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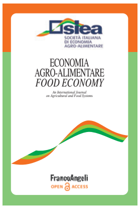

The Hidden Harvest: An Efficiency Indicator for Agricultural Residues Production

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Abstract

This study assesses the efficiency of agricultural residue production across regions within the framework of a circular economy. The objective is to identify the key factors driving performance and to provide insights for optimising resource use in line with the European Green Deal and the Common Agricultural Policy (2023-2030). We have integrated Data Envelopment Analysis (DEA) with Multi-Criteria Decision Analysis (MCDA-DEA), developing a composite efficiency indicator that enables the design of targeted policies based on the main determinants of regional performance. This indicator was applied to the Poland's NUTS-2 regions and incorporates variables such as irrigation, agricultural land, employment, machinery, and crop type, allowing for a more refined evaluation of efficiency. Our approach offers a robust tool to support evidence-based policymaking. The findings underscore Poland's potential to capitalise on significant agricultural residue surpluses for bioenergy and bio-based products, and advocate for tailored policy interventions, integrated evaluation methodologies, and enhanced support to address economic, environmental, and logistical challenges – thereby fostering a resilient circular economy.

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Introduction

Large quantities of agricultural waste are produced daily to meet the demands of a rapidly growing population, with agriculture being a major cause of food loss due to its heavy reliance on the significant residues produced during the cultivation and harvesting stages (Koul *et al.*, 2022).

The issue of agricultural residues is particularly relevant in conventional farming systems, which primarily follow a linear resource consumption model of "produce, use, dispose" and are widely reported for their inherent unsustainability (Alan and Köker, 2023). This has prompted a proactive shift toward implementing a circular economy characterized by closed-loop systems, efficiently decreasing waste and aiming to reduce reliance on external inputs by valorising agricultural products (Carus and Dammer, 2018). Within this paradigm, challenges related to agricultural residues are often discussed using a range of overlapping terms – such as co-products, secondary products, and residues – which are frequently used interchangeably in the literature (Santana-Méridas *et al.*, 2012). This terminology reflects the ambitions of the European Green Deal, launched in 2019, which seeks to address the environmental externalities associated with harmful practices such as open burning – responsible for the release of pollutants and greenhouse gases – or the uncontrolled accumulation of residues in fields, which can impede crop growth, disrupt nutrient cycles, and promote pests and diseases (Pawłowski and Sołtysiak, 2024; Skjærseth, 2021). The overarching objective is to reframe these residues as a valuable resource for the production of renewable fuels, energy, and everyday goods such as bioplastics and other materials, all while avoiding competition with food production (Torres-León *et al.*, 2018; Medina *et al.*, 2015; Bentsen *et al.*, 2014). In a nutshell, this entails transforming agricultural residues from "bad outputs" into "good outputs", shifting from linear to circular economic models in agricultural production and waste management systems to enhance sustainability (Skjærseth, 2021). This shift is strongly underscored by the European Union's Common Agricultural Policy (CAP) for 2023-2030, which includes a 50% reduction in nutrient losses, a 20% reduction in fertilizer usage without compromising soil fertility, and a 50% reduction in chemical pesticide use (Skevas, 2025).

The transition towards a circular economy is based on rethinking the use of agricultural residues, prompting scientific literature to investigate their potential implications. Within this perspective, the generation of residues represents an intrinsic characteristic of crop production, since they emerge unavoidably alongside the principal outputs, both being derived from the same combination of inputs. This co-production implies that residues are not merely incidental, but constitute an inescapable component of the agricultural production process (Scarlat *et al.*, 2019).

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The literature has extensively examined residue generation and proposed indicators for its quantification (Xu *et al.*, 2025; Sarkar *et al.*, 2020) also providing invaluable datasets (Smerald *et al.*, 2023) and methodological frameworks, often employing residue-to-product ratios (Skoutida *et al.*, 2025) and satellite-derived land use data to project theoretical, ecological, and technically recoverable potentials at national and global scales (Daioglou *et al.*, 2016).

Within this framework, the present study aims to assess the efficiency of residue production, treating residue quantities as a proxy for the technical potential of secondary biomass in accordance with circular economy principles, which prioritise recycling and reuse from both environmental and sustainability perspectives (Sherwood, 2020).

Building on this foundation, our study addresses the following research questions:

RQ1: *Which regions, given their quantified levels of residue production, are operating below optimal efficiency?*

RQ2: *Which specific policy or management measures could be implemented to improve their production efficiency?*

To achieve this objective, a multi-stage methodological approach was employed, integrating an input-oriented Data Envelopment Analysis (DEA) with Multi-Criteria Decision Analysis (MCDA). This combined framework supports the development of a more comprehensive efficiency indicator, providing a systemic perspective that highlights the complex interplay of factors influencing secondary biomass production at the regional level.

The indicator was tested using data from Polish regions. Poland was chosen due to its role as a key agricultural producer within the European Union, characterised by a diverse crop structure and strong regional variation in output. Agricultural residues represent a significant opportunity for advancing the country's circular economy agenda; however, this potential is unevenly distributed. Between 1999 and 2018, for example, Poland generated an average annual surplus of 12.5 million tonnes of straw – equivalent to 4.2 million tonnes of oil equivalent – yet the regional distribution of these surpluses varied substantially (Havrysh *et al.*, 2021). Nonetheless, several challenges persist. The environmental targets set by the European Green Deal risk lowering yields, particularly on small farms that lack access to modern technologies. Additional obstacles include economic constraints, fragmented land ownership, and ongoing soil contamination. Moreover, the efficient use of residues continues to be hampered by logistical barriers and limited policy support (Söderholm, 2020).

The paper is structured as follows: Section 1 provides the theoretical background. Section 2 presents the case study. Section 3 outlines the

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methodological approach, while Section 4 shows the results, followed by a discussion in Section 5. Finally, the paper concludes with some final remarks.

