circular economy practices in agri-food industrial parks, focusing on social value.
14	Mapping the barriers to circular economy adoption in the construction industry: A systematic review, Pareto analysis, and mitigation strategy map	Wuni. 2022	Construction	Barrier Theory, Pareto Analysis	Provides a systematic review of barriers to circular economy adoption in the construction industry, offering a Pareto analysis and mitigation strategies.
15	Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations	Jabbour et al, 2018	Various Industries	Management Theories	Proposes a research agenda and roadmap for integrating Industry 4.0 with circular economy principles, based on management theories.

Table 3 – Theoretical underpinning the Literature review for identified constructs

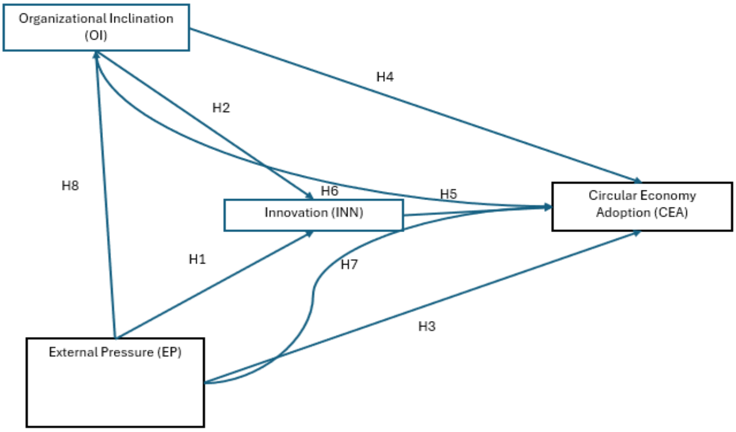
Subtheme	Relevant Theory	Key Reference
Organizational Inclination	Theory of Planned Behavior	Ajzen, 1991
	Organizational Culture Theory	Schein, 1992
	Resource-Based View	Barney, 1991
Innovation	Diffusion of Innovations	Rogers, 1962
	Economic Theory of Innovation	Schumpeter, 1942
	Transaction Cost Economics	Williamson, 1979
External Pressure	Institutional Theory	DiMaggio & Powell, 1983
	Competitive Dynamics Theory	Porter & Advantage, 1985
	Globalization Theory	Giddens & Pierson,1998

6. Methodology

6.1. Research design

The study employed quantitative research that helped in the development of measuring the scale of circular economy potential determinants in the oil and gas industries in the MENA region. This research employed the following five-step process: literature-based map construction, construction of a measurement scale, data collection via survey, analysis of data using SPSS, and presentation of results using a frequency table. This research method corresponds to other research studies carried out by Larimian et al. (2020), Tang et al. (2018), Shah (2019), Fatma et al. (2016), and Cabral & Dhar (2019), who have been able to devise and assess the reliability of the scale of measurements for their research thus establishing the methodological soundness of this study. Theoretical model for empirical analysis is developed based on the literature review and presented in Figure 2.

Figure 2 – Theoretical Framework



Direct relationships

H1: External Pressure (EP) positively influences Innovations (INN) in CE adoption.

H2: Organizational Inclination (OI) positively influences Innovations (INN) for CE adoption.

H3: External Pressure (EP) positively influences Circular Economy Adoption (CEA).

H4: Organizational Inclination (OI) positively influences Circular Economy Adoption (CEA).

H5: Innovations (INN) positively influence Circular Economy Adoption (CEA).

Mediation

H6: The relationship between Organizational Inclination (OI) and Circular Economy Adoption (CEA) is mediated by Innovations (INN).

H7: The relationship between External Pressure (EP) and Circular Economy Adoption (CEA) is mediated by Innovations (INN).

Moderation

H8: The effect of Organizational Inclination (OI) on Circular Economy Adoption (CEA) is moderated by External Pressure (EP), such that the relationship is stronger when EP is high.

Data collection

The second phase entailed developing and disseminating survey instruments, which were questionnaires bearing quantitative measures of the circular economy in the MENA oil and gas sector. For this reason, a digital survey with 38 statements was provided to up to 600 industry workers in Nigeria, Kuwait, Saudi Arabia, UAE, Bahrain, Oman, and Qatar. The survey was electronic, where participants were emailed a brief on the projects, instructions on how to fill out the survey, and a link (https://forms.gle/ptUszP27vuLpsjVM9) to the online survey. To meet the multilingual nature of the region, the questionnaire was translated into both Arabic and English, and further improvements were made based on what was observed during the pilot testing.

Participant sampling

Using convenience sampling, we tried to reach about 600 employees of the oil and gas industries in the MENA region through an online survey that was forwarded via email. This method helped carry out fast data collection from effortlessly conspicuous people. These countries are Kuwait, Saudi Arabia, UAE, Bahrain, Oman, Qatar, and Nigeria because they are primary producers and consumers in the oil and gas industries and play a very instrumental part in the global oil market. The actions of these countries in moving to sustainable practice are very informative in understanding the applicability and implications of circular economy and their results under comparable geopolitical and economic circumstances. Two hundred and thirty responses were received, which yielded a 38 percent response rate. Given the current sampling level, it is believed that the subsequent analyses are adequate; moreover, according to Boomsma (1985), at least 100 observations are required for conducting exploratory and confirmatory factor analysis. The demographic information section, including the age, gender, employment position, and years of experience of the participants, is presented in Table 4 to afford a general view of the participants' demography and their roles in the industry.

