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Assessing the Sustainability of Agricultural Bioenergy Potential in the European Union

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Abstract: The present study aims to assess the sustainability of bioenergy potential from agriculture in the European Union in the period 2012–2021, with a particular focus on material flow and emissions management, bioenergy and recycling impacts, while assessing the potential of bioenergy from agriculture and analyzing the degree of self-sufficiency and import dependency in the biomass economy. While biomass has significant potential in the EU energy transition, its use is accompanied by challenges related to sustainability, carbon neutrality, efficiency and economic viability. Using a quantitative approach based on official statistical data, this research tracked the evolution of biomass imports, exports, domestic extraction and consumption, providing a comprehensive picture of the stability and adaptability of the biomass economy in the European Union. The results indicate a steady increase in domestic extraction and a stability in consumption, reflecting a high capacity of the European Union to manage biomass resources; thus, the degree of self-sufficiency has been high throughout the period, with a moderate dependence on imports, showing an adaptable economy. The conclusions suggest that in order to maintain this stability, the European Union must continue to develop balanced economic and environmental policies that support the sustainable use of biomass and contribute to the energy transition and environmental objectives.

Keywords: biomass; sustainability; energy transition; self-sufficiency; circular economy

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1. Introduction

Biomass will play a central role in the European Union's energy mix by 2030, providing a reliable and flexible renewable energy source that can supplement the inconsistencies of other sources such as wind and solar, contributing to energy security and diversification of energy supply [1]. At the same time, biomass is expected to be a major factor in achieving the European Union's target of at least 32% of energy from renewable sources, particularly in areas such as heating and biofuels for transport, under the Renewable Energy from Renewable Energy Sources II (RED II) Directive, and will be essential to reach the European Union's climate targets [1–4], contributing to carbon neutrality by offsetting CO_2 emissions released during combustion with CO_2 absorbed by plants; having a key role in decarbonizing sectors that are difficult to electrify, such as heavy industry and transport, biomass will also support the decarbonization of heat and power generation, particularly through combined heat and power (CHP) plants [5], and will have significant potential to generate negative emissions by integrating technologies such as bioenergy with carbon

capture and storage (BECCS), contributing to eliminating more CO_2 emissions than are produced [6,7].

By 2030, sustainable production and supply of biomass will be important for the European Union, requiring the application of strict sustainability criteria to prevent negative impacts on biodiversity, food security and land use, involving sustainable forest management, use of agricultural residues and integration of biomass into the circular economy, reducing waste and increasing resource efficiency [2,8]. At the same time, biomass will play a key role in decarbonizing hard-to-electrify sectors such as air transport, maritime transport and heavy industry, where advanced biofuels produced from nonfood sources will provide sustainable alternatives to fossil fuels [3]. This will be particularly important in industries that require high temperature processes, such as cement, steel and chemicals, where other renewable energy options are not yet viable on a large scale [9]. Through these measures, biomass will not only make a significant contribution to achieving the EU's climate objectives but will also support the transition towards a more sustainable and resilient economy, capable of ensuring its energy security and reducing dependence on fossil energy imports [4,8].

The aim of this research is to assess the sustainability of bioenergy potential from agriculture in the European Union through a detailed analysis of material flow and emissions management, bioenergy and recycling impacts, as well as the degree of self-sufficiency and import dependency in the biomass economy in the period 2012–2021. This research aims to provide an in-depth understanding of how bioenergy can contribute to the European Union's energy transition and climate neutrality goals, while ensuring long-term economic and ecological sustainability.

Research objectives include the following:

O1: *Assessment of material flows and emissions associated with bioenergy use from agriculture in the European Union, identifying trends and their environmental impacts in the period 2012–2021.*

O2: *Analysis of the impact of recycling and biomass use on the economic and environmental sustainability of the European Union, with a focus on how these practices contribute to emission reductions and the circular economy.*

O3: *Determine the degree of self-sufficiency and import dependency in the EU biomass economy, assessing its stability and adaptability in the face of economic and environmental change.*

This study makes an original contribution in the context of existing research by assessing the sustainability of bioenergy from agriculture in the European Union, using an integrated approach on material flows, emissions and recycling for the period 2012–2021. This paper fills an important gap in the literature by assessing how the use of bioenergy can contribute to the EU's climate neutrality goals [2,3,7–9], while analyzing the impact on agricultural self-sufficiency and import dependence, and paying particular attention to identifying the interdependencies between biomass flows and environmental sustainability, an aspect that has not been sufficiently explored in previous studies. The originality of this study also derives from the linked analysis of the impact of EU policies such as the Renewable Energy Directive (RED II) on biomass supply chains, but also from the inclusion of an assessment of the circular economy and recycling practices, which are key to reducing waste and increasing resource efficiency in the bioenergy sector.

2. Literature Review

Biomass has a key role to play in the transition to renewable energy sources and in achieving the European Union's climate targets, but its large-scale use entails a number of challenges and limitations that require careful management to ensure sustainability and efficiency [4,10]. Thus, Banja et al. [11] review the support for bioenergy in the European Union, highlighting the diversity in measures adopted by member states, and that support mechanisms, such as support tariffs and support premiums, are essential for bioenergy, but vary significantly between EU countries. The authors recommend harmonization of

support measures at European level and their integration with the Renewable Energy Directive to ensure stable and long-term support necessary for bioenergy to succeed.

The first major issue to consider is sustainability and environmental impacts, as biomass production can compete with other land uses such as agriculture and conservation, creating significant risks of resource misuse; for example, mono-crop plantations for biomass can lead to biodiversity loss and soil degradation, replacing diverse ecosystems with single species crops [10,12–14]. Sikkema et al. [15] examine the contribution of solid biomass to achieving the European Union's renewable energy targets for 2020 and 2030, focusing on greenhouse gas (GHG) emission reductions and safeguards in the energy and forestry sectors. The authors highlight the growth of solid biomass as an important source of renewable energy, noting an increase from 6.1% to 8% of gross final energy consumption in the EU between 2010 and 2018. The study classifies EU countries into three groups: leaders (Sweden, Finland, and Estonia), which have reached or are close to reaching the 2020 targets, intermediate and laggards (France and Germany), which are having difficulties in reaching the targets. The paper also emphasizes the need for sustainable use of forest resources to ensure biomass growth without negatively affecting forest carbon stocks. In addition, expanding biomass production can lead to deforestation, which not only releases large amounts of carbon stored in trees, but also destroys natural habitats and disrupts fragile ecosystems [13,15–19]. These risks highlight the need for strict sustainable forest and agricultural land management practices to protect biodiversity and maintain ecological integrity while maximizing the energy benefits of biomass [1,11,13].

The second major challenge concerns carbon neutrality and emissions associated with biomass use [14,20]. Although biomass is often considered carbon-neutral, this implies a balance between carbon released during burning and carbon absorbed by new plants as they grow; thus, Kuznetsov et al. [16] explore the process of ignition and flame propagation in woody biomass particles used as an alternative to coal in thermal power plants. Experimental results have shown that the flame propagation rate depends significantly on the ambient temperature. At low-temperature conditions (873 K), flame propagation is minimal, but at higher temperatures (1273 K), the ignition rate increases four to five times. The study identifies two heating regimes, with a critical threshold at 873 K, affecting biomass particle size and behavior. However, there can be a significant time lag between carbon release and re-absorption, creating what is known as "carbon debt", which is particularly problematic when using woody biomass from forests [21,22]. This gap can take years or even decades to close, compromising short-term CO_2 reduction targets, and biomass burning produces not only CO_2 but also other air pollutants such as fine particulate matter, nitrogen oxides and volatile organic compounds, which can contribute to air quality problems and have negative effects on human health, especially in regions where biomass use for heating and cooking is intense [21,23]. In addition, burning biomass can generate methane and nitrous oxide, greenhouse gases much more potent than CO_2, which have an even greater impact on global climate change. Thus, in the case of Reference [24], Saeed et al. explore the combustion and explosion characteristics of pulverized wood treated by mild pyrolysis. It analyzes the explosive performances and flame propagation velocity for untreated and torrefied woody biomass (a mild heat treatment process). The study highlights the need for improved safety measures in biomass processing plants, given the increased risk of explosion for torrefied biomass compared to raw biomass, and Santamaría-Herrera et al. [25] investigate factors influencing the explosiveness of wood powders, such as particle size distribution, moisture content and microscopic structure. Among other things, the study highlights that wood dust with smaller particles and low moisture content has a much higher risk of creating an explosive atmosphere. Research included testing the flammability of sawdust and determining minimum explosive concentrations and minimum ignition temperatures for dust clouds and dust layers. The results showed that dust samples with fine and dry particles have higher explosive potential compared to dust collected from cutting processes, which tends to be less hazardous due to larger particle size and higher moisture content. The study emphasizes the importance of proper dust management in

wood processing industries to prevent explosion accidents. Danzi et al. [26] investigate the impact of the aging process on the ignition sensitivity of lignocellulosic dust, mainly used as biomass for energy production. Biomass was tested after a hydrothermal aging treatment to simulate long-term storage conditions. Results showed that ageing affects the chemical composition, morphology and brittleness of the materials, with a significant impact on the sensitivity to ignition and explosion. In addition, the efficiency of biomass to energy conversion varies considerably depending on the technology used [27], with traditional combustion systems being less efficient than modern technologies such as combined heat and power (CHP) plants or advanced biofuel production methods, highlighting the need for continued technological development to maximize energy efficiency and reduce emissions [28–31].

