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The Energy Potential of Agricultural Biomass in the European Union

Abstract: The objective of this study is to conduct a quantitative assessment of the theoretical potential of agricultural biomass in EU countries for energy production. It explores various biomass sources, such as agricultural residues, animal husbandry by-products, and energy crops. Using data, the study examines the potential biomass across different EU countries, emphasising the disparities due to diverse agricultural practices. The analysis underscores the need for customised biomass strategies tailored to each Member State's specific agricultural conditions. The study identifies biomass as a vital energy source for the EU's energy independence and reducing fossil fuel reliance. It also highlights the necessity for future research on improving biomass conversion technologies and policy development for integrating agricultural biomass into the energy framework, considering the unique aspects of each country's agricultural sector.

Keywords: bioenergy market, energy biomass, agricultural biomass, energy security

JEL Classification: P28, Q16, Q42

Introduction

Biomass, as a term, has evolved and diversified in its meaning across various scientific and industrial contexts. Initially defined simply as the total quantity or weight of organisms in a given area or ecosystem at a given time (Ward, 1983), the term has expanded to encompass a wide range of materials of biological origin, particularly in the context of renewable energy and environmental sustainability. In the realm of renewable energy, biomass is predominantly considered as plant-derived materials. This includes agricultural residues, by-products of industrial processes, and dedicated energy crops (Hames, 2009). This definition aligns with the growing emphasis on sustainable and renewable energy sources, highlighting the role of biomass as a key player in this sector. From a broader biological perspective, biomass includes all living entities across the three domains of life – Archaea, Eukarya, and Bacteria – along with their wastes (Polizeli, et al., 2011). This definition underscores the comprehensive nature of biomass, encompassing both the living and the by-products of the living, thereby playing a crucial role in the carbon cycle and ecological balance. The concept of biomass also extends into specific applications such as biochar and biofuels. Biochar, for instance, is derived from biomass that is heated in the absence of or at low concentrations of oxygen, primarily for soil application (Madari, et al., 2012). This application not only highlights the versatility of biomass but also its significance in soil enhancement and carbon sequestration. In the context of the United Kingdom's

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renewable energy strategy, biomass is defined more specifically as a substance derived from plant or animal matter, with a focus on energy crops grown for burning (Wood, 2004). This definition reflects the policy and economic dimensions of biomass, particularly in the context of national energy strategies and sustainability goals. Agricultural biomass plays a significant role in enhancing energy security within the European Union (EU). The EU's transition to a low-carbon economy heavily relies on biomass as an alternative to fossil resources. In this context, agriculture is a primary source of biomass, contributing 68% of the total supply (Beluhova-Uzunova, et al., 2021). This significant contribution underscores the importance of agricultural biomass in the EU's bioeconomy strategy, which aims for a resource-efficient, competitive, and sustainable economy. The demand for biomass in the EU is projected to increase from 7 EJ to 10 EJ by 2023, indicating a growing reliance on this renewable energy source (Wieruszewski & Mydlarz, 2022). This increase is partly due to the EU's commitment to reducing greenhouse gas emissions and increasing the use of renewable energy sources. Agricultural biomass, including forest biomass, agricultural residues, and energy crops, is expected to play a crucial role in this transition. The potential land availability for energy crops in the EU is also significant. It is estimated that up to 26.2 million hectares could be available for non-food crops by 2030 (Krasuska, et al., 2010). This availability of land for biomass production is vital for the EU's energy security, as it reduces dependence on imported fuels and contributes to the sustainability of the energy sector. Furthermore, the use of agricultural biomass for energy purposes aligns with the EU's broader environmental and economic goals. For instance, the production of bioenergy from agricultural biomass can lead to cost-effective climate change mitigation and employment creation (Berndes & Hansson, 2007). In countries like Poland, agriculture plays a significant role in ensuring energy security, with the potential for dynamic growth in energy crop farming (Bielski, et al., 2021).

The ongoing challenges of climate change and the imperative to diversify energy sources have become pivotal global issues. Recognising this, the European Commission unveiled the 2020 Energy Strategy, urging EU member states to escalate the integration of renewable resources in their energy frameworks. Concurrently, the European Council has articulated a long-term vision with specific operational guidelines. This strategic direction aligns with the broader commitment of the EU and other industrial nations to ambitiously curtail greenhouse gas emissions by 80-95% by the year 2050, marking a decisive step towards environmental sustainability and energy resilience (European Commission, 2014).

The EU bioenergy market's prominence, driven by policy and economic factors, underscores the strategic importance of bioenergy, particularly biomass, in the EU's renewable energy portfolio. Government policies, notably the Renewable Energy Directive (RED) and its subsequent amendments, shape the bioenergy landscape, influencing the development and adoption of bioenergy across member states. The EU's policies, including the "Fit for 55" package and the REPowerEU plan, reflect its commitment to increasing renewable energy targets, advocating for renewable fuels like biomass in various sectors.