Analysis techniques

The third phase of the study tested the applicability of exploratory factor analysis to the data employed by the PCA with Varimax rotation – an orthogonal rotation technique. This step was essential to deciding based on 38 survey statements and determining components or factors without expecting any relationship. Therefore, in the fourth phase, the Confirmatory Factor Analysis (CFA) was undertaken using Analyses of Moments Structures (AMOS 18) to confirm the measurement model and the theoretical relationships postulated in the EFA. This step helped establish the model's fitness in the study and test the reliability and validity of the constructs used. Following the validation of the measurement model through CFA, hypotheses were developed to test the relationships among the identified factors. Structural Equation Modeling (SEM) was then employed to analyze these relationships, facilitating a deeper understanding of the dynamics influencing the adoption of circular economy practices in the oil and gas sector of the MENA region.

Table 4 – Demographic Characteristics of Sample (N=230)

Category	Variable	Number	Percentage (%)
Gender	F	59	25.7
	M	171	74.4
Age	20-30	20	8.7
	30-40	32	13.9
	40-50	121	52.6
	50-60	57	24.8
Location	Bahrain	34	14.8
	Kuwait	88	38.3
	Nigeria	2	0.9
	Oman	36	15.7
	Qatar	10	4.4
	Saudi	52	22.6
	UAE	8	3.5
Experience	0-5	17	7.4
	5-10	16	7.0
	10-15	13	5.7
	15-20	49	21.3
	20-25	65	28.3
	25-30	43	18.7
	30-35	27	11.7

7. Data analysis

7.1. Exploratory Factor Analysis (EFA)

The suitability of the data for exploratory factor analysis was evaluated prior to factor extraction. There were two tests run. First, the Kaiser-Meyer-Olkin (KMO) test assessed the sample's adequacy. Second, Bartlett's sphericity test was run. Using Principal Component Analysis (PCA) with Varimax rotation, a kind of orthogonal rotation, four dimensions were obtained from the 38 statements. Table 5 demonstrates that all four dimensions have eigenvalues above Kaiser's criterion of 1, collectively explaining 69.608 percent of the underlying variation. The factor loadings of the items are shown in Table 5, while the items under examination and their respective values are provided in Table 6.

Table 5 – Rotated Component Matrix^a

	Component			
	1	**2**	**3**	**4**
INN1	0.79			
INN2	0.827			
INN3	0.787			
INN4	0.861			
INN5	0.822			
INN6	0.813			
INN7	0.828			
INN8	0.798			
INN9	0.818			
INN10	0.813			
OI1		0.838		
OI2		0.752		
OI3		0.8		
OI4		0.804		
OI5		0.787		
OI6		0.807		
OI7		0.779		
OI8		0.801		
OI9		0.844		
OI10		0.822		
EP1			0.788	
EP2			0.816	
EP3			0.811	
EP4			0.757	
EP5			0.793	
EP6			0.804	
EP7			0.791	
EP8			0.815	
EP9			0.803	
EP10			0.756	
CEA1				0.803
CEA2				0.784
CEA3				0.83
CEA4				0.802
CEA5				0.79
CEA6				0.837
CEA7				0.831
CEA8				0.817
Eigen Value	7.123	6.939	6.764	5.625
% of Variance	18.745	18.262	17.799	14.802
Cronhbach's Alpha	0.953	0.947	0.950	0.951

Table 6 – Statements for enquiry

Dimension	Statement
OI1	Our organization actively seeks new methods to integrate circular economy (CE) principles.
OI2	There is a strong willingness within our organization to adopt CE practices.
OI3	Our leaders regularly discuss the importance of CE.
OI4	Employees are encouraged to propose ideas related to CE.
OI5	CE is considered a priority in our strategic planning.
OI6	Our organization rewards initiatives that promote CE.
OI7	Training about CE is regularly offered to employees.
OI8	Senior management leads by example in the implementation of CE.
OI9	Our organization's mission statement includes commitments to CE.
OI10	There is a clear policy for adopting CE practices in our operations.
INN1	Our organization invests in new technologies that promote recycling and reuse.
INN2	Innovative technologies are deployed to reduce resource consumption.
INN3	We actively participate in technology forums focused on CE.
INN4	Our technical teams are trained specifically in CE technologies.
INN5	CE practices have reduced costs in our operations.
INN6	Investments in CE have shown a positive return on investment.
INN7	We collaborate with external experts to enhance our CE practices.
INN8	Partnerships with academic institutions have enhanced our CE efforts.
INN9	We use technology to track and reduce our carbon footprint.
INN10	Economic assessments include sustainability performance.
EP1	Government regulations require us to adopt certain CE practices.
EP2	We are influenced by national policies on sustainability.
EP3	Competitive advantages gained through CE are crucial for our success.
EP4	Pressure from market leaders in CE drives our own efforts.
EP5	International trends in CE shape our strategies.
EP6	Global environmental concerns compel us to adopt CE practices.
EP7	We adapt to global market demands for sustainable products.
EP8	International agreements and commitments influence our CE policies.
EP9	Our CE efforts are influenced by international thought leaders.
EP10	Global supply chain pressures necessitate CE adaptations.
CEA1	Our organization has a clear and actionable plan for CE in the oil and gas sector.
CEA2	We have successfully integrated CE principles into our core operations.
CEA3	CE is a critical factor in our competitive strategy.
CEA4	Our investments in CE have significantly reduced environmental impacts.
CEA5	We measure the success of our CE initiatives through specific KPIs.
CEA6	We have achieved noticeable improvements in resource efficiency through CE.
CEA7	Our company has made substantial progress in reducing waste through CE practices.
CEA8	The leadership actively supports and promotes the expansion of CE initiatives within the company.