1. Background

Agricultural residues encompass food loss and waste arising from both primary farming and industrial food processing, and can broadly be categorised into two groups: those generated on farms at harvest time, and those remaining after the processing of raw agricultural products (Awogbemi, 2022). The first group includes non-edible parts of crops – such as straw, stubble, stalks, leaves, roots, twigs, and pruning waste – typically left in the field after harvesting cereals, vegetables, fruits, and energy crops. The second group, known as agro-industrial residues, comprises by-products like fruit peels, bagasse, sawdust, husks, and pomace produced during food and wood processing. In some classifications, the term "tertiary materials" refers to waste generated after the processing of secondary materials (Santana-Méridas *et al.*, 2012).

Agricultural residues have been traditionally viewed as unwanted waste and typically removed through harmful practices like open-field burning (Prateep Na Talang *et al.*, 2024). This view reflected a linear approach to agriculture, focused on production and quick disposal of what was considered useless. Today, with the growing importance of sustainability, these residues are increasingly recognized as useful resources that can be transformed into valuable products such as biofuels and bioplastics. This change in perspective supports the integration of circular economy principles in agriculture, where waste is minimized, and materials are reused or recycled to create a more sustainable and efficient system (Rao *et al.*, 2024; Kapoor *et al.*, 2020).

In the context of biofuel production from agricultural residues, recent scientific research has focused on their valorisation as a promising feedstock for bioethanol, owing to their high lignocellulosic content and widespread availability (Melendez *et al.*, 2022). Two main pathways have emerged for the reuse of these residues, each with distinct characteristics and advantages. On one hand, biorefineries are capable of producing both liquid biofuels – such as bioethanol and biodiesel – and biochar, a carbon-rich by-product derived from biomass pyrolysis. Biochar has garnered attention for its agronomic benefits: it enhances soil structure, improves water retention, and supports beneficial microbial communities, thereby contributing to long-term soil fertility and carbon sequestration. Land application of biochar safely reduces heavy metals and pesticide residues in the soil, aiding in making agriculture safe and sustainable (Rajput *et al.*, 2022). On the other hand, bioethanol, biodiesel, and biohydrogen, among other liquid biofuels, come from items

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that are left over after farming and treated either through fermentation or chemical methods (Kumar Sarangi *et al.*, 2023). As a renewable and safe option, biofuels help power many aspects of transportation and cut down on dangerous greenhouse gases. Several studies have looked into converting corn stover, rice straw, and bagasse into biogas to combat the current energy shortage (Alengebawy *et al.*, 2024; Guddaraddi *et al.*, 2023). Apart from providing energy, they impact agroecology by adding nutrients to the soil and directing how water flows on the farm. From this perspective, agricultural residues should not be seen as something to throw away, but should be utilized in a circular and bio-based economy (Bentsen *et al.*, 2014).

On the other hand, bioplastics – plastics derived from bio-based polymers – represent a promising avenue for supporting more sustainable plastic life cycles within the broader framework of a circular economy. This approach involves the use of renewable or recycled feedstocks for the production of virgin polymers, the adoption of carbon-neutral energy sources during manufacturing, and the design of products that are reused, recycled, or biodegraded at the end of their life (Rosenboom *et al.*, 2022). Compared to conventional fossil-based plastics, bio-based alternatives often have a smaller carbon footprint and offer favourable material properties. Many bioplastics can be integrated into existing recycling systems and, in certain cases, are capable of biodegrading under controlled or well-defined environmental conditions. The production of bioplastics from agricultural residues – such as straw, bagasse, and other lignocellulosic by-products – represents a particularly promising development (Kapoor *et al.*, 2020). These residues are indeed rich in cellulose, hemicellulose, and lignin, and can be converted into biodegradable polymers like polylactic acid (PLA) and polyhydroxyalkanoates (PHA) through biochemical fermentation or thermochemical conversion processes (Chan *et al.*, 2021), thus minimizing pollution and reducing greenhouse gas emissions (European Bioplastics, 2024). Moreover, the integration of bioplastic production into biorefineries – alongside the aforementioned biofuels – enhances resource efficiency and supports the development of sustainable agricultural systems (Saha *et al.*, 2019). By closing material loops and reducing dependence on fossil resources, bioplastics contribute to climate mitigation strategies and to the long-term sustainability of rural economies.

Although agricultural residues represent valuable feedstocks for bioenergy and bioplastic production, their practical utilisation is constrained by several limitations, including limited scalability and underdeveloped waste management infrastructure for compostable or biodegradable materials (Velasco-Muñoz *et al.*, 2022), as well as the high costs of collection, processing, and transportation, which disproportionately affect regions characterised by underdeveloped infrastructure and fragmented land holdings

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(Gontard *et al.*, 2018; Guddaraddi *et al.*, 2023). Furthermore, complex logistics, shaped by the distance to processing facilities and the harvesting systems employed, pose significant environmental challenges (Suardi *et al.*, 2019).

From a social standpoint, the advantages of circular economy initiatives in agricultural residue management are not intrinsic. Although processors may benefit from intensive utilisation and smallholder farmers could access new markets, inequalities in access to technology, training, and capital can hinder equitable participation (Härri et al,2023).

Overcoming these barriers will require coordinated efforts in policy support, technological innovation, and market development. Accordingly, this study enables the identification of regions operating below optimal efficiency, as well as the formulation of targeted policy and management recommendations, thereby providing evidence-based insights to support policymakers and promote territorial development.