The European Union bioenergy market reflects its prominence as a leading renewable energy source, with bioenergy maintaining a dominant position in the EU's renewable energy portfolio (Mandley et al., 2020). Biomass is the most extensively used renewable energy source across member countries (Anca-Couce et al., 2021), exemplified by the increasing application of biofuels in the transportation sector. This aligns with the EU's broader strategic goals of reducing dependence on imported hydrocarbons and mitigating climate change (Bórawski & Bełdycka-Bórawska, 2019). The EU's focus on advancing biofuels aims to address concerns about using food crops for energy and enhance sustainable development in the bioenergy sector (Anca-Couce et al., 2021). The trajectory is shaped by the EU's renewable energy goals and policies, indicating the strategic significance of bioenergy in achieving medium and long-term climate objectives (Mandley et al., 2020.; Anca-Couce et al., 2021). However, challenges remain, such as sustainable supplies of liquid biofuels and pressure on high bioenergy-consuming countries, which must be carefully managed to balance energy needs with environmental stewardship (Mandley et al., 2020).

Biomass plays a significant role in the energy strategies of the European Union and is a key component in achieving objectives related to renewable energy. Some studies indicate that its share in the renewable energy resources of the EU ranges from 50% to almost 60% (European Commission, 2023). The heating and cooling sector is the largest end-user, using about 75% of all bioenergy. However, the exact percentage contribution of biomass to renewable energy resources may vary depending on the source and methodology of the research (European Commission, 2023).

The profound impact of policy on the EU bioenergy market is undeniable. Government policies and regulations fundamentally shape the bioenergy landscape, dictating the pace and direction of its development (Faaij, 2006). This is further affirmed by the Renewable Energy Directive (RED) of 2009, a key policy measure adopted by the EU to strengthen the bioenergy sector (Albrecht et al., 2017). RED and similar strategies underscore the Union's commitment to promoting bioenergy, as these policies establish clear goals and provide the necessary legal frameworks to encourage investment and development (Faaij, 2006). The effectiveness of these policies is evident in how member states have incorporated them into national legislation, ensuring a harmonised approach across the Union in developing bioenergy (Albrecht et al., 2017). Thus, EU policy decisions not only set the stage but also actively drive the evolution of the bioenergy market, illustrating the inseparable link between policy and market dynamics (Faaij, 2006). In July 2021, as part of the "Fit for 55" package, the Commission proposed an amendment (RED II) to the Renewable Energy Directive to align its renewable energy targets with the new climate goals. The Commission suggested increasing the EU's binding target for renewable energy in its energy mix to 40% by 2030, advocating for the use of renewable fuels such as hydrogen in industry and transport while setting additional targets. In May 2022, under the RE Power EU plan following Russia's aggression in Ukraine, the Commission proposed the first amendment (RED III) to accelerate the transition to clean energy in line with the gradual reduction of dependency on Russian fossil fuels. The Commission proposed the installation of heat pumps, increased capacity of photovoltaic systems, and the import of renewable hydrogen and biomethane to raise the renewable energy target to 45% by 2030. On November 9, 2022, the Commission proposed the second amendment (RED IV) to the Council Regulation to accelerate the deployment of renewable energy. According to the proposal, power plants using renewable energy sources would be considered to be in the public interest, enabling expedited permitting for renewable energy projects and specific exemptions from EU environmental legislation. In March 2023, the Parliament and the Council informally agreed to increase the renewable energy target for 2030 to 42.5%, with member states aiming to achieve a target of 45%. For the first time, industry was included by establishing binding targets (42% of renewable hydrogen in total hydrogen consumption by 2030) and indicative targets (a 1.6% annual increase in renewable energy consumption) (European Commission, 2023).

In the EU, the shift towards bioenergy is largely driven by a complex interplay of economic, environmental, and political factors. Rising costs of conventional energy sources, exacerbated by their finite nature, underscore the urgent need for alternative solutions to meet growing energy demand. Energy security remains a primary concern for the EU, with bioenergy offering a renewable option that can reduce reliance on imported fuels, thereby addressing energy security issues. Moreover, the risks and costs associated with nuclear energy have reduced its attractiveness as a sustainable energy source, propelling bioenergy as a more viable alternative (McCormick & Kåberger, 2007). The EU's commitment to mitigating climate change has necessitated a shift away from high-emission fuels like coal and oil, making bioenergy a key player in transitioning to a low-emission economy. However, the bioenergy sector faces significant barriers, including economic conditions affecting affordability and profitability, lack of institutional capacity, and supply chain coordination challenges. Despite these obstacles, supportive EU policies, such as financial incentives and regulatory frameworks, play a crucial role in promoting the adoption and development of bioenergy, signalling collective efforts to overcome barriers and leverage favourable factors for a sustainable and secure energy future (Philippidis et al., 2018.; McCormick & Kåberger, 2007).