7.2. Confirmatory Factor Analysis (CFA)

Confirmatory Factor Analysis (CFA) was conducted using AMOS 18.0 to validate the previously proposed correlations in the measurement model (Netemeyer et al., 2003). Prior to determining the accuracy of the measurement model, the adequacy of the model's fit was verified. A model fit index of satisfactory quality was achieved, as shown in Table 7. Although the Chi-square ($\chi^2 = 832.411$, $p < .000$) is significant, which typically suggests a lack of fit, this test is known to be sensitive to large sample sizes, where even small discrepancies can lead to significant results. To address this, the CMIN/DF (Normed Chi-Square) value of 1.263, which is well below the threshold of 2, suggests a good model fit. The Root Mean Square Residual (RMR) value of .113, while not extremely close to zero, remains within an acceptable range, especially when other fit indices are favourable. The Goodness-of-Fit Index (GFI = .847) and Adjusted Goodness-of-Fit Index (AGFI = .828) are slightly below the ideal threshold of 0.90, indicating a marginal but still reasonable fit.

Table 7 – Goodness- and badness-of-fit indices of first-order CFA

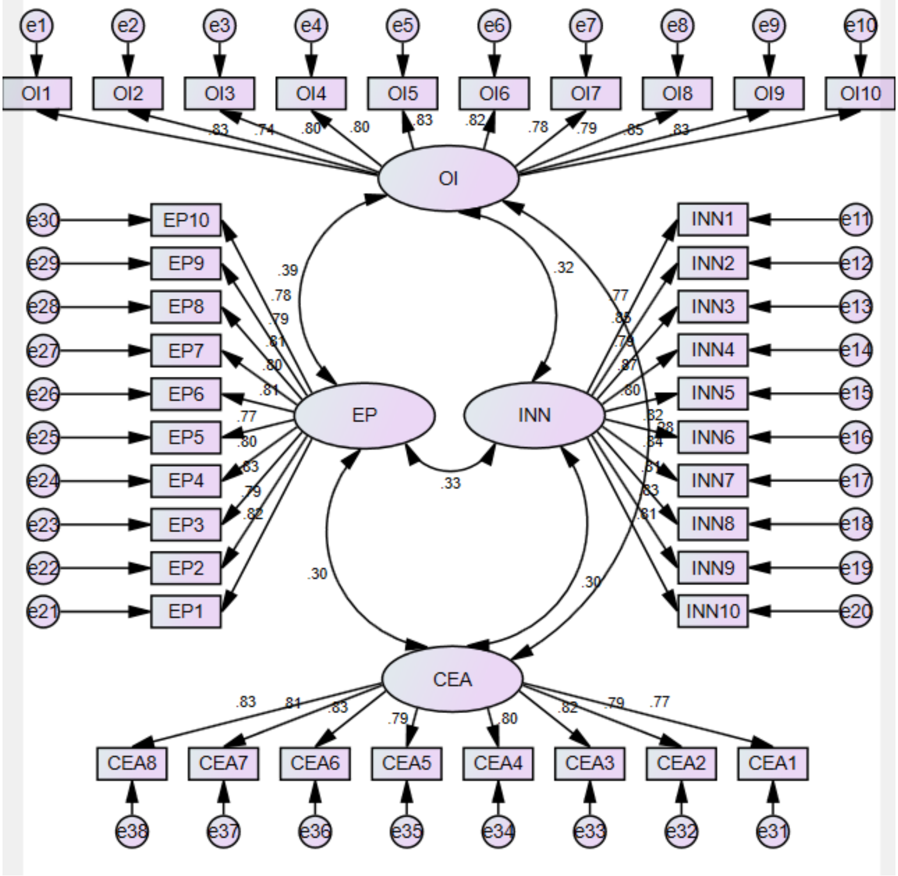
Goodness-of-fit Indices	**Model Values**
Absolute Goodness-of-fit Index	
Chi-Square (CMIN)	832.411
Degree of Freedom (DF) 679	659
Probability Level	0
Normed Chi-Square (CMIN/DF)	1.26314264
Goodness of Fit Index (GFI)	0.847
Absolute Badness-of-fit Index	
Root Mean Square Error of Approximation (RMSEA)	0.034
Incremental Fit Measure	
Adjusted GFI	0.828
Comparative Fit Index (CFI)	0.975
Parsimony Fit Measurement	
Parsimony GFI	0.753
Parsimony CFI	0.914
Parsimony Normed Fit Index	0.834

We assessed both the discriminant and convergent validity of the measurement model depicted in Figure 2. According to Steenkamp and Van Trijp (1991), convergent validity is verified by evaluating how closely each measurement is related to other observations of the same core factor and if the range of statements are consistent on a single factor across the estimation procedure. Convergent validity was assessed using the Hair et al. (2010) technique, which suggests that the average variance extracted (AVE) should be 0.5 or higher and that the composite reliability (CR) should be more than the AVE. According to Hair et al. (2010), discriminant validity is the lack of any association between several constructs, signifying that each notion is unique and distinguished by catching events that the other conceptions do not capture. The Hair et al. (2010) technique, which suggests that the maximum shared variance (MSV) should be less than the average variance extracted (AVE), was used to evaluate discriminant validity. The model's constructs exhibit good dependability and distinct discriminant validity, as seen in Table 8. The results of confirmatory factor analysis (CFA) and exploratory factor analysis (EFA) offer strong evidence for the measurement model's discriminant validity. The CFA model is displayed in Figure 3.