Energy production from biomass can be more costly than other renewable sources such as wind or solar due to supply [17,28,32], and transportation and conversion costs, and the biomass market is often volatile, influenced by supply and demand dynamics and policy changes; in addition, the economic viability of biomass is often dependent on government subsidies, and the long-term uncertainty related to these subsidies and policy support can threaten the sustainability of biomass projects, especially in the face of technological advances and changes in global energy priorities [23,29,33]. Thus Antar et al. [34] provide a detailed analysis of global biomass production and utilization to support a sustainable bioeconomy, exploring the potential of biomass from agricultural, forestry and urban waste sources and emphasizing the important role of beneficial microorganisms and genome editing technologies to enhance biomass production. The authors propose the use of microbial plant signaling compounds, such as lipo-chitooligosaccharides, which have demonstrated the ability to increase plant productivity, especially under stress conditions, and Karras et al. [35] examine the costs and prices of residual biomass, waste and secondary products in Europe, used as key economic parameters in techno-economic models. The analysis shows that prices for residual biomass range from 0 EUR/Mg for "organic waste from private households" to 1097 EUR/Mg for "woody biomass from vineyards". More than half of the sources analyzed did not take regional differences into account and many of the indicators used in the literature do not provide data with detailed temporal or spatial resolution.

Vlad and Toma [36] analyze the development of the bioeconomy and biomass sectors in central and eastern European (CEE) countries, with a focus on bioeconomy-based agriculture and biomass utilization between 2008 and 2019. The authors emphasize that these countries, after the enlargement of the European Union, have made a significant contribution in terms of agricultural and forest land area, which has created great potential for biomass used in bioenergy. In 2019, the bioeconomy market in CEE countries reached a turnover of around 324 billion EUR, representing 14% of the EU level. Of this, agriculture-based sectors generated 79 billion EUR, while food sectors contributed 116.8 billion EUR. Similarly, the study reveals that in 2019, 6.9 million people were employed in the bioeconomy sectors in these countries, almost 40% of the total number of people employed in the EU bioeconomy. Over the period under review, biomass production in these countries increased by 7.1%, contributing 27.8% to total EU production. However, the authors also highlight some challenges, such as low productivity and insufficient or underutilized use of biomass resources. Janiszewska and Ossowska [17] analyze the potential of agricultural biomass in the countries of the European Union, with a focus on its use for energy purposes. The study estimates the theoretical and technical potential of agricultural biomass from straw, hay, natural fertilizers, energy crops and residual wood from permanent crops. According to the research, agricultural biomass is an important resource for energy production in the European Union, as about 15% of the theoretical potential can be used for energy purposes. Of all the sources analyzed, straw from cereal crops and energy crops grown on fallow land have the highest potential. The authors also emphasize the significant geographical diversity in agricultural biomass potential in member states of the European Union, which may affect the economic efficiency of using this resource. Moreover,

Wieruszewski and Mydlarz [37] emphasize the role of biomass in European energy policies and strategies and estimate an increase in biomass energy demand from 7 EJ today to 10 EJ by 2023. The study underlines that biomass has the potential to play a key role in the EU's energy security, helping to reduce dependence on fossil fuels and contribute to greenhouse gas reduction targets. A significant increase in forest and agricultural biomass potential is expected in the coming years, supported by imports from non-EU countries, but also by the modernization of biomass conversion technologies. In conclusion, the study calls for increased investment in green technologies and their integration into the energy sector to meet the growing demand for renewable energy, as well as enhanced international cooperation to support the transition to a low-carbon society.

By 2030, second generation biofuels from lignocellulosic biomass will become a central pillar of the European Union's energy strategy, due to their ability to provide higher energy yields and lower greenhouse gas emissions compared to first-generation biofuels; thus, Duca and Toscano [38] provide a detailed analysis of biomass resources and bioenergy sustainability, focusing on the quality of the feedstock used for bioenergy production. The study emphasizes that in the context of the current challenges of climate change and fossil fuel dependency, biomass is becoming an essential resource for the transition to renewable energy sources. The authors emphasize the importance of using residual biomass, especially agricultural and industrial waste, to avoid competition between energy and food production. The conclusions of the study indicate that bioenergy plays a key role in the EU's renewable energy mix, contributing to the reduction of CO_2 emissions; however, to improve sustainability, greater efficiency in the biomass supply chain and standardization of biomass quality are needed. At the same time, biogas production and its conversion into biomethane will increase significantly, contributing to the decarbonization of the gas grid and providing an essential renewable energy source for heating and electricity generation [10,12,25,29]. Technological innovations in biomass conversion processes, such as advances in gasification and pyrolysis technologies, will increase energy efficiency and reduce emissions, thereby strengthening the role of biomass in the European Union's energy mix. In the context of the increasing use of bioenergy as a renewable energy source, Wang et al. [18] explore the challenges and opportunities presented by its development in different regions of the world. The authors emphasize that current assessments of bioenergy sustainability often focus on a single aspect, such as impacts on the environment or economic implications; in contrast, their study aims to integrate all relevant dimensions to obtain a complete picture of bioenergy sustainability. They also point out that there are discrepancies in the conclusions of existing studies on the net effects of bioenergy on carbon abatement, depending on the sources and production methods used.

In addition to these technological advances, policy and regulatory framework will play a key role in supporting the growth of biomass as a sustainable energy source; thus, the consolidation of the Renewable Energy Directive (RED II) will be vital to ensure that biomass contributes significantly to the achievement of the EU's renewable energy and climate objectives [2,3,7–9] through the introduction of stricter sustainability criteria, improved monitoring and rigorous reporting requirements. Thus, Saleem [39] analyzes the progress of the European Union (EU) member states in developing the bioeconomy and sectors that produce and process biomass. The research uses hierarchical cluster-based analysis to assess the performance of EU countries over the period 2015–2020, based on data published by the European Commission and Eurostat. During this timeframe, Belgium and Denmark revealed themselves as top performers, being identified as examples of best practice in bioeconomy; on the other hand, central and eastern European countries, although making progress, continue to face challenges in fully transitioning to the bioeconomy. In conclusion, the study provides a detailed analysis of bioeconomy developments in the EU, highlighting differences between member states and identifying opportunities for improvement, for less developed regions in particular.

Firoiu et al. [19] explore the potential of agricultural biomass as a regenerable and sustainable energy source, emphasizing that fossil fuel reserves are finite, with a projected

depletion by 2060, and that agricultural biomass offers a promising alternative, being available in significant quantities globally. The study discusses the various techniques for converting biomass to energy, including direct burning, gasification, pyrolysis and fermentation. Saleem [39] also analyzes the technical, economic and environmental challenges associated with using agricultural biomass for bioenergy production. These include soil impacts, competition between food and energy uses, and greenhouse gas emissions. The authors conclude that agricultural biomass can be used in a viable and sustainable way, given the development of modern technologies and the implementation of appropriate control measures, suggesting that the widespread adoption of agricultural bioenergy can support the transition to a green economy, contributing to energy security without jeopardizing food production. At the same time, financial incentives, such as subsidies and tax exemptions [11,15], will be essential to support sustainable biomass projects, especially those involving advanced biofuels and biogas production, thereby encouraging investment in sustainable supply chains. Carbon pricing, through mechanisms such as the European Union Emissions Trading System (EU ETS), will continue to incentivize the use of biomass over fossil fuels, particularly in sectors where carbon reduction is more difficult to achieve. These combined efforts will ensure that biomass not only contributes to the EU's climate goals, but also supports the transition to a circular and sustainable economy capable of reducing dependence on fossil resources and improving the region's long-term energy security.