The diversification of biomass resources has become a cornerstone of the renewable energy landscape in the EU, with agricultural residues, forest residues, and surplus forest wood serving as primary components (Van Dam et al., 2007). However, the cultivation of energy crops plays a significant role, especially considering the strategic use of land that does not compete with food and feed production. This is particularly true in Central and Eastern European countries, where energy crops represent a dominant biomass potential, reflecting regional agronomic practices and land-use dynamics. Long-term prospects suggest that energy crops, due to their high yield potential and compatibility with existing agricultural systems, may contribute the most to bioenergy production in the EU (Van Dam et al., 2007). EU strategic planning, as evidenced by research, consistently focuses on potential biomass supplies from agricultural lands, emphasising understanding the relative contribution of forest lands to this supply. Furthermore, the use of wheat yields as an indicator of energy crop yields highlights the nascent stage of energy crop cultivation, underscoring the need for further development and reliable data to optimise production (Ericsson & Nilsson, 2006). Overall, this suggests that energy crops not only play a key role in the current biomass resource portfolio but are also expected to become the forefront of biomass for energy purposes in the EU in the 21st century (Bentsen & Felby, 2012).

As the EU increasingly relies on bioenergy, sustainability criteria have become essential to ensure that renewable energy goals do not inadvertently lead to environmental degradation. The EU has implemented detailed sustainability criteria for biomass energy, including stringent regulations on greenhouse gas emissions and land use to mitigate any potential negative impacts. These criteria are crucial, given that sustainable biomass resource development depends on factors such as biomass origin and the efficiency of its conversion to energy. However, the implementation and effectiveness of these criteria are subjects of ongoing debate and concern, reflecting the complexity of balancing energy needs with ecological management (Proskurina et al., 2016). As the EU Renewable Energy Directive sets ambitious targets, a significant emphasis has been placed on woody biomass, which is expected to play a substantial role in achieving the goal of a 20% share in renewable energy consumption by 2020. However, this focus raises difficult questions about carbon neutrality, considering that woody biomass is not inherently carbon-neutral, and concerns about the potential for deforestation, which could undermine the environmental objectives of using biomass for energy purposes. Therefore, while the EU strives to achieve its energy policy goals and reduce greenhouse gas emissions through biomass resources (Bentsen et al., 2012), it must proceed cautiously to ensure that the use of these resources does not threaten the same sustainability goals it seeks to maintain.

The strategic significance of biomass resources in the European Union cannot be overstated, especially considering the medium and long-term climate goals to which the region is committed. Estimates indicating that the technical potential of domestic biomass for energy purposes by 2050 could vary significantly from 9 to 25 exajoules per year (eJyr-1) make it clear that there is a substantial domestic resource base that could theoretically meet future demands entirely (Moiseyev et al., 2011). However, this potential is not without challenges. Part of the biomass resource base may be economically inaccessible due to various factors, such as extraction or transportation costs. This economic accessibility is further complicated by uncertainties, including raw material yields, contributing to a wide range of potential biomass resource estimates. Moreover, the development and integration of biomass resources in the EU are influenced by the complex interplay of factors such as forestry economics, land availability, and policy frameworks, which in turn are shaped by the political landscape, as noted earlier, under the influence of EU policies and strategies on the bioenergy market. Additionally, forest biomass is particularly promising, as it can significantly contribute to the EU's renewable energy (RES) targets (Moiseyev et al., 2011). Thus, the development of biomass resources in the EU presents a multifaceted challenge, encompassing technical, economic, and political dimensions, each requiring careful consideration to harness the full potential of biomass in transitioning to a more sustainable energy system.

From a global perspective on energy production, it is of paramount importance to enhance the utilisation of renewable resources, particularly biomass. This emphasis stems from the growing recognition of biomass as a sustainable and eco-friendly alternative to conventional fossil fuels. Biomass, as a renewable energy source, offers a plethora of benefits, including the reduction of greenhouse gas emissions and the promotion of energy diversification. Moreover, the strategic deployment of biomass aligns with global efforts to mitigate climate change and fosters a transition towards a more sustainable energy paradigm. Therefore, the increased adoption and integration of biomass into the global energy mix not only addresses environmental concerns but also contributes to the resilience and sustainability of energy systems worldwide (Turkenburg, 2020; Böttcher et al. 2010; De Wit et al. 2008; Ericsson and Nilsson, 2006; Andersen et al. 2021; Fischer et al. 2007). The European Union has distinguished itself by establishing renewable energy goals that are notably more ambitious compared to other global regions. This is exemplified by the revised Renewable Energy Directive, which was adopted in 2023. This directive escalates the EU's mandatory renewable energy target for 2030 to a minimum of 42.5% (European Commission, 2023). Notably, the EU had already surpassed its 2020 target, achieving a 22.1% share of gross final energy consumption from renewable energy sources. In contrast, the United States, through its Energy Policy Act, promotes a diverse spectrum of renewable energy sources, including wind, solar, hydro, geothermal, and biomass, with a particular emphasis on the development of liquid biofuels. This Act is indicative of a wider international trend towards diversification of energy sources, highlighting the growing global consensus on the pivotal role of renewable energy in fostering sustainable development (European Commission, 2023). This trend reflects an increasing awareness of the need for a sustainable energy transition and the critical role renewable energy plays in this global shift. Numerous studies conducted over the past two decades on energy biomass resources in Europe and globally have demonstrated an increase in bioenergy potential. This growth is anticipated to provide a larger supply of biofuels derived from wood and agricultural biomass for both industrial and various other applications (Fischer & Schrattenholzer, 2001; Haberl et al., 2010; Hoogwijk et al., 2005).