Table 8 – Validity of the measurement model

	CR	AVE	MSV	MaxR(H)	EP	OI	INN	CEA
EP	0.947	0.640	0.154	0.947	**0.800**			
OI	0.950	0.653	0.154	0.951	0.393	**0.808**		
INN	0.953	0.671	0.110	0.954	0.331	0.325	**0.819**	
CEA	0.937	0.650	0.093	0.937	0.298	0.275	0.305	**0.806**

Figure 3 – CFA Model

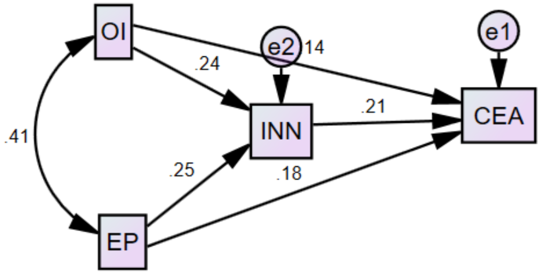


7.3. Hypotheses testing (structural model)

Direct relationship testing

To examine the relationship between organizational inclination (OI), Innovation (INN), External pressure (EP) and Circular Economy Adoption (CEA) in oil and gas industry we used the structural equation modelling using the AMOS path analysis by imputing the Factor Score from CFA using AMOS. As part of hypotheses testing, we tested INN as a mediator and EP and a moderator in relationship between OI and CEA. Figure 4 shows the graphical representation of structural model followed by results.

Figure 4 – Measurement model



The analysis reveals several significant relationships between variables. Organizational inclination (OI) has a positive impact on innovation (INN) with a standardized coefficient of .213, indicating that higher organizational inclination is associated with higher levels of innovation. This relationship is statistically significant, with a p-value less than .001. Similarly, external pressure (EP) positively influences innovation with a coefficient of .221, also significant at the $p < .001$ level, suggesting that increased external pressures lead to greater innovation within organizations.

In terms of circular economy adoption (CEA), organizational inclination contributes positively, though the effect is relatively weaker with a coefficient of .132 and a p-value of .034. This indicates a significant but modest relationship between organizational inclination and the adoption of circular economy practices. External pressure also impacts circular economy adoption, with a coefficient of .165 and a p-value of .007, reinforcing the idea that external pressures can effectively encourage the adoption of these practices. Additionally, innovation plays a crucial role in promoting circular economy adoption, evidenced by a significant coefficient of .213 and a p-value of .002, suggesting that innovations within an organization significantly boost the adoption of circular economy practices. Table 9 shows Direct relationship Hypothesis testing.

Table 9 – Hypothesis testing results

H. No.	Paths	Estimate	S.E.	C.R.	P	Remarks
H1	EP→INN	0.221	.059	3.771	<0.001***	H1 Supported
H2	OI→INN	0.213	0.059	3.583	<0.001***	H2 Supported
H3	EP→CEA	0.165	0.062	2.675	.007**	H3 Supported
H4	OI→CEA	0.132	0.062	2.122	0.034*	H4 Supported
H5	INN→CEA	0.213	0.067	3.153	0.002**	H5 Supported

***<.001, **<.01, *<.05

Mediation testing

The mediation analysis is conducted by treating OI, EP as independent variables, CEA as dependent variable, and INN as mediator. The mediation analysis is based on the analysis of indirect effects based on the guideline by Baron and Kenny (1986) classical approach We performed mediation analysis by using the direct and indirect effects based on bootstrap procedures (2000 samples) and bias-corrected bootstrap confidence interval (90%). The results are provided in the following table.

Table 10 – Mediation Analysis

H. No.	Path	Total Effects	Direct Effects	Indirect Effects	Remarks
H6	OI→INN→CEA	0.212**	0.165*	0.047***	H6 Supported
H7	EP→INN→CEA	0.178**	0.132*	0.045***	H7 Supported

***<.001, **<.01, *<.05

Hypothesis H6, examined the pathway from Organizational Inclination (OI) through Innovation (INN) to Circular Economy Adoption (CEA). The findings revealed a total effect of 0.212, significant at the .01 level, indicating a strong combined influence of direct and mediated paths from OI to CEA. The direct effect of OI on CEA was also significant at the .05 level with a value of 0.165, suggesting that organizational inclination has a substantial independent impact on circular economy adoption. Furthermore, the indirect effect through innovation was highly significant at the .001 level with a value of 0.047, highlighting that a notable portion of OI's impact on CEA is mediated by innovation. These results support H6, confirming that innovation mediates the effect of organizational inclination on circular economy adoption.