3. Materials and Methods

To assess the sustainability potential of bioenergy from agriculture in the European Union, we analyzed a number of key indicators reflecting the economic, environmental and industrial developments in the period 2012–2021. These analyses focus on material flows, such as biomass, metal ores, non-metallic minerals and fossil energy carriers, as well as associated emissions and material accumulation in the economy [40,41].

The European Union was selected as a region of interest because it is at the forefront of energy transition policies towards renewables, biomass plays a central role in the European Union's decarbonization and energy security strategy, and EU directives such as RED II [10] regulate the use of biomass and set ambitious targets for 2030 [9], making this region a key topic for studying the potential of bioenergy. The choice of the European Union also reflects the geopolitical relevance of the region in the global discussions on energy and sustainability.

A 10-year timeframe (2012–2021) was selected as the period of analysis because it represents a period of significant changes in EU energy policies, culminating in the adoption of clear targets to reduce carbon emissions and increase the share of renewables. The period also includes important economic and political fluctuations, including the implementation of the RED II Directive and initiatives under the European Green Pact [3], which have influenced bioenergy production and consumption, allowing to capture these developments and the impact of the policies adopted. Various quantitative methods of analysis such as descriptive statistical analysis, temporal analysis and data linkage were used in this study, which are appropriate, as they allow for a detailed and accurate assessment of trends and relationships between different indicators. In the context of the transition towards a circular and sustainable economy, quantitative analysis is essential to identify trends and interdependencies in material flows and emissions, and the use of key indicators such as self-sufficiency and import dependence helps to understand the long-term sustainability of bioenergy in the European Union.

The data used in this analysis were collected from official databases of the European Union—Eurostat [42] and the European Environment Agency (EEA) [43]—which provide detailed and up-to-date statistics on imports, exports, emissions and use of natural resources, and were processed and aggregated to reflect annual trends over the decade under analysis (2012–2021).

Data were collected for the following main categories:

- Biomass imports and exports (thousand tons);
- Materials processed, including biomass and other resources (thousand tons);
- Biomass storage (thousand tons);
- Greenhouse gas emissions associated with biomass (thousand tons);
- Biomass use efficiency (%).

The research used quantitative methods to analyze the developments and trends of the indicators mentioned. The analysis included the following:

- Descriptive statistical analysis: means, medians and standard deviations were calculated for each indicator to better understand general trends over the period analyzed;
- Temporal analysis: the evolution of each indicator was assessed on an annual basis to identify periods of increase, decrease or stabilization and to correlate these trends with relevant economic and political events;
- Annual analysis: annual increases and decreases were analyzed to highlight year-to-year fluctuations, thus allowing for the impact of EU policies and market conditions on material flows and emissions to be interpreted;
- Correlation of data: the correlation between different indicators (e.g., between imports and associated emissions, or between processed biomass and material accumulation) was used to understand the interdependencies and side-effects of bioenergy and recycling on the environment and the EU economy.

Key indicators analyzed:

1. Self-sufficiency (%) is an indicator measuring the proportion of gross inland consumption of raw materials covered by domestic production. This indicator is calculated using the formula:

$$\text{Self-sufficiency (\%)} = \text{Domestic extraction}/\text{Gross inland consumption of raw materials} \times 100 \quad (1)$$

2. Import dependence (%) measures the percentage of gross inland consumption of raw materials that is covered by imports, using the following formula:

$$\text{Import dependence (\%)} = \text{Imports in raw material equivalents}/\text{Gross inland consumption of raw materials} \times 100 \quad (2)$$

3. Percentage exports (%) shows the percentage of domestic extraction of raw materials that is exported:

$$\text{Percent exports (\%)} = \text{Exports in raw material equivalents}/\ \text{Inland extraction} \times 100 \quad (3)$$

4. Gross inland consumption is the total natural resources used directly by an economy, calculated as follows:

$$\text{Gross inland consumption} = \text{Domestic extraction} + \text{Imports in raw material equivalents} - \text{Exports in raw material equivalents} \quad (4)$$

5. Trade balance is an indicator that measures the difference between exports and imports in raw material equivalents, indicating whether a country is a net exporter or a net importer of agricultural biomass. The formula used is as follows:

$$\text{Trade balance} = \text{Exports in raw material equivalents} - \text{Imports in raw material equivalents} \quad (5)$$

To achieve the above objectives, this paper will answer the following research questions:

1. What has been the evolution of agricultural biomass self-sufficiency in the European Union between 2012 and 2021 and what are the main drivers of the observed changes?
2. To what extent is the European Union dependent on agricultural biomass imports and how does this dependence affect agricultural sustainability and food security?
3. How has gross domestic consumption of agricultural biomass in the EU evolved and what is its relationship to self-sufficiency and import dependence?
4. What is the impact of the trade balance on the sustainability of agricultural biomass in the EU and how does it relate to self-sufficiency and import dependence?

5. What policies and strategies can be implemented to increase the sustainability of agricultural biomass in the EU while reducing import dependency and optimizing gross inland consumption?

4. Results

4.1. Managing Material Flows and Emissions in the European Union: The Impact of Bioenergy and Recycling 2012–2021

While biomass has the potential to play a significant role in the EU energy transition, it faces several limitations that need to be carefully managed; these include sustainability and environmental impacts, carbon neutrality concerns [3,9,44–46], efficiency and technological challenges, economic viability, social acceptability and regulatory complexities. Thus, the long-term impact of biomass in the EU is multi-faceted, with significant opportunities and challenges [46–48]. Biomass has the potential to play a key role in achieving carbon neutrality, supporting rural development and enhancing energy security; however, its long-term success depends on addressing sustainability concerns [49–52], managing land use efficiently, advancing conversion technologies and ensuring that policy frameworks are supportive and stable [32,33,53]. To maximize the positive impact of biomass, the European Union needs to focus on sustainable supply, integrate biomass into the circular economy, invest in technological innovation and develop sound policies that promote responsible use of biomass. In doing so, biomass can continue to contribute to the EU's energy and climate transition objectives well into the future [2,3,7,8,54–56].

Biomass is set to play a versatile and significant role in the European Union's energy mix, particularly in providing reliable base load electricity, decarbonizing heating systems and supplying advanced biofuels for transport [9,57]. Its role will be influenced by its ability to complement other renewable energy sources, contribute to energy security and support rural economies; however, [58], the long-term sustainability of biomass, both in terms of environmental impact and resource availability, will be key in determining its future contribution to the energy mix, and to maximize its potential, the European Union will need to continue to invest in technical innovation, apply strict sustainability criteria and integrate biomass into a broader strategy that includes other renewable sources and energy efficiency measures [56]. If these challenges are met, biomass can remain a cornerstone of the EU's energy transition and can make a significant contribution to the EU's climate and energy objectives up to 2030 and beyond.

Figure 1 shows the evolution of imports of waste for recovery and recycling in the European Union over the period 2012–2021.

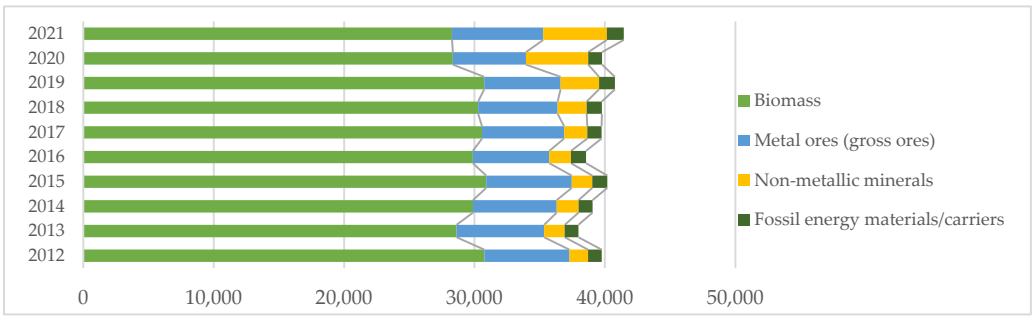


Figure 1. Imports of waste for recovery and recycling in the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total imports of waste for recovery/recycling have varied slightly over the period 2012–2021; thus, a gradual increase in total imports can be observed, culminating in 2021 with a maximum of 41,450 thousand tons, compared to a minimum of 37,967 thousand tons in 2013.

Biomass accounts for the largest share of total imports, and values have fluctuated slightly over the years, with a maximum in 2015 (30,895 thousand tons) and a mid-point in

2021 (28,272 thousand tons), while imports of metal ores have varied more significantly compared to biomass, with a minimum in 2020 (5598 thousand tons) and a maximum in 2021 (6995 thousand tons). Imports of non-metallic minerals have been increasing steadily with a notable increase between 2018 and 2021. In particular, a significant increase is observed in 2020 and 2021, indicating a possible increase in demand for non-metallic minerals due to demand in construction or other industries. Imports of fossil energy-bearing materials remained relatively constant over the years, with small fluctuations. The highest volume was recorded in 2021 (1301 thousand tons) and the lowest in 2020 (1050 thousand tons). Imports excluding imports of waste for recovery and recycling in the European Union in the period 2012–2021 are presented in Figure 2.