2. Case study

Poland represents a key agricultural country within the EU, accounting for approximately 43% of its total agricultural output from plant production, and ranking second for arable land area (Sawinska *et al.*, 2020). Agricultural sector is a cornerstone of its economy, contributing significantly to the Polish gross value added, with agriculture, forestry, and fisheries being twice the EU average (European Commission, 2022). The country's diverse farm structure supports the cultivation of cereals such as wheat, triticale, rye, barley, and maize, alongside non-cereal crops like oilseed rape, sugar beet, and potatoes. The Wielkopolska Voivodeship, recognized as Poland's leading agricultural region, exemplifies high productivity due to its fertile soils and advanced farming practices (Pawłowski and Sołtysiak, 2024). However, regional disparities exist, with areas like Dolnośląskie and Lubelskie also showing significant crop yields, particularly in wheat and triticale, which account for nearly 50% of the national grain harvest (Havrysh *et al.*, 2021) (Figure 1).

Despite its strengths, Polish agriculture faces challenges in aligning with the European Green Deal's environmental objectives, which mandate a 50% reduction in plant protection products and a 20% reduction in fertilization. These requirements could reduce crop yields, particularly for small and medium-sized farms that lack the financial capacity to adopt precision agriculture technologies. Additionally, the sector struggles with structural issues, including fragmented land ownership and capital shortages, which limit modernization efforts (Pawłowski and Sołtysiak, 2024).

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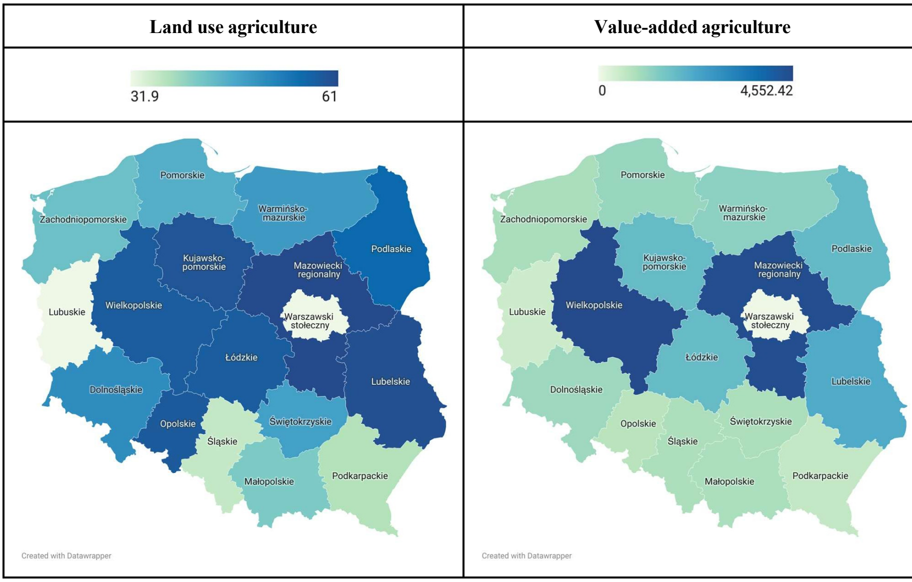
Figure 1 - Regional disparities in agricultural land use and value-added in Poland



Agricultural residues, including straw, stover, stalks, and animal husbandry waste, represent a significant resource for bioenergy production in Poland. Between 1999 and 2018, Poland generated an average annual surplus of 12.5 million tonnes of straw, corresponding to 4.2 million tonnes of oil, with notable surpluses in Dolnośląskie, Kujawsko-Pomorskie, Lubelskie, Wielkopolskie, and Zachodniopomorskie voivodeships (Havrysh *et al.*, 2021). Straw is the second most important biofuel in Poland after wood, capable of covering up to 15% of national power generation (Zabed *et al.*, 2017). Additionally, residues from the agri-food industry, such as maize silage, slurry, and distillery waste, are increasingly used as substrates for biogas production (Adamski *et al.*, 2009).

The management of these residues is critical to reducing environmental impacts. Inadequate handling of organic waste can lead to methane emissions from decomposing manure or soil degradation if residues are not returned to fields. However, the use of residues for bioenergy, such as co-firing straw with fossil fuels or anaerobic digestion for biogas, offers a sustainable alternative. For instance, in the Braniewo district of Warmia and Mazury, approximately 41,531 tonnes of straw are available annually for energy purposes, equivalent to 24,088 tonnes of coal (Marks-Bielska *et al.*, 2019). Despite this potential, logistical challenges, such as the lack of integrated methodologies

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for assessing residue availability and spatial distribution, hinder efficient utilization.

Polish agriculture faces several challenges that impact residues management and overall sustainability. Economic factors are a primary concern, particularly for organic farming, where low yields and high production risks deter farmers. A study by Łuczka and Kalinowski (2020) revealed that over 80% perceive organic production as highly risky during the conversion period, with nearly 60% maintaining this view post-conversion, largely due to insufficient financial support. The European Green Deal's stringent environmental regulations exacerbate these concerns, as reduced pesticide and fertiliser use may lower productivity, particularly for smaller farms unable to invest in modern technologies (Pawłowski and Sołtysiak, 2024).

Environmental challenges also persist. Long-term studies in Bałcyny, Poland, detected DDT residues in soils five decades after its last use, highlighting the persistence of chemical contaminants (Łuczka and Kalinowski, 2020). Furthermore, the management of agricultural residues must balance energy production with soil conservation needs, as excessive removal of straw can deplete soil organic matter (Marks-Bielska, 2019). The lack of consumer awareness and limited policy support for sustainable practices further complicates the adoption of residue-based bioenergy systems (Bednarek *et al.*, 2023).