Hypothesis H7, focused on the impact of External Pressure (EP) on Circular Economy Adoption (CEA) through the mediator Innovation (INN). This analysis demonstrated a total effect of 0.178, significant at the .01 level, reflecting a robust overall influence of EP on CEA through both direct and mediated routes. The direct effect of EP on CEA was significant at the .05 level, recorded at 0.132, indicating that external pressure directly and significantly promotes circular economy adoption. The indirect effect, significant at the .001 level with a value of 0.045, confirmed that a significant portion of EP's influence on CEA is channeled through innovation. This result lends support to H7, verifying that innovation acts as a critical mediator in the relationship between external pressure and circular economy adoption.

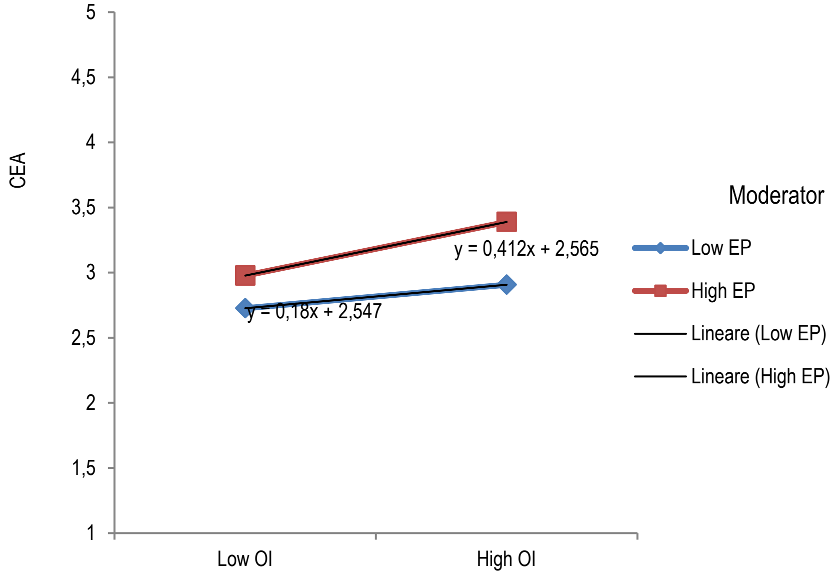
Moderation Testing

The moderation analysis is conducted by treating OI and INN as independent variables, CEA as dependent variable, and EP as moderator variable. The results are calculated by creating interaction terms from standardized score of variables using SPSS. We tested EP as moderator, results indicate interaction term of EP and OI exert positive but insignificant influence on CEA.

Table 11 – Moderation Testing

H. No.	**Interaction**	**Estimate**	**S.E.**	**C.R.**	**P**	**Remarks**
H8	EP*OI→CEA	0.058	0.063	0.926	0.355	Not Supported

Figure 5 – Interaction graph – External pressure (EP) as Moderator between Organizational Inclination (OI) and Circular Economy Adoption (CEA)



8. Results and discussion

The analysis of the structural equation modeling provided robust evidence for significant relationships between organizational inclination (OI), external pressure (EP), innovations (INN), and circular economy adoption (CEA) within the MENA region's oil and gas sector. Specifically, Hypotheses H1 through H5 were validated, confirming that OI and EP significantly drive innovation with standardized coefficients of 0.213 and 0.221, respectively, both significant at less than 0.001. This indicates a strong impetus for innovation influenced by both internal dispositions and external demands. Furthermore, EP and OI were found to have direct, positive impacts on CEA, with coefficients of 0.165 and 0.132 and p-values of 0.007 and 0.034, respectively, underlining a modest yet significant direct relationship between these pressures and the adoption of circular economy practices.

Moreover, innovation emerged as a crucial mediator, significantly bridging the gap between internal and external motivators and the adoption of circular economy principles, as evidenced by a significant coefficient of 0.213 and a p-value of 0.002 for Hypothesis H5. The mediation analysis (H6 and H7) further supported this, revealing robust indirect effects where OI and EP influence CEA significantly through INN, with total effects recorded at 0.212 and 0.178, respectively. Both direct and indirect effects were significant, highlighting innovation's role not merely as a byproduct but as a necessity for integrating sustainable practices effectively within the sector.

Contrastingly, the moderation hypothesis (H8) tested whether external pressure (EP) could intensify the impact of organizational inclination (OI) on circular economy adoption (CEA). The results indicated an insignificant interaction effect ($p = 0.355$), suggesting that while external pressures do shape organizational strategies towards sustainability, they do not significantly amplify the impact of organizational inclination on the adoption of circular economy practices within the studied context.

These findings elucidate the complex interplay of internal motivations and external pressures in fostering sustainable practices within the oil and gas industry. They extend previous research, offering a clearer understanding of the mechanisms through which the sector can progress towards sustainability. The significant roles of innovation and external pressure reflect the industry's dynamic response to global sustainability trends and regulatory pressures, making this study particularly relevant for policymakers and corporate strategists focused on enhancing sustainability initiatives in resource-intensive industries.

9. Implication

The practical implications of this study are significant for the oil and gas sector in the MENA region, emphasizing the critical role of innovation in driving the adoption of circular economy practices. Companies should invest in innovative technologies and processes that facilitate recycling, reduce resource consumption, and improve efficiency. This investment not only aligns with global environmental standards but also positions firms to leverage regulatory pressures as a catalyst for sustainable growth, enhancing competitiveness in an increasingly eco-conscious market.