The primary objective of this study is to quantitatively evaluate the theoretical potential of agricultural biomass as a renewable energy source within the European Union. This research aims to provide a comprehensive analysis of the capacity of agricultural biomass, considering the varied geographical and agricultural landscapes across EU countries. By assessing the potential of this resource, the study seeks to contribute to the strategic development of sustainable energy policies within the EU, aligning with its broader goals of energy diversification and environmental sustainability.

The research problem addressed by this study centres on the lack of a detailed, quantitative understanding of the potential of agricultural biomass for energy production across the EU. Despite biomass being a key component in the EU's renewable energy mix, a significant gap exists in the assessment of its full potential, particularly in the context of agricultural sources. This study aims to bridge this gap by systematically analysing the available agricultural land resources, the sustainability of biomass production, and the potential energy yield from these sources across different EU member states. The investigation focuses on unravelling the disparities and prospects of agricultural biomass utilisation for energy production, thereby providing a foundation for informed policy-making and strategic planning in the EU's renewable energy sector.

The paper is organised as follows: the next section describes the methodology, i.e., the study's aim, description of methods used, and data sources. The subsequent section presents the empirical findings, and the final section offers the conclusions.

Data and methods

The objective of this study is to conduct a quantitative assessment of the theoretical potential of agricultural biomass in EU countries for energy production. In the study, a series of statistical methods were employed to conduct an analysis of the collected data. The following statistical methods were used in the study:

- Mean: The mean was calculated for each biomass category across the entire data set. This method involves summing all values within a category and then dividing by the number of values to obtain a central point reflecting the typical magnitude of biomass potential in the European Union. The mean is a fundamental indicator of central tendency, providing a general idea about the data distribution;

- Median: The median, representing the middle value of an ordered data set, was calculated to provide a measure of central tendency less affected by outlier values. In cases of asymmetric data distribution, the median often better reflects the "typical" value than the mean, avoiding the influence of extreme observations;
- Standard Deviation and Variance: These two measures were used to quantify the degree of variability or dispersion of biomass potential values relative to their mean. Standard deviation is a measure of data spread, while variance, being the square of standard deviation, offers deeper insight into the variability of the data. Higher values of both indicators suggest greater differences between individual values and the mean;
- Skewness: Skewness was calculated to assess whether the data distribution is symmetrical around the mean or skewed. A positive skewness value indicates a distribution with a majority of data on the right side of the mean (right-skewed), suggesting a concentration of lower values and the presence of higher outlier values. This is crucial for understanding how the data distribution deviates from normality;
- Kurtosis: Kurtosis was determined to evaluate the "tailedness" of the distribution. Higher kurtosis values indicate a distribution with 'heavy tails', meaning a larger number of extreme values (outliers). Lower kurtosis values suggest a less extreme, more flattened data distribution. This is important in the context of identifying and analysing outlier values, which can have a significant impact on data interpretation and the conclusions drawn.

Data on the theoretical potential of agricultural biomass in EU countries in 2019 come from Eurostat, the European Commission, and Janiszewska & Ossowska (2022).

Research results

Agricultural production is based on agricultural land resources. In the case of Poland, in 2020, it occupied 14 681.6 thousand hectares. In the domestic structure of agricultural land, the largest area was occupied by cultivated land - 10 741.9 thousand hectares, and then permanent grassland - 350.2 thousand hectares, while permanent meadows were cultivated on an area of 2 775.1 thousand hectares, and permanent pastures on an area of 414.5 thousand hectares (Statista, 2023).

The pursuit of sustainable energy solutions has become a cornerstone of environmental policy within the European Union, catalysing extensive research and development in the field of renewable energy. This paradigm shift is driven by the urgent need to mitigate climate change impacts and reduce reliance on fossil fuels. Recent studies in the EU have focused on evaluating the efficacy, scalability, and socio-economic impacts of various renewable energy sources, including solar, wind, hydroelectric, and biomass. These investigations are critical in informing policy decisions and guiding the transition towards a more sustainable and resilient energy infrastructure. The integration of renewable energy sources into the existing grid, the optimisation of energy storage technologies, and the exploration of innovative financing models are among the key areas of focus. The findings from these studies are expected to provide valuable insights into the feasibility, challenges, and opportunities presented by renewable energy adoption in the EU context. Key types of renewable energy utilised within the EU include wind power, which harnesses the energy of wind currents; solar power, generated from sunlight; hydroelectric power, derived from the energy of moving water; biomass, which includes organic materials like wood and agricultural waste; and geothermal energy, sourced from the natural heat of the Earth.