The aforementioned regional differences in residues availability and agricultural practices offer both challenges and opportunities. Beyond simple disparities in yields, Polish regions also display distinct patterns of productive specialisation. For instance, Wielkopolskie is strongly oriented toward cereals and oilseed rape, supported by mechanisation and large-scale farms. Lubelskie combines high wheat and triticale output with significant sugar beet cultivation, while Dolnośląskie maintains an important role in grain production, particularly triticale (Havrysh *et al.*, 2021). By contrast, Podlaskie and Podkarpackie are more specialised in livestock, generating larger quantities of manure and slurry residues rather than crop-based by-products. Other regions, such as Kujawsko-Pomorskie and Zachodniopomorskie, are characterised by significant straw surpluses, reflecting their cereal-oriented production systems (Stanek *et al.*, 2018). This productive specialisation shapes both the type and the volume of residues available, reinforcing the idea that residue management strategies must be tailored not only to economic and infrastructural disparities but also to regional agricultural profiles. Voivodeships like Wielkopolskie and Lubelskie, with high crop yields, have significant residue surpluses, making them ideal for biomass-based power generation (Havrysh *et al.*, 2021). In contrast, smaller farms in less productive regions struggle with the costs of residue collection and

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transport, limiting their participation in bioenergy markets (Jezierska-Thöle *et al.*, 2016). Community-Supported Agriculture (CSA) models, with 13 active farms reaching 1,200 people as of 2023-2024, present a promising avenue for sustainable residue management by fostering local networks and reducing waste (Onyszkiewicz, 2024).

However, economic risks, environmental regulations, and logistical barriers continue to challenge the efficient management of agricultural residues. To fully unlock the potential of Poland's "hidden harvest", it is therefore essential to gain a deeper understanding of regional disparities in residue generation efficiency. These differences are shaped by a complex interplay of agronomic, infrastructural, and socio-economic factors which may vary significantly across regions.

Studying these regional dynamics is crucial for designing place-based policy interventions that reflect local realities and enhance the contribution of agricultural residues to a sustainable and resilient agri-food system. Regional disparities, in addition to the agronomic and structural factors mentioned above, are further reinforced by socio-economic conditions. In Poland, such disparities significantly influence the efficiency of agricultural residue management, reflecting economic and educational inequalities across Poland regions. Wealthier regions, such as Warszawski stołeczny (EUR 28,900 GDP per capita) and Dolnośląskie (EUR 15,600), stand in sharp contrast to less affluent regions like Lubelskie (EUR 10,100) and Podkarpackie (EUR 10,200). This economic divide enables more prosperous regions to invest in advanced technologies, including bioenergy generation from crop residues, while poorer areas face financial constraints, exacerbated by fragmented land ownership. Educational inequalities add to these challenges: in Podkarpackie (6.8%) and Lubelskie (6.5%), a higher share of the population has only primary education, compared with just 2.5% in Warszawski stołeczny. Such disparities limit the capacity of farmers in less-educated regions to adopt technical innovations. Together with marked differences in regional unemployment rates, these economic and educational gaps help explain the uneven efficiency of residue management across the country. Affluent and better-educated regions such as Wielkopolskie benefit from economies of scale and a skilled workforce, while less developed and more fragmented regions like Lubelskie face persistent logistical and technical barriers.

Poland's decentralised governance structure offers a framework for addressing these disparities through targeted regional policies. This autonomy allows wealthier regions such as Wielkopolskie to expand residue management initiatives, including the development of biogas plants, while less affluent regions such as Lubelskie and Podkarpackie can draw on EU funds to support small-scale farmers and mitigate land fragmentation (Zgut, 2022). By combining regional autonomy with EU funding, regions are able

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to design tailored strategies, such as subsidies for technology adoption and training programmes aimed at enhancing technical skills in less-educated areas, in line with the EU's bioeconomy objectives (Ronzon and M'Barek, 2018). Such a decentralised approach ensures that policies are responsive to regional economic and educational contexts, thereby promoting more sustainable agricultural residue management across Poland.

3. Materials and methods

To answer our research question, we started by investigating whether the efficient production of agricultural residues in Poland results from economies of scale or from inefficient input use. For this purpose, we applied DEA (Charnes *et al.*, 1978), a non-parametric method used to assess the efficiency of production across decision-making units (DMUs), in this case, the Polish regions.

An important advantage of DEA is that it does not require a predefined production function, making it particularly suitable for identifying the specific sources of inefficiency across regions. Although DEA has been increasingly employed in recent years to develop indicators for assessing efficiency in agriculture (see, for instance, Wang *et al.*, 2025; Fusco *et al.*, 2023; Toma *et al.*, 2017), to the best of our knowledge, it has not yet been applied to evaluate the efficiency of agricultural residue production, treating residues as a good output within a circular economy perspective. The analysis considered land, labour, and capital as inputs, and agricultural residues as the output. To determine whether inefficiencies arose from scale or from poor input allocation, we considered both constant returns to scale (CRS) and variable returns to scale (VRS) (Banker *et al.*, 1984; Charnes *et al.*, 1978) models. Under CRS, all DMUs are assumed to operate at an optimal scale, whereas VRS allows efficiency to be separated into pure technical efficiency and scale efficiency components.

DEA can follow either an input-oriented or output-oriented approach. The first aims to minimize inputs while maintaining output levels, whereas the second focuses on maximizing outputs without increasing inputs. Given the aims of our study, we adopted an input-oriented approach, as it aligns more closely with sustainable agriculture practices. This orientation promotes indeed the efficient use of resources, helps reduce environmental impact, and supports strategies for agricultural waste valorisation (Zhang *et al.*, 2008).

It is important to elucidate the rationale for selecting the constant returns to scale (CRS-DEA), variable returns to scale (VRS-DEA), and multi-criteria decision analysis (MCDA-DEA) models, as well as their specific contributions to assessing the efficiency of agricultural residue production

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in Polish regions. The CRS-DEA model assumes that all decision-making units operate at an optimal scale, providing a measure of overall technical efficiency (Charnes *et al.*, 1978). This model is valuable for benchmarking regions against an ideal production frontier, capturing inefficiencies arising from both suboptimal input use and scale effects (Coelli *et al.*, 2005). However, the CRS assumption may not fully reflect the diverse operational scales of Polish regions, where agricultural practices vary due to differences in land availability, labour, and capital endowments (Banker *et al.*, 1984).

