Special issue – The circular economy as a lever for decarbonization

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

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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.

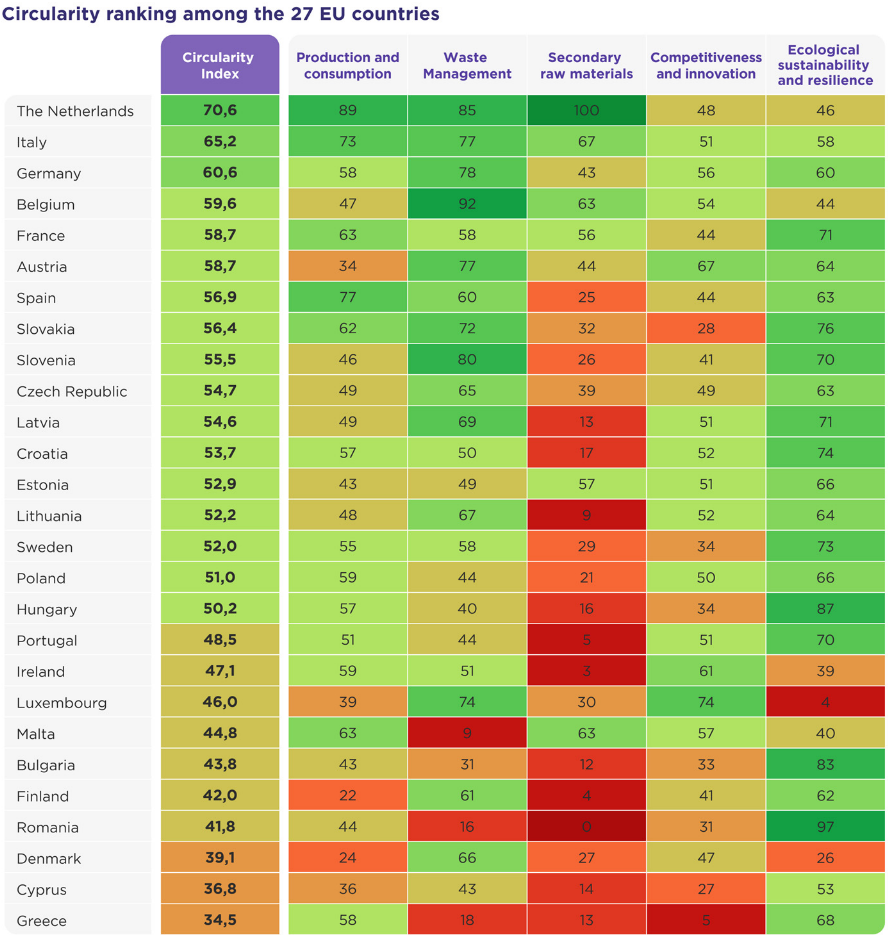
3. The transition towards a more circular economy in EU

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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