The transition to renewable energy sources is a pivotal element of the European Union's strategy for achieving sustainability and energy independence. This study presents an analysis of the progression in renewable energy adoption by EU member states over a three-year period from 2020 to 2022. The data encapsulate the percentage share of energy derived from renewable resources as a part of each country's final gross energy consumption, reflecting the collective and individual efforts towards meeting the EU's ambitious climate targets. The European Union has been at the forefront of the global shift towards renewable energy, implementing policies and incentives to promote the use of wind, solar, hydroelectric, biomass, and geothermal energy. The integration of these renewable sources into national grids is crucial for reducing carbon emissions and mitigating the impact of climate change. Our data analysis focuses on quantifying the extent to which EU countries have increased their renewable energy usage, contributing to the overall EU objective of a sustainable energy future. The dataset under study provides a yearly breakdown of the total share of renewable energy consumption for the EU as a whole and for individual member states. The following key observations have been made: Overall, the EU saw a modest increase in renewable energy share from 22% in 2020 to 23% in 2022. Denmark demonstrated a significant rise, with renewable energy consumption jumping from 32% in 2020 to 42% in 2022. Estonia also showed notable growth, with an increase from 30% in 2020 to 38% in 2022. In contrast, Croatia observed a slight decrease, moving from 31% in 2020 to 29% in 2022. Sweden maintained the highest percentage share, climbing from 60% in 2020 to 66% in 2022. The data for countries like Bulgaria, Italy, and Romania exhibit stability in renewable energy consumption with minimal variation over the three years. These figures underscore the varying rates of adoption of renewable energy technologies across the Union, influenced by national policies, resource availability, and economic factors.

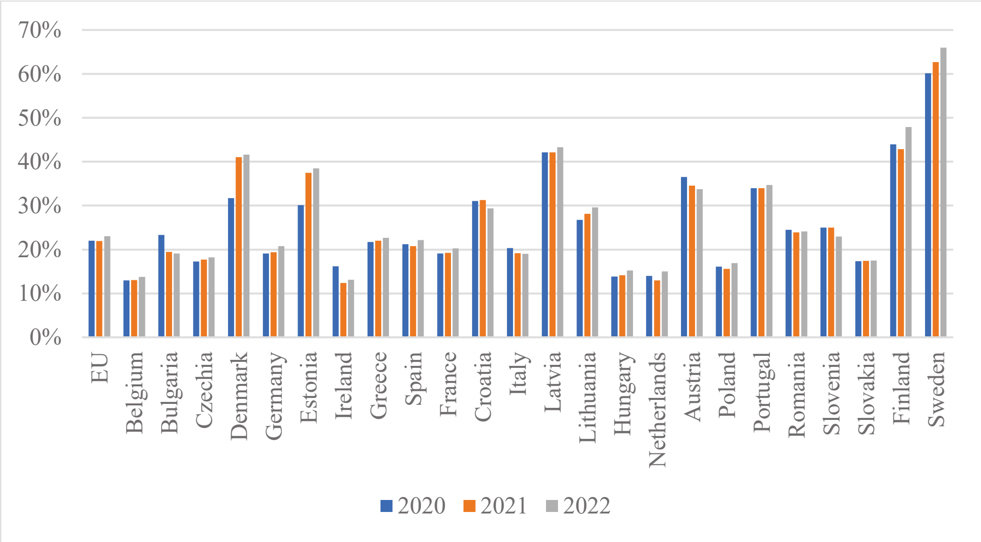

Fig. 1. The percentage share of renewable energy in individual EU member states between 2020 and 2022.

Source: Own elaboration based on Eurostat data.

The incremental, yet positive, trend in renewable energy uptake across the European Union signals a steady commitment to a greener energy portfolio; however, while some countries showcase accelerated progress, others maintain a steady course or display minor fluctuations. Continued investment and policy support are essential for sustaining growth in renewable energy use, ultimately contributing to the EU's long-term environmental and economic objectives.

The composition of the energy portfolio within the European Union (EU) is a complex amalgamation of domestically produced energy and imports from external nations. To comprehensively understand the EU's energy landscape, it is imperative to consider both these aspects in tandem. In the year 2021, approximately 44% of the EU's energy requirements were met through domestic production, while the remaining 56% was supplemented through imports. Predominantly, the EU's energy framework in 2021 was characterised by a diverse array of sources. The predominant contributor was crude oil and petroleum products, accounting for 34% of the energy mix. This was followed by natural gas at 23%, renewable energy sources at 17%, nuclear energy at 13%, and solid fossil fuels comprising 12% of the mix. However, this distribution of energy sources exhibited significant variability across different EU member states. For instance, in 2021, Cyprus (86%), Malta (85%), and Luxembourg (61%) predominantly relied on petroleum products. In contrast, natural gas was a major energy contributor in Italy (40%), the Netherlands (35%), and Hungary (34%). Renewable energy sources were most prevalent in Sweden (48%) and Denmark (41%), whereas nuclear energy formed a substantial part of the energy mix in France (41%) and Sweden (25%). The reliance on solid fossil fuels was notably high in Estonia (56%) and Poland (43%). This diverse energy landscape within the EU underscores the region's multifaceted approach to energy sourcing, reflecting a blend of traditional and renewable energy sources tailored to the unique geographical and economic contexts of each member state (Eurostat, 2023)

In the context of climate change and the increasing demand for bioenergy, the agricultural sector is confronted with a spectrum of opportunities and challenges. Table 1 illustrates how modern technologies and practices can support agriculture in adapting to these global trends, while simultaneously emphasising the necessity of natural resource management and environmental protection.