This limitation necessitated the inclusion of the VRS-DEA model. The VRS-DEA model relaxes the CRS assumption, enabling the decomposition of efficiency into pure technical efficiency (PTE) and ES (Banker *et al.*, 1984). PTE measures the efficiency of input utilization, while ES indicates whether a region operates at an optimal scale. By calculating ES, we can pinpoint whether inefficiencies stem from poor input allocation or non- optimal scale (Cook, 2001). This distinction is critical for formulating targeted policy recommendations, as it differentiates between inefficiencies addressable through resource management improvements and those requiring scale adjustments (Fare *et al.*, 1994).

While CRS-DEA and VRS-DEA provide robust efficiency assessments, their flexibility in allowing DMUs to select individual weights can lead to multiple regions being classified as fully efficient ($\theta = 1$), reducing discriminatory power (Doyle and Green, 1994). To address this, we employed the MCDA-DEA model as a complementary approach. Unlike traditional DEA, MCDA-DEA uses a common set of weights across all DMUs, ensuring a fairer and more comparable evaluation (Hatefi & Torabi, 2010). By generating a composite indicator, MCDA-DEA enhances discriminatory power, reduces the number of fully efficient units, and provides a ranking of regions based on shared efficiency criteria (Gomes and Lins, 2008). This is particularly relevant in a circular economy context, where consistent efficiency metrics support resource allocation and waste valorisation strategies (Dyckhoff and Allen, 2001). The integration of CRS-DEA, VRS-DEA, and MCDA-DEA is justified by their complementary roles. CRS-DEA offers a baseline for overall efficiency, VRS-DEA disaggregates inefficiencies into technical and scale components, and MCDA-DEA provides a discriminative and comparable ranking of regions. Together, these models ensure a comprehensive analysis that informs both the sources of inefficiency and the prioritization of policy interventions for sustainable agricultural residue production.

Let us consider a set of n DMUs, each employing the same types of inputs to generate the same types of outputs. Let y_{ik} represent the quantity of output k produced by DMU i, and x_{ik} the quantity of input k used by DMU i. The weights assigned to each output and input – u_{ik} and v_{ik}, respectively – are

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endogenously determined by the model and may vary across DMUs. The technical efficiency of DMU i under the CRS assumption is denoted by θ_i. . The input-oriented CRS-DEA model can therefore be expressed as follows:

$$\begin{cases} \max \theta_i = \sum_{k=1}^{m} u_{ik} y_{ik} \\ s.t. \\ \frac{\sum_{k=1}^{m} u_{ik} y_{ik}}{\sum_{k=1}^{m} v_{ik} x_{ik}} \leq 1, i = 1, 2, \ldots, n \\ u_{ik} \geq 0, k = 1, 2, \ldots, m \\ v_{ik} \geq 0, k = 1, 2, \ldots, m \end{cases} \quad [1]$$

Model [1] determines the highest possible performance score for entity i, generating a set of efficiency scores θ_1, θ_2, …, θ_n by solving the model iteratively for each decision-making unit.

As before, let y_{ik} and x_{ik} represent the outputs and inputs, respectively. Now define w_{ik} as the variable weights assigned endogenously by the model to the inputs and outputs of each entity; x_{dk} as the input vector for the evaluated DMU *d*; y_d as its output vector; and θ_i as the technical efficiency score of DMU *i* under VRS. The input-oriented VRS-DEA model for a single DMU can therefore be expressed as follows:

$$\begin{cases} \min \theta_i = \sum_{k=1}^{m} u_{ik} y_{ik} \\ s.t. \\ \sum_{k=1}^{m} w_{ik} x_{ik} \leq \theta_d x_{dk}, i = 1, 2, \ldots \\ \sum_{k=1}^{m} w_{ik} y_{ik} \geq y_d, i = 1, 2, \ldots, n \\ \sum_{k=1}^{m} w_i = 1 \\ w_k \geq 0, k = 1, 2, \ldots, m \end{cases} \quad [2]$$

The constraint $\sum_{k=1}^{m} w_i = 1$ introduces the VRS assumption, which distinguishes the VRS model from the CRS one. This condition allows for the identification of cases where DMUs operate under non-constant returns to scale. Alongside Models [1] and [2], we also calculated scale efficiency (SE),

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defined as the ratio of CRS to VRS efficiency, to assess the extent to which deviations from optimal scale affect overall performance.

Models [1] and [2] can sometimes identify multiple entities as equally efficient, thereby failing to single out the top performer. To enhance the robustness of our results, we complemented the DEA analysis with a MCDA-DEA. Unlike the CRS-DEA, the MCDA-DEA derives a common set of weights simultaneously for all entities, preventing any individual entity from biasing the evaluation by selecting weights in its own favour. This method provides a fairer assessment based on composite indicators calculated using shared weights. Let I_{ik} denote the value of each sub-indicator k (including both inputs and outputs) for entity i, w_{ij} the weights assigned to these sub-indicators, and di the deviation of entity i's efficiency from unity during evaluation. The MCDA-DEA model is then expressed as follows:

$$\begin{cases} \min M \\ M - d_i \geq 0, i = 1,2,\dots,n \\ s.t. \\ \sum_{k=1}^{m} w_{ik} I_{ik} + d_i = 1 \\ w_{ik} \geq \varepsilon, k = 1,2,\dots,m \\ d_i \geq 0, i = 1,2,\dots,n \end{cases} \qquad [3]$$

The constraints $M - d_i \geq 0$, $6i$ assure that $M = max\ \{d_i, i = 1, 2, \dots, m\}$.