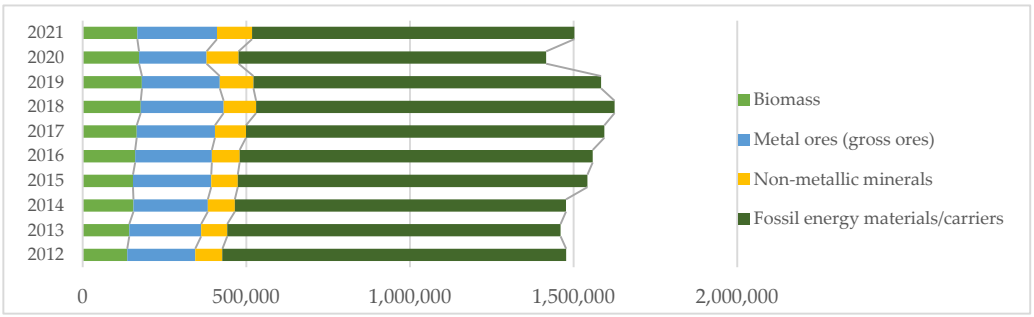


Figure 2. Imports excluding imports of waste for recovery and recycling in the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total imports steadily increased from 1,524,840 thousand tons in 2012 to a peak of 1,692,681 thousand tons in 2018. After this increase, there was a slight decrease in 2019 and 2020, followed by a partial recovery in 2021 to 1,577,490 thousand tons.

Biomass imports increased gradually from 136,062 thousand tons in 2012 to a peak of 180,978 thousand tons in 2019. After this peak, imports decreased slightly in 2020 and 2021.

Imports of metallic ores showed a steady increase with a peak in 2021 of 243,263 thousand tons, a steady increase reflecting a robust demand for these resources in the European Union. Imports of non-metallic minerals varied steadily, with a significant increase between 2017 and 2021, reaching a maximum of 107,385 thousand tons in 2021, while imports of fossil energy-bearing materials fluctuated, with a maximum in 2017 (1,094,746 thousand tons) and a minimum in 2020 (939,428 thousand tons).

Figure 3 shows the evolution of exports of waste for recovery and recycling in the European Union from 2012 to 2021.

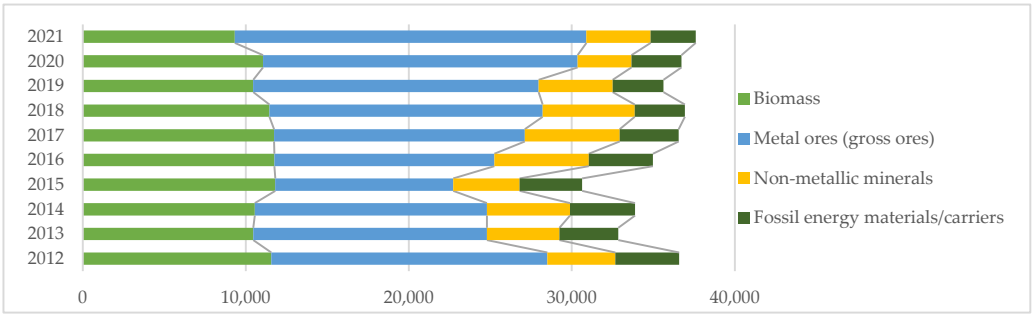


Figure 3. Exports of waste for recovery and recycling in the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total exports have fluctuated moderately over the period analyzed, with a minimum in 2015 (30,635 thousand tons) and a maximum in 2021 (37,608 thousand tons), indicating a gradual increase in the quantities of waste exported for recovery and recycling, with a rebound from a minimum in 2015.

Biomass exports varied slightly, with a minimum in 2021 (9325 thousand tons) and a maximum in 2015 (11,805 thousand tons), indicating a slight downward trend in biomass exports towards the end of the period under analysis. Exports of metallic minerals showed a general increase, peaking at a maximum of 21,568 thousand tons in 2021, while exports of non-metallic minerals fluctuated over the years, with a maximum in 2014 (5100 thousand tons) and a minimum in 2020 (3306 thousand tons). Exports of fossil energy-bearing materials decreased gradually over the period, from 3912 thousand tons in 2012 to a minimum of 2767 thousand tons in 2021. The evolution of exports excluding exports of waste for recovery and recycling in the European Union in the period 2012–2021 are shown in Figure 4.

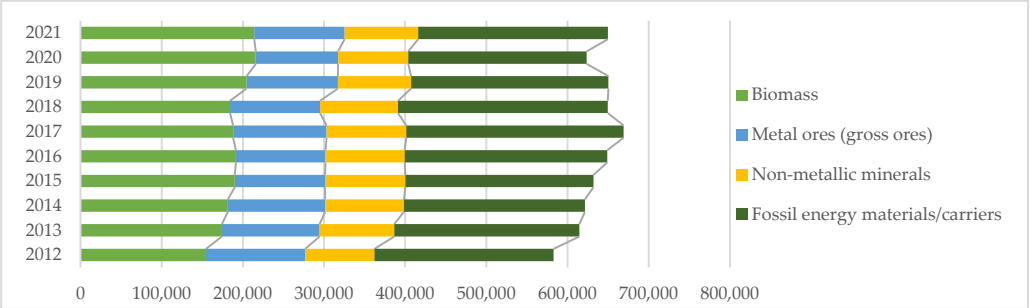


Figure 4. Exports excluding exports of waste for recovery and recycling to the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total exports had a steady increase from 633,083 thousand tons in 2012 to a peak of 728,377 thousand tons in 2017, after which the volume of exports remained relatively stable, with a slight decrease in 2020 and a rebound in 2021 to 708,648 thousand tons. Biomass exports increased gradually from 154,563 thousand tons in 2012 to a peak of 215,835 thousand tons in 2020, a steady increase indicating a growing demand for biomass in the European Union, while exports of metal ores varied slightly over the years, with a minimum in 2020 (101,565 thousand tons) and a maximum in 2017 (115,163 thousand tons), variations reflecting fluctuations in global demand for metal ores. Exports of non-metallic minerals remained relatively constant, with small fluctuations between a minimum of 85,275 thousand tons in 2012 and a maximum of 98,852 thousand tons in 2015, the stability indicating a constant demand for these materials, while exports of fossil-bearing materials showed a general upward trend, reaching a maximum of 267,664 thousand tons in 2017, after which exports decreased slightly, reaching 233,783 thousand tons in 2021.

Figure 5 shows the evolution of processed materials, including direct materials inputs and their recovery for recycling and backfilling from the European Union in the period 2012–2021.

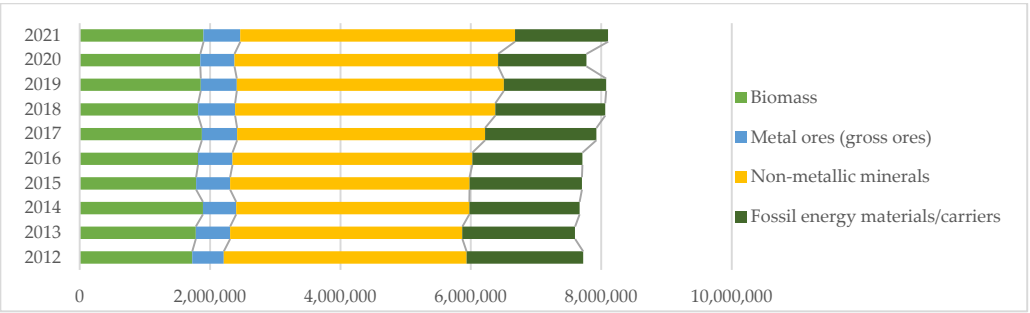


Figure 5. Materials processed, including direct input of materials and their recovery for recycling and backfilling, (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total materials processed increased from 7,769,666 thousand tons in 2012 to 8,180,066 thousand tons in 2021, a steady increase in material recycling and recycling activities in the European Union. Biomass processed has had a relatively steady increase, with a minimum of 1,726,688 thousand tons in the year 2012 and a maximum of 1,898,645 thousand tons in the year 2021, indicating an increasing use of biomass in recycling and recovery processes, while imports of metal ores varied moderately, with a minimum of 483,403 thousand tons in the year 2012 and a maximum of 568,093 thousand tons in the year 2018. Volumes of non-metallic minerals processed have steadily increased, with a minimum of 3,562,062 thousand tons in 2013 and a maximum of 4,212,932 thousand tons in 2021, indicating an increasing demand for these materials in recycling and recovery processes, while fossil-bearing materials have shown a slightly downward trend, with a maximum of 1,787,675 thousand tons in 2012 and a minimum of 1,354,617 thousand tons in 2020. Figure 6 shows the accumulation of materials in the European Union in the period 2012–2021.