Table 1. Opportunities and challenges of developing agricultural biomass production in EU countries

Opportunities	Challenges
• Introduction of advanced agricultural machinery (implementing cutting-edge agricultural equipment and machinery to enhance farming efficiency and productivity). • Optimisation of crop management techniques (refining agricultural practices to maximise crop yield and resource utilisation through effective management strategies). • Adoption of precision agriculture (utilising data-driven approaches and technology in farming to achieve more accurate and controlled agricultural processes). • Development of region-specific crop varieties (breeding and cultivating new plant varieties that are specifically tailored to thrive in local agroecological environments). • Expansion of agricultural knowledge via digital tools (leveraging intelligent applications to broaden agricultural understanding, coupled with the engagement of a growing number of young, innovative farmers). • Sustainable soil management practices (implementing soil health improvement techniques, such as organic matter enrichment and erosion control to sustain long-term agricultural productivity). • Integration of renewable energy sources in farming (incorporating solar, wind, and energy solutions in agricultural operations to reduce the carbon footprint and enhance energy efficiency).	• Pressure for eco-friendly land utilisation (encouraging the transformation of agricultural lands to support environmental enhancements, including carbon sequestration and biodiversity conservation). • Addressing land degradation (implementing measures to prevent soil erosion, replenish nutrients, and counteract salinisation, thereby combating the deterioration of agricultural land). • Implementation of sustainable water management practices (adopting efficient irrigation techniques and water conservation strategies to mitigate the impact of agriculture on water resources). • Promotion of agroforestry practices (integrating tree planting with agricultural activities to enhance ecological balance, improve soil quality, and increase biodiversity on farmlands).

Source: own study.

Table 1 encapsulates the intricate interplay of opportunities and challenges in modern agriculture. While advancements in technology and practices offer pathways for enhanced efficiency and sustainability, the sector must also navigate complex environmental and resource management challenges. Addressing these challenges is essential for ensuring the sustainable development and resilience of agricultural practices, particularly in the face of global challenges such as climate change and the growing demand for bioenergy.

The strategic harnessing of agricultural biomass as a pivotal renewable energy resource underscores a commitment to the European Union's sustainability objectives and energy independence directives. This analysis delves into the theoretical potential of agricultural biomass across EU member states in 2019, drawing from an extensive dataset encapsulating diverse biomass sources.

An examination of the dataset reveals a total potential of 198.3 thousand Ktoe, with an intricate composition stemming from various agricultural residues and by-products. Notably, cereal straw constitutes a substantial 41.2% of the total potential, underscoring its pre-eminence as a bioenergy feedstock. In close parity, permanent grassland hay represents 40.0% of the potential, reflecting the extensive pastoral landscapes prevalent across the continent. Natural fertilisers from animal husbandry contribute a significant 10.5%, while energy plantations, such as willow, account for 7.9%. Waste wood from permanent crops, albeit the smallest contributor at 0.4%, highlights the comprehensive utilisation of agricultural resources.

Country-specific potentials exhibit a broad spectrum, ranging from a modest 6.4 Ktoe to a robust 34,528.5 Ktoe, with an average of 7,082.9 Ktoe. The heterogeneity in potential is pronounced, with smaller EU nations like Malta (6.4 Ktoe), Cyprus (76.1 Ktoe), and Luxembourg (160.5 Ktoe) manifesting the lower end of the spectrum. In contrast, France emerges as the frontrunner with an impressive potential of 34,528.5 Ktoe, followed by Spain and Germany, collectively amassing over 40% of the EU's total theoretical biomass potential.

The disparities observed can be attributed to a multitude of factors, including geographical size, agricultural land utilisation, and energy policy frameworks. For instance, France's extensive agricultural land and diversified cropping systems facilitate a higher biomass yield, whereas Malta's limited land area inherently constrains its potential.

The implications of this analysis are manifold, extending to energy policy formulation and agricultural management. The robust potential of biomass as an energy source could significantly contribute to the EU's energy self-sufficiency and reduce dependence on fossil fuels. Furthermore, the sustainable management of agricultural residues and by-products can foster circular economy principles within the agro-energy sector. In conclusion, this data-driven exploration highlights the substantial, yet varied, potential for agricultural biomass across EU countries. It underscores the need for tailored strategies that leverage the unique agricultural landscapes and conditions of each member state. Future research should focus on optimising biomass conversion technologies and developing policies that incentivise the integration of agricultural biomass into the energy matrix.