This research contributes to academic literature by delineating the mediation role of innovation between organizational inclination and external pressures, and their collective impact on circular economy adoption. It provides empirical evidence that supports the theoretical linkages within circular economy frameworks, particularly in resource-intensive industries. Future studies could explore these relationships in different contexts or industries, thereby testing the generalizability of these findings and further refining the theoretical models that govern sustainable business practices.

From a managerial perspective, the findings underscore the necessity for strategic alignment of innovation initiatives with organizational goals towards sustainability. Managers should prioritize fostering an internal culture that actively supports sustainable practices through continuous training, rewards, and leadership engagement. Additionally, understanding the external pressures and effectively utilizing them can enhance the organization's sustainability efforts, turning compliance into opportunity. Managers can leverage these insights to better navigate the complex landscape of regulatory requirements and market expectations.

10. Limitations and future research direction

This study, while insightful, has several limitations that offer avenues for future research. Firstly, the convenience sampling method, although practical, may limit the generalizability of the findings across the broader oil and gas industry in the MENA region. Future studies could employ a stratified random sampling technique to enhance the representativeness of the sample. Additionally, the study's reliance on self-reported data could introduce response bias. Implementing methods such as triangulation, involving secondary data analysis, could provide more robust validation of the findings. Furthermore, this research focused primarily on the MENA region, which, while providing critical insights, also limits the applicability of the findings to other geographical areas with different regulatory and cultural contexts. Subsequent research might explore similar models in different global contexts or compare regions to explore how regional variations influence the adoption of circular economy practices. Lastly, the impact of technological advancements and digital transformation on the adoption of circular economy practices remains an underexplored area that could significantly advance our understanding of sustainable practices in the oil and gas industry.

11. Conclusion

This study successfully explored the influence of organizational inclination and external pressures on the adoption of circular economy practices within the MENA region's oil and gas sector, highlighting the pivotal role of innovation as a mediator. The findings reveal that both internal motivations and external demands robustly drive sustainable practices through innovative processes. These insights not only enrich the academic discourse around sustainable development in resource-intensive industries but also provide practical strategies for companies aiming to enhance their environmental footprint. This research serves as a foundation for further inquiry into sustainable practices across different regions and industries.

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Appendix

Table A1 – Detailed literature review table

Author Name (APA)	Journal Name	Methodology	Identified Constructs	Objective	Findings
Faisal-E-Alam et al. (2024)	*Sustainability*	Survey (n = 280), regression analysis	Environmental consciousness, Innovation propensity, Leadership commitment, Training and development	To examine individual and organizational factors influencing CE implementation in Bangladeshi SMEs	Both individual and organizational factors significantly predict CE adoption.
Al Rawashdeh et al. (2024)	*International Journal of Organizational Analysis*	Survey (n = 438), SEM	Top management commitment, Organisational motivation	To assess impact of leadership and motivation on CE adoption in UAE SMEs	Motivation partially mediates leadership impact; both constructs positively influence CE.
Kirchherr et al. (2018)	*Ecological Economics*	Survey (n = 208), 47 interviews	Cultural, Market, Governmental, Technological barriers	To identify CE barriers in the EU	Cultural and market barriers dominate; tech barriers not significant.
Agyemang et al. (2019)	*Management Decision*	Survey and interviews	Drivers: Profit, Cost reduction, Environment; Barriers: Awareness, Cost, Expertise	To identify CE drivers and barriers in Pakistan's auto industry	Profit and cost savings drive CE; lack of awareness and expertise are key barriers.
Tura et al. (2019)	*Journal of Cleaner Production*	36 interviews, 4 case orgs	Environmental, Economic, Social, Political, Tech, Supply chain, Org. factors	To develop framework of CE drivers and barriers	Practical framework offered; barriers and drivers vary across areas.
Liu & Bai (2014)	*Resources, Conservation and Recycling*	Survey (n = 157), interviews	Awareness vs. behavior gap	To explore awareness and behavior gap in CE in China	Firms aware but not proactive; reasons for gap explored.
Mura et al. (2020)	*Journal of Cleaner Production*	Multi-method: survey, interviews, FGDs	CE practices, Barriers, Enablers, Strategy-performance link	To explore CE actions and perceptions in Italian SMEs	Waste separation common; resource saving rare; CE seen as opportunity.
Akinwale (2024)	*Problems and Perspectives in Management*	Survey (n = 301), logistic regression	Awareness, Leadership, Training, Finance, Tech, Product upgrade	To assess CE awareness and its effect on performance in Saudi MSMEs	Awareness high; adoption low; drivers improve financial performance.
Ormazabal et al. (2018)	*Journal of Cleaner Production*	Survey in Spain, Factor analysis	CE perception: Material, Reuse, Finance; Barriers: Hard, Human-based	To explore CE challenges and potential in Spanish SMEs	Cost-saving focus; barriers categorized for tailored solutions.
Soni et al. (2023)	*Journal of Business Research*	Semi-structured interviews (n = 30)	Distributed leadership, Collaboration, Delegation, Trust	To examine leadership influence on CE in Indian SMEs	Distributed leadership promotes CE adoption through empowerment.
Castro-Lopez et al. (2023)	*Journal of Business Research*	Survey (n = 218)	Institutional pressures, Organizational agility	To test external/internal factors influencing CE at strategic level	Organizational capability drives innovation; external forces affect recycling.
Assmann et al. (2023)	*Business Strategy and the Environment*	Systematic literature review (67 articles)	54 determinants across 8 categories	To review CE business model adoption factors	Comprehensive categorization of drivers and barriers.
Govindan & Hasanagic (2018)	*International Journal of Production Research*	Systematic review	Drivers, Barriers, Practices in supply chain	To map CE trends in supply chains	Government role most impactful for CE success.
Sohal et al. (2022)	*Journal of Business Research*	Qualitative, 4 SME case studies	STS theory, Motivation, Enablers, Strategy	To study CE transition in Indian SMEs	CE practices informal; social and technical factors key.