Using this model, the composite indicator for the *i-th* entity is calculated as $CI_i = 1 - d_i$, $6i$. As highlighted by Hatefi and Torabi (2010), model [3] presents several advantages compared to models [1] and [2]. Notably, because all common weights are constrained to be strictly positive (i.e., $w_{ik} \geq s$), the model incorporates the contribution of all sub-indicators when assessing production efficiency. Furthermore, model [3] offers greater discriminatory power by reducing the number of entities classified as fully efficient with a composite indicator equal to 1.

In models [1], [2], and [3], y_{ik} denotes the quantity of agricultural residues in each region, while x_{ik} refers to the percentage of land use, the number of agricultural machineries employed, and the percentage of agricultural labour, respectively, for each region.

We created radar charts for each Polish region to draw policy conclusions from our findings. These visual tools allowed us to clearly identify, for each region, the variables that were optimised – represented near the outer rim of the chart – while also highlighting those requiring further improvement, which appeared closer to the centre.

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The empirical analysis draws on data from two main sources: Eurostat, which provides socio-economic, demographic, and infrastructural indicators, and the S2BIOM Tool, which supplies information on resource endowments. The dataset refers to the year 2020 and covers all 17 NUTS-2 regions of Poland. Table 1 offers a detailed description of the variables considered, alongside their descriptive statistics

Table 1 - Description of variables used and descriptive statistics

Variable	**Description**	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Agr res	Agricultural residues (ton/km^2)	17	70.77	39.86	.05	148.50
Agr land	% land use agriculture	17	48.43	10.33	31.9	61
Low edu	% low educated people (less than primary and secondary)	17	7.28	2.36	3.2	13.5
Empl agr	% workers in agriculture	17	10.38	5.68	2.22	19.33
Road	km/1000 km^2	11	8.82	4.64	1	19
Mach	No. of machinery	17	11.79	4.81	7.59	24.87
Colture type	% of high-residue crops in total production	17	14.15	4.99	7.01	25.45
Irrigation	Number of farms by size of irrigated area/km^2	15	4.52	2.61	1.30	9.42

4. Results

Figure 2 illustrates the efficiency of agricultural residues across Polish regions using DEA and MCDA-DEA, in map form.

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Figure 2 - Results of the DEA and MCDA-DEA

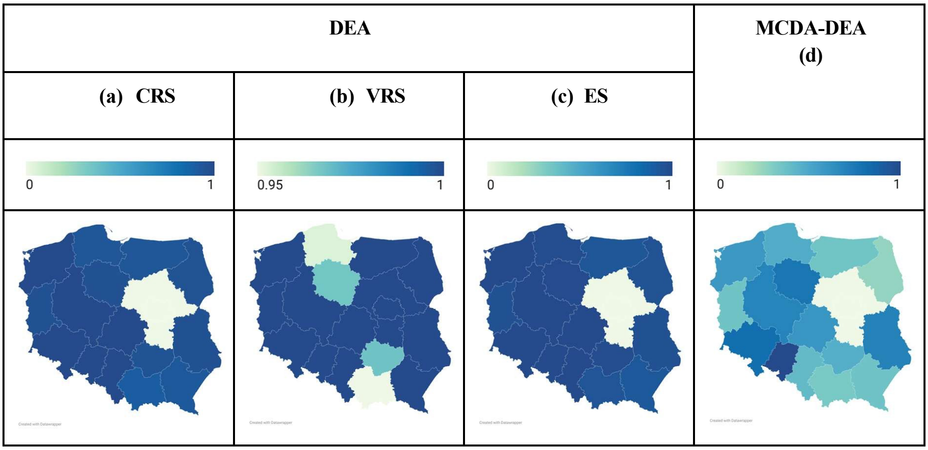

Table 2 - Results of the DEA and MCDA-DEA

NUTS code	Label	CRS	VRS	ES	MCDA-DEA
PL21	Małopolskie	0,89491916	0,9513711	0,94066256	0,32494081
PL22	Śląskie	1	1	1	0,4044935
PL41	Wielkopolskie	1	1	1	0,68664387
PL42	Zachodniopomorskie	1	1	1	0,57772987
PL43	Lubuskie	0,96428245	1	0,96428245	0,35328419
PL51	DolnoŚląskie	1	1	1	0,80163992
PL52	Opolskie	1	1	1	1
PL61	Kujawsko-pomorskie	0,9604584	0,9679462	0,99226421	0,76227864
PL62	Warmińsko-mazurskie	0,93581212	1	0,93581212	0,34794989
PL63	Pomorskie	0,93635035	0,954132	0,98136359	0,47500998
PL71	Łódzkie	1	1	1	0,5893226
PL72	Świętokrzyskie	0,95230204	0,968658	0,98311478	0,46104932
PL81	Lubelskie	0,96404308	1	0,96404308	0,69957392
PL82	Podkarpackie	0,92468512	1	0,92468512	0,35743935
PL84	Podlaskie	0,95554751	1	0,95554751	0,25992817
PL91	Warszawski stołeczny	0,0003254	1	0,0003254	0,00033671
PL92	Mazowiecki regionalny	0,00024248	1	0,00024248	0,00033671

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The CRS-DEA map shows a predominantly dark blue coloration, indicating high efficiency scores, with a notable white area in the central-east, likely Warmia-Mazury or Podlaskie, suggesting the lowest efficiency. The VRS-DEA map displays a similar dark blue pattern; however, it features a broader light green area in the centre – particularly in regions like Kujawsko-Pomorskie and Wielkopolskie – indicating a decline in efficiency when accounting for scale flexibility. The ES map confirms the results of CRS-DEA. The MCDA-DEA map displays varying efficiency levels, suggesting a more refined assessment when multiple criteria are integrated.