Table 2. The theoretical potential of agricultural biomass in EU countries in 2019

The theoretical potential of agricultural biomass						
Country	Straw from cereal crops	Permanent grassland hay	Natural fertilisers from animal husbandry	Growing energy crops on fallow land	Waste wood from permanent crops	Total
			Ktoe			
Belgium	650.2	608.7	655.3	25.2	1.3	1940.7
Bulgaria	3023.1	1803.2	120.6	339.9	10.1	5296.8
Czechia	1988.2	1269.8	291.6	51.2	2.7	3603.5
Denmark	2317.9	264.6	799.0	93.4	1.6	3476.6
Germany	9822.5	6082.8	3019.8	858.4	13.2	19797
Estonia	406.8	370.2	55.4	45.9	0.3	878.6
Ireland	508.8	5223.9	1164	9.1	0.1	6905.9
Greece	773	2728.8	121.8	349.2	79.3	4052.1
Spain	4981.8	9289.5	2460.5	6570.8	329.8	23632
France	17.323.3	12303.5	3570.8	1261.3	69.6	34.528.5
Croatia	1137.7	776.0	115.2	50.2	4.9	2084.0
Italy	4042.9	4854.4	1442.7	1039.6	159.9	11540.0
Cyprus	12.9	2.0	28.2	31.1	1.8	76.1
Latvia	778.6	809.0	80.6	145.1	0.6	1813.8
Lithuania	1260.4	930.9	129.7	187.3	2.0	2510.3
Luxembourg	37.3	86.9	35.5	0.6	0.1	160.5
Hungary	4789.0	1011.9	272.8	387.2	11.3	6472.2
Malta	0.0	0.0	3.9	2.4	0.1	6.4
Netherlands	341.1	982.6	1136.3	20.3	2.5	2482.8
Austria	1545.1	1611.5	430.8	138.0	4.4	3729.9
Poland	7445.9	4004.3	1548.3	455.7	22.5	13477.0
Portugal	325.8	2402.9	383.0	692.7	51.6	3856.0
Romania	9326.3	5693.8	486.2	1069.1	20.8	16596.0
Slovenia	195.3	355.6	91.7	2.9	1.8	647.3
Slovakia	1204.6	663.7	99.4	122.1	1.2	2091.0
Finland	957.5	30.1	186.5	500.7	0.2	1675.1
Sweden	1433.6	590.5	296.6	474.6	0.2	2795.6
Total	59306.3	64751.1	19026.2	14924.0	793.9	141596.8

Source: own elaboration based on data from Eurostat, the European Commission, and Janiszewska & Ossowska (2022).

This study quantifies the theoretical potential of agricultural biomass in various European Union countries, as exemplified in the comprehensive data table. The data delineates potential biomass sources, including straw from cereal crops, hay from permanent grassland, natural fertilisers from animal husbandry, energy crops grown on fallow land, and waste wood from permanent crops, with their cumulative potential quantified in kilotonnes of oil equivalent (Ktoe). The analysis reveals significant heterogeneity in biomass potential across countries. For instance, France exhibits a remarkably high potential, primarily driven by straw from cereal crops and permanent grassland hay, amounting to a total of 34,528.5 Ktoe. In contrast, smaller countries like Malta and Luxembourg show minimal biomass potential, with totals of 6.4 Ktoe and 160.5 Ktoe, respectively. This variability underscores the diverse agricultural landscapes and practices prevalent across the EU. The data also highlights the predominant role of certain biomass sources in specific countries. For instance, Spain's significant contribution of 23,632 Ktoe is largely attributed to its high potential in both straw from cereal crops and permanent grassland hay. Conversely, countries like Denmark and Ireland demonstrate considerable potential in natural fertilisers from animal husbandry, reflecting their specific agricultural practices. Overall, the table presents a comprehensive view of the agricultural biomass potential in the EU, offering vital insights for policy-making and strategic planning in the renewable energy sector. The data underscores the vast, yet varied, potential for agricultural biomass across Europe, emphasising the importance of region-specific strategies for biomass utilisation and sustainable energy production.

Table 3. Statistical analysis of the theoretical potential of agricultural biomass in selected EU countries in 2019

Category	Mean	Median	Standard Deviation	Variance	Skewness	Kurtosis
Straw from cereal crops	4179.56	2153.05	5442.82	2.96243e+07	1.9344	3.5121
Permanent grassland hay	3994.50	2266.00	4153.82	1.72542e+07	1.0890	0.1709
Natural fertilisers from animal husbandry	1225.88	727.15	1309.63	1.71514e+06	0.9380	-0.7282
Growing energy crops on fallow land	960.44	216.65	2014.68	4.05893e+06	2.9265	8.8365
Waste wood from permanent crops	50.80	6.40	102.41	1.04869e+04	2.7180	7.7568
Total biomass potential	10411.18	4674.45	11452.64	1.31163e+08	1.3507	0.6967

Source: own calculations based on data from Table 2.