Author Name (APA)	Journal Name	Methodology	Identified Constructs	Objective	Findings
Kwarteng et al. (2022)	*Social Responsibility Journal*	Survey (n = 617)	CE initiatives, Organizational culture	To assess CE effects on financial performance in Ghana	CE improves financials; culture strengthens positive effect.
Ali et al. (2024)	*Sustainable Futures*	Survey (n = 200), SEM	Gov. support, Org. culture, CE, Eco-innovation	To evaluate mediators between support and sustainable performance	CE and EI mediate effects of support; culture plays direct role.
Barros et al. (2021)	*Cleaner Environmental Systems*	Systematic review	CE impact across 10 business areas	To map CE influence across business functions	Key-impact map developed for strategic integration.
Barboza et al. (2022)	*Revista de Administração de Empresas*	Multi-method, Case study	29 organizational values	To identify values that support CE culture	HRM crucial for nurturing circular values.
Teixeira (2025)	*Merits*	Statistical analysis using Eurostat	SHRM strategies, Green skills, Circular materials	To compare CE workforce strategy in Portugal vs. Sweden	Sweden outperforms; SHRM vital to SDGs.
Sivula (2021)	Unpublished (case study)	Case study of 10 forestry firms	CBMI process, External/internal barriers	To study CE innovation in Finnish forestry	Linear model structures hinder CE innovation.
Bocken et al. (2018)	*Environmental Innovation and Societal Transitions*	Action research, 8 case studies	Business model experimentation	To explore experimentation in CE transitions	Iterative learning and collaboration are key enablers.
Segarra-Blasco et al. (2024)	Business Strategy and the Environment	Merged Flash Eurobarometer surveys (2015, 2017, 2021); Factor analysis; Multivariate probit model	Knowledge spillovers, Environmental spillovers	To analyze institutional factors influencing CE adoption in European SMEs	Both spillovers positively influence CE; environmental impact is increasing over time.
Castro-Lopez et al. (2023)	Journal of Business Research	Survey (n = 218), Model testing	Institutional pressures (mimetic, coercive, social), Organizational agility	To examine how pressures and capabilities affect circular business model and practices	Capabilities impact innovation/production; external pressures affect recycling.
Ranta et al. (2018)	Resources, Conservation and Recycling	Multiple case study across China, US, Europe	Institutional drivers and barriers	To compare CE drivers/barriers across regions	Recycling dominant due to regulation; reuse hindered by cultural norms; China relies more on informal sector.
Calzolari et al. (2023)	Journal of Cleaner Production	Delphi-like panel (30 experts), Qualitative synthesis	Institutional pressures, Supply chain integration	To explore how pressures and integration affect CE practice adoption	Coercive pressures most impactful; integration promotes incremental CE but may hinder radical shifts.
De Jesus & Mendonca (2018)	Ecological Economics	Literature synthesis	Eco-innovation drivers/barriers	To understand factors influencing CE via eco-innovation	Transformative innovation essential; framework aids in designing supportive policy.
Jain et al. (2020)	Business Strategy and the Environment	Survey (n = 280), Moderated mediation analysis	Institutional pressures, EMS, Organizational flexibility	To examine how pressures and flexibility affect CE via EMS	Flexible orgs leverage EMS more effectively to achieve CE goals.
Melati et al. (2022)	Stockholm Environment Institute	Policy brief (qualitative insights)	Drivers: Info access, Consumer/supplier/investor support; Barriers: Finance, Knowledge, Policy	To identify barriers/drivers to CE in enterprises	Firms aware of CE benefits but lack support; knowledge and finance are key barriers.
Jakhar et al. (2019)	Management Decision	Survey, SEM	Stakeholder pressure, Innovation capability (exploratory/exploitative)	To explain CE adoption heterogeneity under stakeholder pressure	Exploratory innovation fosters CE adoption; exploitative hinders it.