Figure 3 displays radar plots grouped into four clusters based on similar patterns, with respect to five key variables, thus illustrating the distinctive characteristics of the classified regions:

- irrigation: number of farms by size of irrigated area/km^2;
- agricultural land: percentage of land use agriculture;
- agricultural employment: percentage of workers in agriculture;
- machinery: number of machineries employed in agriculture;
- crop type: percentage of high-residue crops in total production.

The results offer a comprehensive assessment of inefficiencies across clusters, providing an efficiency indicator that yields important insights into the performance of agricultural systems and underscores the need for region-specific policy interventions aimed at improving agricultural residue production.

Agricultural land consistently emerges as the most efficient variable across all clusters, representing the least problematic input. This suggests that land allocation and utilization are relatively optimized, requiring only marginal adjustments in selected regions. By contrast, machinery and crop type display widespread inefficiencies, signalling persistent challenges in mechanization and crop selection that constrain residues production. Irrigation appears to be a major bottleneck, particularly in clusters III and IV, indicating notable deficiencies in water management infrastructure or practices. Agricultural employment exhibits variable performance: cluster II demonstrates the most significant inefficiency, pointing to structural problems in labour allocation or workforce skills that warrant immediate policy attention. These patterns reveal substantial heterogeneity in inefficiencies across clusters, underscoring the limitations of uniform policy approaches.

In cluster I, pervasive inefficiencies are observed in irrigation, agricultural employment, machinery, and crop type – necessitating a comprehensive policy response. Cluster II is marked by pronounced inefficiency in agricultural employment, coupled with low performance in irrigation, crop type, and machinery; here, labour and equipment constraints constitute the primary barriers. In cluster III, irrigation is the most critical issue, followed by agricultural employment, machinery, and crop type, reflecting challenges

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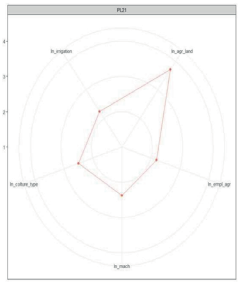
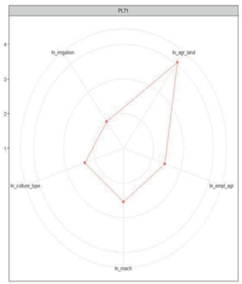
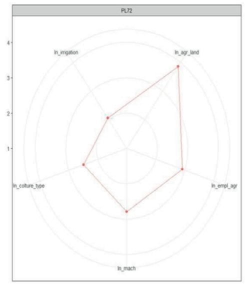
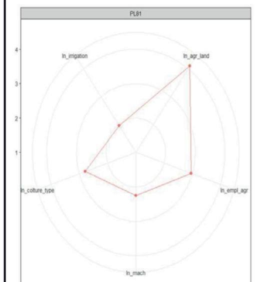
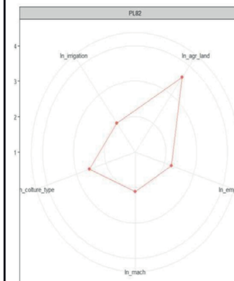
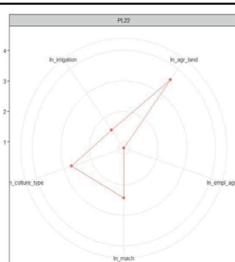
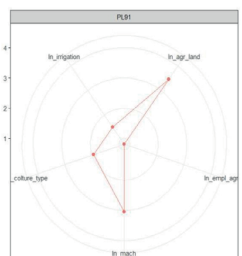
Figure 3 - Radar plots

Cluster I	**PL21**	**PL71**	**PL72**	**PL81**	**PL82**
					
Cluster II	**PL22**	**PL91**			
					

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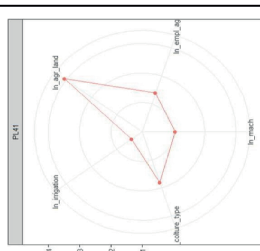
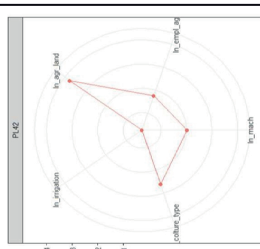
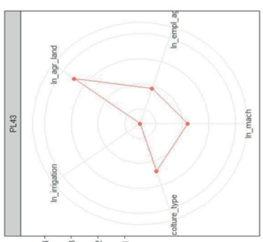
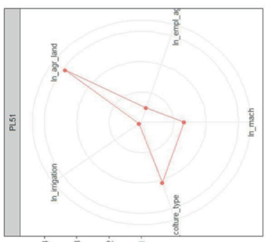
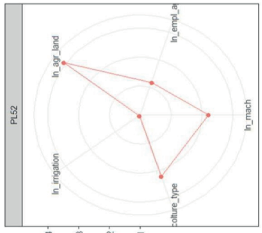
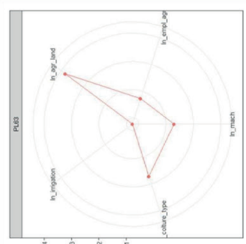
Cluster III	PL41	PL42	PL43	PL51	PL52
					
	PL61	PL62	PL63		
					

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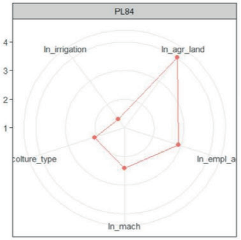
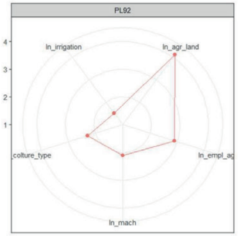
Cluster IV	PL84	PL92			
					

Note: The axes are arranged clockwise starting from the top-left: ln_irrigation (log-transformed irrigated area), ln_agr_land (log-transformed agricultural land), ln_empl_agr (log-transformed agricultural employment), ln_mach (log-transformed machinery intensity), and ln_colture_type (log-transformed crop diversity index). Each axis is scaled from 0 to 4, with higher values indicating greater relative intensity.