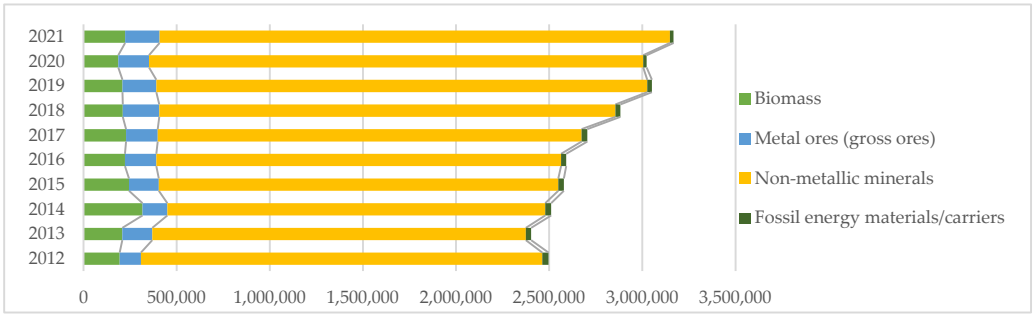


Figure 6. Accumulation of materials in the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total material accumulation has steadily increased from 2,496,634 thousand tons in 2012 to 3,167,661 thousand tons in 2021, indicating a general trend of increasing storage or accumulation of materials in the European Union in the context of growing economic and industrial activities. Biomass accumulation has varied over the years, with a maximum of 316,658 thousand tons in 2014 and a minimum of 186,757 thousand tons in 2020, indicating significant variability in biomass storage in the European Union, and metal ore accumulation has varied moderately, with a minimum of 114,174 thousand tons in 2012 and a maximum of 195,504 thousand tons in 2018. The accumulation of non-metallic minerals increased steadily, from 2,154,407 thousand tons in 2012 to 2,739,562 thousand tons in 2021, suggesting a continued increase in the demand and stockpiling of these materials in the economic processes in the European Union, while the accumulation of fossil-bearing materials had a general downward trend, with a minimum of 18,403 thousand tons in 2020 and a maximum of 33,966 thousand tons in 2012, reflecting a reduction in the use or storage of these materials in the context of the transition to more sustainable energy sources. The evolution of emissions in the European Union over the period 2012–2021 are presented graphically in Figure 7.

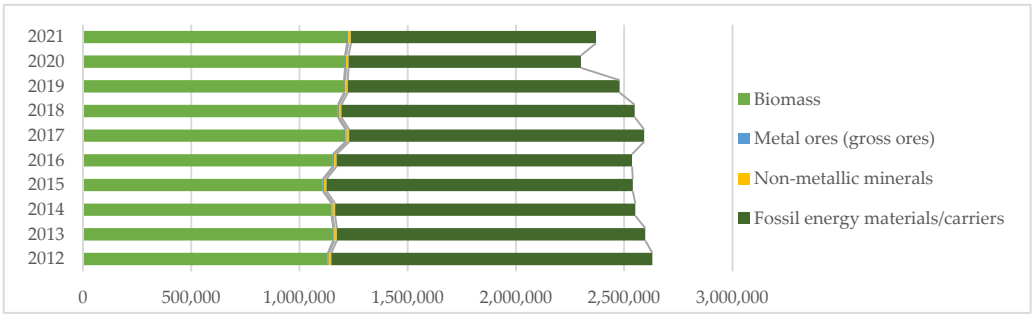


Figure 7. EU emissions (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total emissions gradually decreased from 2,630,080 thousand tons in 2012 to 2,369,933 thousand tons in 2021, an overall reduction in emissions as a result of the transition to more sustainable practices and the implementation of emission reduction policies in the European Union. Emissions from biomass were relatively stable with a slight increase between 2012 and 2021, from 1,130,344 thousand tons to 1,219,629 thousand tons, indicating a steady use of biomass for energy, possibly with some improvements in conversion efficiency, while emissions from metal ores remained relatively constant and low, ranging slightly between 5155 thousand tons in 2020 and 5788 thousand tons in 2021. Emissions from non-metallic minerals remained relatively constant with slight fluctuations around the range of 11,200 thousand tons, e.g., in the year 2021, emissions were 12,138 thousand tons, which is a slight maximum for the period under consideration, and emissions from fossil energy-bearing materials decreased significantly from 1,483,190 thousand tons in the year 2012 to 1,132,379 thousand tons in the year 2021.

Figure 8 shows the development of emissions excluding emissions from waste incineration in the European Union from 2012 to 2021.

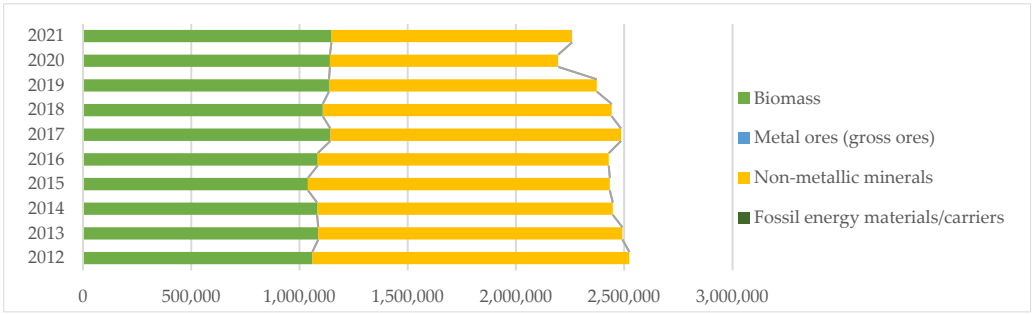


Figure 8. Emissions excluding emissions from waste incineration in the European Union (thousand tons) over the period 2012–2021. Source: Eurostat database [42].

Total emissions, excluding waste incineration, showed a downward trend, decreasing from 2,523,496 tons in 2012 to 2,259,216 tons in 2021; this decrease is in line with the overall reduction in emissions in the European Union, driven by reduced dependence on fossil fuels and increased energy efficiency in different sectors. Biomass emissions increase slightly from 1,059,429 tons in 2012 to 1,147,545 tons in 2021, suggesting that although biomass is increasingly used as an energy source, it remains a semi-significant contributor to overall emissions. However, these emissions are generally lower than those from fossil fuels, reflecting the cleaner nature of biomass. Non-metallic mineral emissions remain consistently minimal, recorded at 51 tons in 2012 and falling slightly to 43 tons in 2021; these minimal emissions suggest that processes involving non-metallic minerals have a negligible impact on emissions outside of waste incineration, and the low values reflect highly controlled emissions or processes with minimal impact on emissions.

Emissions from fossil energy materials show a significant decrease from 1,464,016 tons in 2012 to 1,111,628 tons in 2021; thus, the sharp reduction in fossil energy material emissions underlines the effectiveness of the European Union's policies to reduce fossil fuel consumption and transition to cleaner energy sources.

4.2. Assessing the Potential of Agricultural Bioenergy in the European Union

As the European Union aims to achieve climate neutrality by 2050, identifying and effectively harnessing the potential of agricultural bioenergy becomes essential, as it can not only help reduce dependence on fossil fuels and greenhouse gas emissions, but also contribute to enhancing energy security, stimulating rural development and creating new jobs [56]. By using agricultural residues, energy crops and organic waste, bioenergy from agriculture can become a pillar of economic and environmental sustainability in the European Union [3,9,59]. However, to maximize this potential, it is essential to overcome challenges related to competition for land, sustainability of production and integration

of environmental and energy policies; thus, assessing the potential of bioenergy from agriculture not only provides insight into available resources, but also into opportunities and obstacles to the EU energy transition [59,60]. This analysis aims to explore the many facets of this potential, from the availability of agricultural resources to the economic and environmental impacts, providing a solid basis for future policies.

Net biomass imports, representing the difference between imports and exports of biomass for recovery and recycling, is a key indicator of the EU's dependence on external biomass resources and its capacity to sustain bioenergy production from domestic sources (Figure 9).