Author Name (APA)	Journal Name	Methodology	Identified Constructs	Objective	Findings
Ting et al. (2024)	Environment, Development and Sustainability	Survey (n = 102), PLS-SEM	Motivators, Barriers	To assess CE adoption and impact on sustainable production in Malaysia	Motivators aid CE adoption and sustainability; barriers inhibit both.
Moktadir et al. (2018)	Journal of Cleaner Production	Graph theory, Matrix approach	Drivers of sustainable manufacturing	To prioritize CE drivers in Bangladesh leather sector	CE knowledge key to sustainability; guides strategy formulation.
Schmidt et al. (2021)	Business Strategy and the Environment	Survey (n = 121), SEM	Market orientation, Closed-loop orientation	To study mediation of closed-loop between market and CE practice	Closed-loop orientation mediates market orientationâ€™s impact on CE implementation.
Nassani et al. (2023)	Sustainability	Survey (n = 273), SPSS, SEM	Institutional pressures, Zero waste, Enviropreneurship	To assess mediating/moderating role in CE target performance	Zero waste mediates; enviropreneurship moderates positive CE outcomes.
Agyabeng-Mensah et al. (2024)	Business Strategy and the Environment	Survey (n = 290), PLS-SEM	Stakeholder pressure, EIEC, CIO	To study how pressure drives CSC practices in Ghana SMEs	Pressure drives CSC; EIEC weakens link, CIO enhances it.
Wang et al. (2022)	Not specified	Literature synthesis	CE strategies across sectors	To assess CE as a climate strategy	CE complements decarbonization; most impact from design and consumption-side measures.
Rizos et al. (2016)	Sustainability	Literature review and SME case analysis	Barriers: Finance, Skills; Enablers: Consumer demand, Market value, Policy support	To identify barriers and enablers for CE in SMEs	Barriers remain despite awareness; policy needed to boost enabling conditions.
Sanchez-Garcia et al. (2024)	Environmental Technology & Innovation	Bibliometric analysis	Technologies (AI, blockchain), Resource efficiency, Sustainable models	To explore challenges and opportunities of integrating new tech in CE	New tech enables CE advancement but faces skill gaps and regulatory barriers.
Matarneh et al. (2024)	Environmental Technology & Innovation	Survey (n = 256)	I4.0, Green Supply Chain Integration (GSCI), Sustainable SC Flexibility (SSCF), CE Capabilities	To assess I4.0, GSCI, SSCF impacts on CE capabilities and corporate sustainability	All elements positively influence CE capabilities and sustainability.
Laskurain-Iturbe et al. (2021)	Journal of Cleaner Production	Survey (n = 120), 27 case studies	I4.0 techs (e.g., AI, robotics), CE activities (reduce, reuse, recycle)	To assess I4.0 technologies' influence on CE actions	Additive manufacturing and robotics show strongest CE impact.
Despoudi et al. (2023)	Annals of Operations Research	15 semi-structured interviews, Thematic + cluster analysis	Barriers/enablers to I4.0-CE integration in food SMEs	To explore CE via I4.0 adoption in Indian food SMEs	Identified key resource and capability needs; CE boosts competitiveness.
Luthra et al. (2021)	Journal of Cleaner Production	Editorial review of 21 studies	I4.0, Cleaner Production, CE dimensions	To summarize I4.0-CE-CP theoretical and empirical intersections	Decision-based studies most common; integration promising but underexplored.
Perotti et al. (2025)	Business Ethics, the Environment & Responsibility	Multiple case study (13 orgs)	Open innovation, Circular supply chain/ecosystem	To explore collaborative open innovation for CE	Two OI pathways (supply chain/ecosystem) support circular production.
Dorrego-Viera et al. (2025)	Journal of Innovation & Knowledge	Multiple case study (4 firms)	Open innovation, Technical barriers	To assess how OI supports circular product development	Inbound OI helps overcome barriers; co-creation and university ties vital.
Yin et al. (2025)	Journal of Innovation & Knowledge	Panel data (2003â€“2022), Two-way fixed effects model	Open innovation, CE practices, Green patents	To quantify OIâ€™s effect on CE in Chinese firms	OI boosts CE via patents and collaboration; regional effects matter.

Author Name (APA)	Journal Name	Methodology	Identified Constructs	Objective	Findings
Jesus et al. (2025)	Creativity and Innovation Management	Survey (n = 163), SEM	Open innovation, I4.0, Absorptive capacity	To examine how OI and I4.0 drive CE implementation	OI and I4.0 positively influence CE; absorptive capacity not significant.
Ai et al. (2024)	IEEE Trans. on Engineering Management	Panel data (284 Chinese prefectures)	CE pilot policy, Green innovation	To assess CE policyâ€™s effect on innovation	Policy boosts green patents; stronger in developed and southern cities.
Linder & Williander (2017)	Business Strategy and the Environment	Longitudinal action research	Circular business models, Uncertainty	To identify CE model transformation challenges	Uncertainty hinders CE; capital-intensive models are risky but overcome in some cases.
Geissdoerfer et al. (2023)	Business Strategy and the Environment	Comparative literature review + 21 cases	Drivers/barriers for CBMI types	To categorize CBMI drivers/barriers	Startups driven by markets; incumbents face internal/market/legal barriers.
Pieroni et al. (2021)	Journal of Cleaner Production	Multidimensional scaling of 180 CE firms	Sectoral BM patterns	To reduce uncertainty in sector-specific CBM innovation	Sector patterns help visualize and implement CE models.
Lüdeke-Freund et al. (2019)	Journal of Industrial Ecology	Morphological analysis (26 models)	6 CE business model patterns	To consolidate CE business model types	Six main patterns support CE (e.g., remanufacture, reuse, recycle).
Frishammar & Parida (2019)	California Management Review	Multiple case study (8 firms)	Transformation roadmap	To develop CE model transformation steps	Stepwise roadmap helps incumbents shift to circular models.
de Padua Pieroni et al. (2019)	Proc. of Design Society: Int. Conf. on Engineering Design	Design research methodology	CEBM configurator tool	To support CE business model development	Proposed tool meets practical and conceptual CE model needs.
Franco (2017)	Journal of Cleaner Production	Multiple case studies (Cradle to Cradle firms)	Micro-level CE challenges	To analyze textile firmsâ€™ CE struggles	Collaboration and product design complexity affect CE implementation speed.

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