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similar to those in cluster II. Cluster IV likewise identifies irrigation as the primary area of concern, followed by machinery and crop type, with comparatively better outcomes in agricultural employment and land use.

5. Discussion

The analysis of agricultural residue efficiency across Polish regions underscores the complexity of optimising agricultural systems within different regional contexts. The results provide a robust framework for identifying inefficiencies, offering a nuanced perspective on resource utilisation. These findings are particularly pertinent in the context of Poland's agricultural sector, which plays a pivotal role in the national economy, and advocate for tailored, cluster-specific interventions to effectively address the identified inefficiencies.

For cluster I, a comprehensive strategy is required, involving investment in irrigation infrastructure, workforce training, machinery modernization, and crop diversification to address the multifaceted inefficiencies. Specifically, policymakers could consider implementing integrated development programmes that combine public-private partnerships to fund irrigation infrastructure upgrades and provide subsidies for modern machinery. Additionally, targeted educational initiatives could enhance workforce skills, particularly in regions where agricultural employment inefficiencies are pronounced. Such interventions should be supported by rigorous monitoring and evaluation frameworks to ensure their effectiveness and adaptability to local conditions.

In cluster II, efforts should prioritize reforming agricultural employment through training schemes or labour reallocation, complemented by improvements in machinery and crop selection. For clusters III and IV, urgent investments in irrigation systems – such as advanced water management technologies or infrastructure enhancements – are essential, along with targeted upgrades in machinery and crop optimization. Moreover, the adoption of precision agriculture technologies, such as sensor-based irrigation systems and data-driven crop management tools, could address inefficiencies in irrigation and crop type, particularly in clusters III and IV. These technologies, while requiring initial investment, have the potential to yield long-term efficiency gains by optimising resource use and reducing environmental impacts. Collaborative research initiatives between academic institutions, agricultural extension services, and regional stakeholders could further drive innovation, ensuring that technological advancements are tailored to the specific needs of each cluster.

Across all clusters, the relative strength of agricultural land should be leveraged through policies that promote sustainable land management to

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preserve its efficiency. Furthermore, cross-cluster knowledge exchange and pilot initiatives could facilitate the dissemination of best practices, particularly in machinery use and crop selection, where inefficiencies are most pervasive. Such targeted, evidence-based interventions, grounded in the specific characteristics of each cluster, will enable more effective resource allocation and improve agricultural residues production efficiency throughout Poland – aligning with the imperative for regionally differentiated strategies highlighted in the aforementioned analyses.

Conclusions

This study has undertaken a comprehensive analysis of agricultural residues production efficiency across Poland's NUTS-2 regions, employing an integrated framework combining DEA and MCDA-DEA to investigate the key determinants of residue supply efficiency. This study proposes an efficiency indicator designed to target the key determinants influencing the performance of agricultural residue supply. To achieve this, an integrated framework was adopted, combining Data Envelopment Analysis (DEA) with Multi-Criteria Decision Analysis (MCDA-DEA), and applied to the agricultural residue production across Poland's NUTS-2 regions.

The findings reveal substantial regional disparities in the performance of agricultural systems, shaped by varying levels of inefficiency in irrigation, agricultural employment, machinery, crop type, and – though to a lesser extent – agricultural land. The relatively higher efficiency of agricultural land across all clusters suggests the importance of maintaining sustainable land management practices.

By contrast, widespread inefficiencies in machinery and crop type, along with critical shortcomings in irrigation – particularly in clusters III and IV – and agricultural employment, especially in cluster II, point to structural constraints that hinder the full exploitation of agricultural residues within a circular economy paradigm. These challenges indicate a need for regionally tailored policy responses to improve performance and promote the efficient use of agricultural resources.

For cluster I, a comprehensive strategy is required, involving coordinated investments in irrigation systems, workforce development, machinery upgrades, and diversification of crop choices to address the diverse sources of inefficiency. In cluster II, immediate interventions in agricultural employment are essential, including targeted training initiatives and potential labour reallocation, alongside enhancements in machinery and crop selection. Clusters III and IV necessitate urgent investment in modern irrigation technologies, supported by improvements in mechanization and crop

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optimization. Across all clusters, cross-regional knowledge sharing and pilot schemes could accelerate the dissemination of effective practices, particularly in areas of universal concern such as machinery use and crop selection.

These insights are closely aligned with the objectives of the European Green Deal and the CAP 2023-2030, that prioritize sustainable resource use, waste reduction, and the advancement of circular economic principles in agriculture.

Poland's considerable residues' potential presents a valuable opportunity to convert agricultural by-products into bioenergy and bio-based goods. However, economic uncertainties, stringent environmental regulations, and logistical constraints, including fragmented land ownership and underdeveloped infrastructure, continue to present barriers to efficient residues management. Overcoming these obstacles will require the integration of robust evaluation methods, technological innovation, and strengthened policy support to enable Poland's "hidden harvest" to contribute meaningfully to a sustainable and resilient agricultural sector.

While the current study provides valuable insights into regional inefficiencies, it is not without limitations. The reliance on DEA and MCDA-DEA assumes a certain level of data homogeneity, which may not fully capture micro-level variations within regions.

Future research should pursue longitudinal studies to assess the impact of policy measures over time and examine a broader set of socio-economic and environmental factors influencing residue efficiency indicators. Such efforts will be vital in supporting transition towards a fully realized circular economy framework. Furthermore, future research could incorporate finer-grained data, such as farm-level surveys, to validate these findings and explore additional variables, such as soil quality or climate impacts, that may influence efficiency. Such research would complement the current findings, offering a more comprehensive understanding of agricultural residue efficiency dynamics across Poland.

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