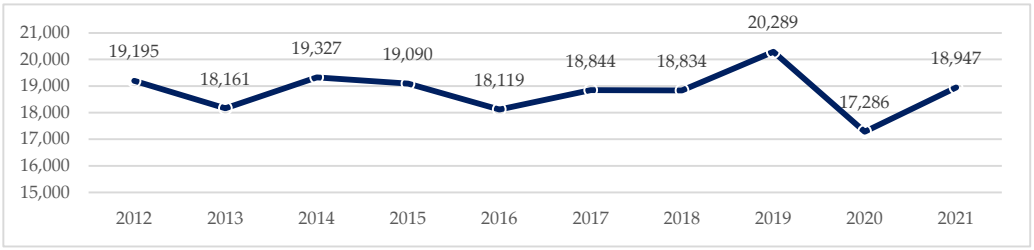


Figure 9. Net biomass imports (thousand tons) into the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

In the period 2012–2021, net biomass imports showed a relatively constant variation, with a slight decrease in recent years; thus, the European Union managed to maintain a stable biomass flow, but the dependence on external imports remained relatively high. A slight decrease may indicate either an increase in internal efficiency in biomass use or an increase in internal recycling and recovery capacity, which would reduce the need for imports. The average net biomass import over the 10 years was about 18,809 tons, with a standard deviation of 811 tons. This shows a moderate variation in biomass supply from external sources, and a relatively constant level of net imports suggests a stability in biomass supply, which is essential for long-term planning of bioenergy capacities.

Processed biomass indicates the total amount of biomass that is processed internally in the European Union, either for energy production or for other industrial uses (Figure 10).

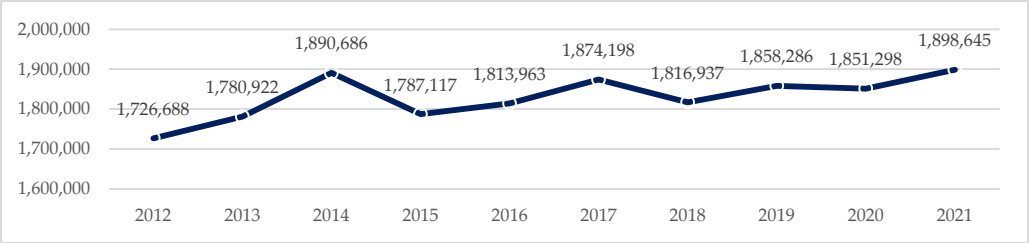


Figure 10. Biomass processed (thousand tons) in the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

Processed biomass has shown a steady upward trend over the period analyzed, peaking in 2021. This reflects an increase in the European Union's capacity to convert biomass into energy and other industrial products, and the increase in processing can be attributed to investments in processing infrastructure and biomass conversion technologies, as well as an increase in the availability of biomass on the internal market. The average biomass processed was about 1,829,874 tons per year, with a standard deviation of about 54,722 tons, indicating a steady and sustained growth of biomass processing capacity in the European Union, suggesting that the bioenergy sector is in an expansion phase.

Biomass accumulation reflects the amount of biomass that is stored or accumulated in the economy without being immediately processed or utilized. This may include biomass accumulated in soils, forests or other forms of storage (Figure 11).

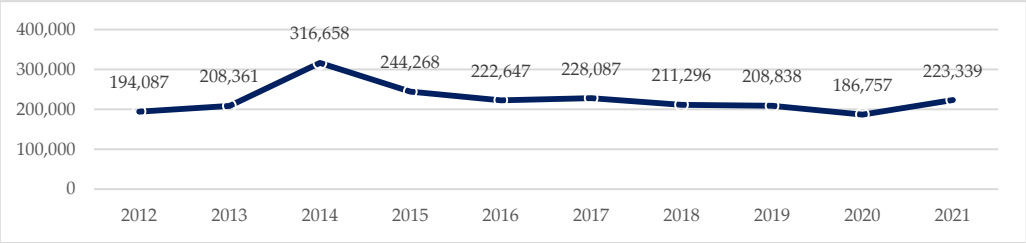


Figure 11. Biomass accumulation (thousand tons) in the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

Biomass accumulation has varied considerably over the years, with a semi-significant peak in 2014 and a slightly increasing trend towards the end of the period analyzed. Thus, fluctuations in biomass accumulation may be caused by factors such as variations in agricultural production, climate change or changes in land management policies. The average biomass accumulation was approximately 224,434 tons with a standard deviation of 36,410 tons. Thus, the fairly large variation in accumulation suggests that this indicator may be influenced by a number of external factors including weather conditions and agricultural policies.

Emissions from biomass reflect the total amount of greenhouse gas emissions generated by burning or using biomass, which is an important indicator of the environmental impact of biomass use (Figure 12).

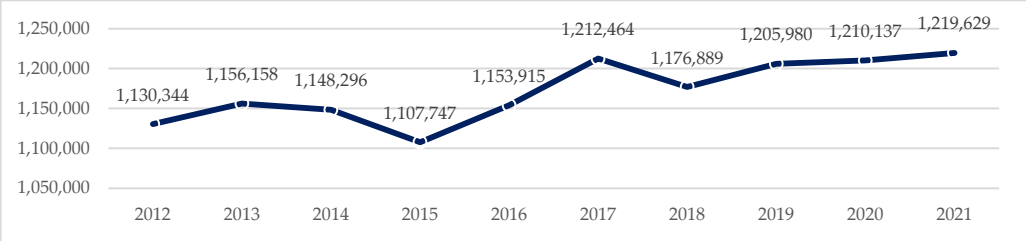


Figure 12. Biomass emissions (thousand tons) in the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

Biomass emissions have been relatively constant over the period analyzed, with slight variations depending on the amount of biomass processed and used each year. The stability of emissions suggests that the European Union has been able to control biomass emissions, even in the context of increasing use of biomass for energy. With biomass emissions averaging about 1,172,156 tons, with a standard deviation of about 38,790 tons, this stability indicates that although biomass use has increased, biomass technologies and practices have been successful in limiting the growth in emissions.

The biomass balance is an indicator of the net biomass availability in the European Union after accounting for imports, exports and processed biomass and is an important indicator of the domestic biomass resources available for use (Figure 13).

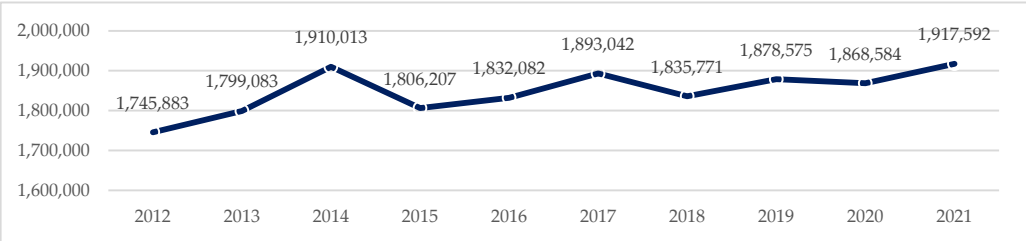


Figure 13. Biomass balance (thousand tons) in the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

The biomass balance showed a general upward trend, suggesting an increase in biomass availability in the European Union, whether as a result of increased domestic biomass production, improved efficiency in biomass use or reduced biomass exports. The average biomass balance was about 1,848,683 tons, with a standard deviation of about 54,814 tons, indicating an increasing availability of biomass for domestic use, which is positive for energy security.

Biomass utilization efficiency reflects the proportion of biomass that is efficiently used for energy production without generating significant waste or pollutant emissions (Figure 14).

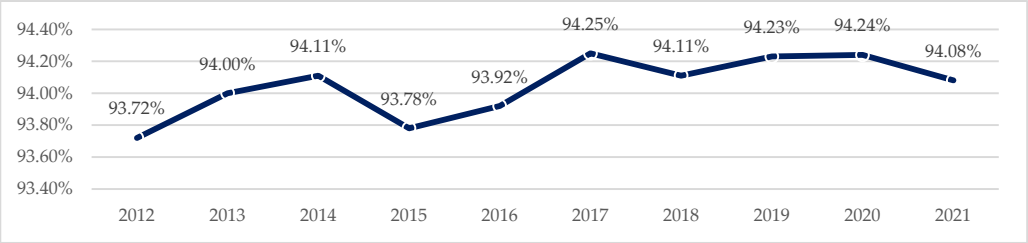


Figure 14. Biomass use efficiency (%) in the European Union over the period 2012–2021. Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

The efficiency of biomass use has been remarkably constant over the period, ranging between 93% and 94% in each year. This consistency suggests that over the years, the European Union has implemented and maintained efficient technologies and practices for the use of biomass in energy production. The fact that the efficiency has remained stable over such a narrow range indicates good management of biomass resources and minimization of waste. The average efficiency of biomass use over the period under review was around 93.8%, with a very small standard deviation, underlining that biomass use in the European Union has been consistently efficient, which contributes to reducing negative environmental impacts.