In this extended statistical analysis of the theoretical potential of agricultural biomass in selected EU countries for the year 2019, the data delineates the quantitative measures across various biomass categories. The mean values suggest an average biomass potential, with straw from cereal crops exhibiting the highest mean potential (4179.56 Ktoe), indicative of its substantial contribution to the agricultural biomass sector. The median values, which are less sensitive to extreme values in the data set, present a more conservative estimate of central tendency, with straw from cereal crops and permanent grassland hay being the most significant contributors at 2153.05 Ktoe and 2266.00 Ktoe, respectively. The standard deviation and variance metrics illustrate considerable variability within each biomass category, particularly in straw from cereal crops and permanent grassland hay, which have higher standard deviation values of 5442.82 and 4153.82, respectively. This variability is further evidenced by the variance, with straw from cereal crops presenting the most pronounced variance (2.96243e+07), signifying diverse biomass potential across countries. Skewness values across all categories confirm the data's deviation from a normal distribution, with a rightward (positive) skewness indicating a distribution with an extended tail on the right side. The skewness is particularly notable in the category of straw from cereal crops (1.9344) and growing energy crops on fallow land (2.9265), suggesting a concentration of countries with lower potential and fewer countries with exceptionally high biomass potential. Kurtosis values provide insight into the peakedness and the presence of outliers within the data distribution. High kurtosis in the categories of growing energy crops on fallow land (8.8365) and waste wood from permanent crops (7.7568) suggests a distribution with heavy tails and a significant presence of outliers, which could potentially be attributed to specific environmental, economic, or agricultural practices unique to certain countries. The tabular presentation encapsulates the complexity and disparity in the theoretical potential of agricultural biomass across EU countries. The right-skewed distributions and high kurtosis in certain biomass categories emphasise the need for tailored strategies to harness the full potential of biomass, taking into consideration the idiosyncratic attributes of each country's agricultural sector.

Conclusion

The examination of scholarly literature highlights that harnessing agricultural biomass for energy yields multifaceted advantages encompassing economic, social, and environmental dimensions. Calculations suggest a considerable capacity for agricultural biomass. Nonetheless, given the diverse applications of biomass within the agricultural sector, only a limited portion of this potential is viable for energy generation. The study reveals significant disparities in biomass potential among EU countries, ranging from a modest 6.4 Ktoe in Malta to a robust 34,528.5 Ktoe in France. This heterogeneity reflects the diverse agricultural landscapes and practices across the EU and underscores the importance of region-specific strategies for biomass utilisation. The data highlights that certain biomass sources play a predominant role in specific countries. For example, Spain's significant biomass potential is largely attributed to straw from cereal crops and permanent grassland hay. This emphasises the need for tailored strategies that leverage the unique agricultural landscapes and conditions of each member state. The extended statistical analysis reveals the average biomass potential across the EU, with cereal straw contributing significantly. The standard deviation and variance metrics indicate considerable variability within each biomass category, suggesting diverse biomass potential across countries. The findings have crucial implications for energy policy formulation and agricultural management in the EU. The robust potential of biomass as an energy source could significantly contribute to the EU's energy self-sufficiency and reduce dependence on fossil fuels. The sustainable management of agricultural residues and by-products can foster circular economy principles within the agro-energy sector. The analysis points to the need for future research focused on optimising biomass conversion technologies and developing policies that incentivise the integration of agricultural biomass into the energy matrix. Understanding the idiosyncratic attributes of each country's agricultural sector is vital for harnessing the full potential of biomass. In conclusion, this data-driven exploration underscores the substantial, yet varied, potential for agricultural biomass across EU countries. It highlights the strategic significance of biomass resources in the European Union, particularly in the context of medium and long-term climate goals. The study's findings contribute to the broader discourse on sustainable energy and environmental policy, providing a foundation for informed decision-making in the renewable energy sector.

The current geopolitical climate in Europe is fostering a growing interest in renewable energy, particularly agricultural biomass. This context is likely to boost energy production from such biomass soon. Agricultural biomass, being primarily derived from the by-products of essential food production, offers a stable source of material for energy. Its resilience to energy crises is further strengthened by its local availability.

The limitations of this study include potential inaccuracies in data collection and analysis, as agricultural biomass estimates are subject to varying methodologies and reporting standards across EU countries. Additionally, the study's focus on theoretical potential may not fully account for practical constraints such as economic feasibility, land use competition, and regional policy variations. The analysis also does not deeply explore the environmental impacts of scaling up biomass production, which is crucial for maintaining sustainable practices. These limitations suggest the need for further research to refine data accuracy and address practical implementation challenges.

The challenge for future research lies in addressing the complexities of sustainable biomass production. This includes enhancing the efficiency of biomass conversion technologies, developing more comprehensive policies for integrating agricultural biomass into energy frameworks, and better understanding the environmental impacts of large-scale biomass utilisation. Future studies should also explore innovative approaches to balance energy production with ecological and social sustainability, particularly in the context of evolving climate change dynamics and regional agricultural practices.

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