4.3. Analysis of Self-Sufficiency and Import Dependence in the Biomass Economy: Stability and Adaptability 2012–2021

Biomass plays a key role in the national economy, influencing a variety of economic and social sectors. Thus, increasing biomass extraction, exports, imports and consumption can contribute to sustainable economic development [61,62], increased international trade and the transition to a green economy; however, these developments bring challenges that require balanced economic and environmental policies to ensure sustainable and equitable development [63]. Thus, an increase in the domestic extraction of biomass and consumption of raw materials indicates an increased use of domestic natural resources, contributing to economic growth through the development of the agricultural, forestry, renewable energy and other related industries, which generates jobs and reflects a dynamic and expanding domestic economy, and increased biomass exports contribute to a positive trade balance and strengthen the national economy, while increased imports reflect high domestic demand and global economic integration, thus influencing exchange rates and economic stability, but also exposing the economy to vulnerabilities due to price fluctuations on the global market [64,65].

The increasing input of raw materials into the economy may signal a shift towards a circular and sustainable economy, with biomass playing a key role in the transition to a green economy, which may lead to stricter environmental policies, innovations in green technologies and new economic opportunities, but also challenges for traditional industries. Thus, the biomass sector contributes to job creation, especially in rural areas, reducing economic disparities, while increased extraction and consumption of biomass can influence energy and food prices [58,63,66], having a direct impact on the cost of living, while increased demand for biomass stimulates technological innovation, improving pro-

duction and utilization processes, thus increasing economic competitiveness and creating new industries [65]. This analysis provides insight into how biomass has been managed, used and marketed over the last decade, reflecting both the growth in the sector and the increasing demand for biomass at home and abroad. The data in Figure 15 can influence the economy in a number of ways, having a significant impact on different sectors and economic indicators.

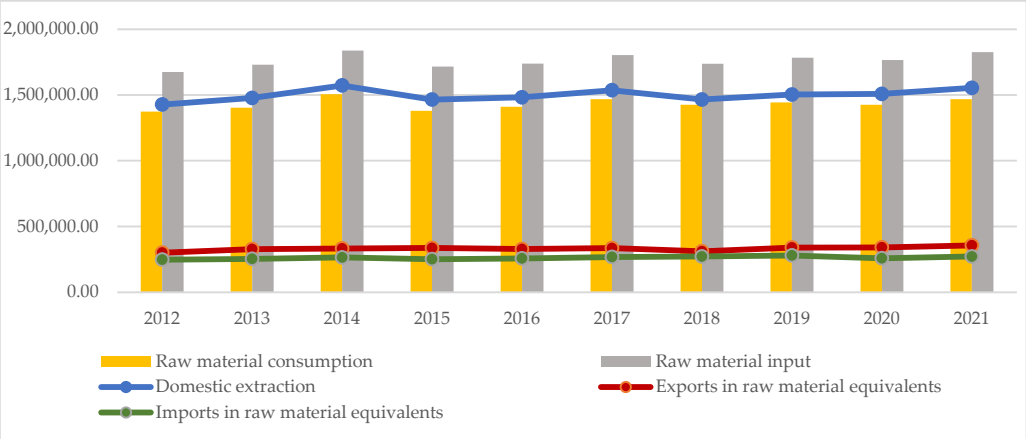


Figure 15. Evolution of domestic consumption, input and import/export flows of biomass in raw material equivalents (thousand tons) in the European Union over the period 2012–2021. Source: Eurostat database [42].

Domestic extraction has shown an upward trend, peaking at 1,553,480 thousand tons in 2021, after starting from 1,426,415 thousand tons in 2012, with minor fluctuations and a notable decrease in 2015 to 1,464,613 thousand tons, while exports in raw material equivalent gradually increased from 301,241.4 thousand tons in 2012 to 356,713.2 thousand tons in 2021, signaling a growing external demand for biomass, with a small decrease in 2016. Imports in raw material equivalents also followed an upward trend, increasing from 247,626.5 thousand tons in 2012 to 271,457.2 thousand tons in 2021, while consumption of raw materials increased from 1,372,800.1 thousand tons in 2012 to 1,468,224 thousand tons in the year 2021, with fluctuations over the years, reaching lower values in the years 2015 and 2018. The inflow of raw materials followed a steady increase from 1,674,041.5 thousand tons in the year 2012 to 1,824,937.2 thousand tons in the year 2021, reflecting stable growth in both domestic extraction and imports.

The data show a clear upward trend in all categories, indicating an overall increase in biomass-related activities including extraction, export, import, consumption and input, although there is an overall increase, and some periods (2015, 2016 and 2020) show slight decreases or stagnation in certain metrics, which could be due to economic, environmental or policy changes in those periods. Increases in both exports and imports suggest an increasingly interconnected global biomass market, playing a greater role in both biomass supply and supply.

Conducting a detailed and in-depth analysis of the percentage increases in the biomass economic indicators from one year to the next over the period 2012–2021 requires a careful examination of each indicator, identifying long-term trends and the factors that have contributed to fluctuations. This analysis highlights the complexity of biomass related economic interactions and the importance of an adaptive economic policy and sustainable development strategy. The percentage increases and decreases observed in different years suggest that the economy has undergone a series of adjustments and recalibrations, influenced by internal and external factors, in an attempt to optimize resource use and respond to global market demand.

Domestic extraction of biomass is one of the most important indicators in the analysis of natural resources, as it shows an economy's ability to secure the raw materials needed

for various industries by using domestic resources. Over the 2012–2021 period, domestic biomass extraction has experienced semi-significant fluctuations, highlighting changes in economic strategies, efficiency of natural resource utilization and external influences such as global demand and environmental policies. Over the 2013–2021 period, domestic biomass extraction experienced significant increases and decreases, reflecting both domestic and global demand dynamics as well as policy and regulatory adjustments. In 2013 and 2014, increases of 3.52% and 6.49% were driven by increased growth and expansion in renewable energy markets. However, in 2015, a decline of 6.86% indicated a policy adjustment due to market saturation and stricter environmental regulations. Stabilization followed in 2016 with an increase of 1.15%, and fluctuations in 2017–2018 (−4.57% and 3.65%) reflected policy uncertainties amid international price movements. In 2019–2021, extraction increased modestly, between 0.31% and 3.04%, signaling a return to stability and an adaptation to new economic conditions.

Biomass exports is a key indicator to understand an economy's position in the global market and its ability to capitalize on natural resources through exports. Growth or decline in exports can be influenced by many factors, including global demand, trade agreements, price competitiveness and the quality of exported products. In 2013, an increase of 8.72% indicated strong international demand for biomass and expanded export capacity due to improved infrastructure or new trade agreements, while between 2014 and 2015, modest increases of 1.40% and 1.35% reflected market stabilization after the rapid growth in 2013, and between 2019 and 2021, exports grew steadily, suggesting a stable upward trend.

Imports of raw materials is another key indicator that reflects an economy's dependence on external resources and its ability to meet its domestic needs through international trade. In 2013, imports of raw materials had an increase of 2.31% compared to 2012, indicating a slight increase in domestic demand. In the year 2014, an increase of 4.46% signaled a higher dependence on imports due to a decrease in domestic production. Between 2016 and 2021, imports fluctuated, with an increase of 5.18% in 2021, suggesting a return to normal demand after the declines in 2020.

Raw material consumption is a direct indicator of a country's economic health, reflecting industrial and manufacturing activity. Increases or decreases in consumption can signal changes in domestic demand, the level of industrial activity and the ability to meet market needs. In 2013, consumption of raw materials grew by 2.16%, which indicated a slight pick-up in economic activity, reflecting solid domestic demand, and in 2014, consumption of raw materials grew by a significant 7.31%, suggesting a strong economic expansion, supported by investment and industrial development. In 2015, the consumption of raw materials fell by 8.39%, and in 2016, the economy began to stabilize with an increase of 2.28%. Between 2017 and 2018, domestic demand fluctuated with an increase of 4.05% followed by a decrease of 2.86%, and between 2019 and 2021, the economy remained stable with moderate fluctuations, culminating in a rebound of 3.04% in 2021.

Input of raw materials into the economy combines domestic extraction and imports, providing an overview of the total availability of raw materials to the economy. In 2013, the indicator showed an increase of 3.34%, reflecting a moderate lack of availability of raw materials and suggesting a healthy economic expansion supported by both domestic and external resources, as in 2014, when it showed an increase of 6.19%. In 2015, the indicator fell by 6.63%, suggesting a significant economic contraction caused by a drop in domestic demand, and in 2016, a modest increase of 1.34% indicated a stabilization of the economy, recovering in 2017, (+3.71%). In 2018, the indicator had a decrease of 3.67%, which showed a further adjustment in the demand for raw materials. In 2019–2021, the increases in 2019 and 2021 (2.65% and 3.36%) reflected a stabilization and a slight rebound in demand, while the 0.96% decrease in 2020 was related to the impact of the COVID-19 pandemic on the global economy.

Over the period 2012–2021, the economy has been marked by a number of fluctuations in domestic extraction, exports, imports, consumption and inflows of raw materials. The observed fluctuations in domestic extraction indicate an economy sensitive to global

demand and domestic policies, with periods of expansion and contraction influenced by economic and regulatory factors. Exports were a major contributor to economic growth, but were also subject to significant variations, reflecting global market dynamics and international competitiveness, while imports and domestic consumption showed a balance between growth and contraction, indicating an economy that has adapted to changes in domestic and external demand and supply. The inflow of raw materials was an indicator that reflected the overall capacity of the economy to sustain production and consumption, highlighting both opportunities and challenges in maintaining a steady flow of resources.

Table 1 shows the evolution of biomass economic and trade indicators over the period 2012–2021.

Table 1. Evolution of biomass economic and trade indicators over the period 2012–2021.

Period	Biomass Trade Balance (Thousand Tons)	Share of Imports in Raw Material Consumption (%)	Share of Exports in Domestic Extraction (%)	Gross Inland Consumption (Thousand Tons)	Import Dependence (%)	Degree of Self-Sufficiency (%)
2012	53,614.89	18.04	21.12	1,071,558.71	14.79	103.91
2013	74,176.91	18.06	22.18	1,074,962.40	14.64	105.29
2014	67,465.11	17.58	21.12	1,172,868.09	14.41	104.48
2015	85,911.74	18.18	22.98	1,042,105.56	14.61	106.23
2016	71,253.54	18.22	22.16	1,081,928.50	14.78	105.05
2017	68,254.76	18.22	21.86	1,131,627.48	14.83	104.65
2018	39,931.79	19.04	21.25	1,113,982.00	15.63	102.80
2019	59,613.09	19.38	22.58	1,103,994.22	15.69	104.13
2020	82,660.45	18.11	22.60	1,084,172.77	14.62	105.80
2021	85,256.00	18.49	22.96	1,111,510.83	14.87	105.81

Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

The trade balance of biomass remains positive throughout the period, indicating that the European Union is a net exporter of biomass, thus the highest values are in 2015 and 2021, indicating a strong export capacity in these years. Over the period analyzed, the biomass trade balance shows significant fluctuations from year to year, however, there is a general trend of maintaining a positive surplus, indicating that biomass exports have exceeded imports in each year. The highest trade balance values were recorded in 2015 (85,911.74 thousand tons), followed by 2021 (85,256.00 thousand tons), suggesting that in these years, exports increased significantly relative to imports, and the lowest value was recorded in 2018 (39,931.79 thousand tons), indicating a year in which the biomass trade surplus was considerably reduced.

The percentage of imports from the consumption of raw materials fluctuates between 17.58% and 19.38%, showing that about 18% of domestic consumption is covered by imports, with a slight increase in 2018 (+0.82% compared to 2017) and 2019 (+0.34% compared to 2018), and the percentage of exports from domestic extraction varies between 21.12% and 22.98%, indicating that a significant part of domestic extraction is destined for export, thus the highest values are in 2015 (18.18%) and 2021 (18.49%). Gross domestic consumption represents biomass available for domestic consumption after the decrease in exports, and the fluctuations reflect the variations in exports and domestic consumption, thus the dependence on imports remains relatively constant, between 14.41% and 15.69%, showing a moderate dependence on imports for the total input of raw materials, and the degree of self-sufficiency is above 100% in all years, indicating a high self-sufficiency capacity, i.e., domestic biomass production is sufficient to cover domestic consumption.

Table 2 presents the statistical analysis of biomass economic and trade indicators for the period 2012–2021.

Table 2. Statistical analysis of biomass economic and trade indicators for the period 2012–2021.

Indicators	Average (2012–2021)	Median	Standard Deviation
Biomass trade balance (thousand tons)	71,813.83	69,754.15	15,840.63
Share of imports in raw material consumption (%)	18.23	18.20	0.46
Share of exports from domestic extraction (%)	21.96	22.17	0.69
Gross inland consumption (thousand tons)	1,098,971.86	1,094,083.50	34,649.52
Import dependence (%)	14.89	14.78	0.41
Degree of self-sufficiency (%)	104.82	104.85	0.99

Source: author's calculations based on Eurostat and European Environment Agency database [42,43].

The average biomass trade balance over this period is a useful indicator to assess the average surplus of exported biomass in relation to imports; thus, the average is 71,813.83 thousand tons, indicating a constant average surplus over the period, and the median trade balance is 69,754.15 thousand tons. The calculated standard deviation is about 15,840.63 thousand tons, suggesting that trade balance values can vary considerably from year to year, reflecting significant volatility in the biomass market.

The average percentage of imports (2012–2021) is 18.23%, indicating that, on average, about 18.23% of raw material consumption was covered by imports during this period, and the median is 18.20%, indicating a fairly even distribution of values around this average. The average of the percentage of exports (2012–2021) is about 21.96%, indicating that, on average, almost 22% of the domestic biomass extraction was destined for exports during this period, and the median is 22.17%, confirming a fairly balanced distribution of values around this average.

Gross inland consumption has varied significantly over the ten years, indicating fluctuations in the amount of biomass used domestically; thus, the average gross inland consumption is about 1,098,971.86 thousand tons, indicating a stable average inland consumption over the period, and the median is 1,094,083.50 thousand tons, indicating a slightly concentrated distribution around the calculated mean.

During the ten years, the value of the import dependence indicator varied in a relatively narrow range, between 14.41% and 15.69%. Thus, the average is about 14.89%, indicating a stable average dependence of the economy on imports during the period analyzed, and the median is 14.785%, indicating a distribution very close to the calculated average; the average of the degree of self-sufficiency is 104.82%, which indicates that, on average, the economy produced about 4.82% more than the domestic demand of raw materials during the period analyzed, and the median is 104.85%, very close to the overall average, suggesting a balanced distribution of values around this average.

5. Discussion

Interpretation of the analysis of the indicators reveals several important trends in the European Union; thus, total imports of waste for recovery and recycling have increased moderately, suggesting an intensification of recycling activities [7,8,11,31,36,44,65], with biomass remaining predominant, reflecting the continued commitment to renewable energy sources [26,49,65–67]. In parallel, rising imports of non-metallic minerals indicate an expanding industrial activity. Total imports, excluding waste for recovery and recycling, showed a steady increase until 2018, followed by a slight decrease, with robust demand for biomass and metal ores.

On the exports side, total waste for recovery and recycling fluctuated moderately, but experienced a general increase towards the end of the period under review [9,10,26,34,66]. Exports of metal ores increased significantly, suggesting strong international demand, while exports of biomass and fossil energy carriers remained relatively stable. Exports excluding waste followed an upward trajectory in the first six years, stabilizing thereafter, with biomass and fossil energy-bearing materials indicating growing demand in international markets, in contrast to stable exports of non-metallic minerals.

The analysis of materials processed, including recovery and recycling, shows a steady increase in the volume of materials processed in the European Union, with biomass and fossil energy bearing materials showing stable growth and non-metallic minerals showing major fluctuations, reflecting adaptations to market demand and environmental policies. In terms of material accumulation, the data show a general increase across the European Union, with non-metallic minerals and pure fossil energy materials showing the largest increases, while biomass and metal minerals showed variability, suggesting a circular economy influence [25,31,46,66,68,69].

On the emissions side, there was an overall decrease in total emissions in the European Union, in particular from fossil energy-bearing materials, indicating the success of carbon abatement policies, while emissions from biomass and non-metallic minerals remained relatively constant, suggesting a stable use of these resources.

The results of the analysis assessing the potential of bioenergy from agriculture in the European Union indicate a general upward trend in net imports of biomass into the European Union between 2012 and 2021, highlighting an increasing dependence on external resources. This trend suggests potential risks for the EU's energy security, making it necessary to develop strategies to increase domestic production and biomass recovery capacities. Thus, processed biomass has steadily increased over this period, reflecting the EU's efforts to harness biomass resources efficiently for energy and other products [3,7,70]. This growth is a positive sign for reducing dependence on fossil fuels and meeting the EU's environmental objectives; however, analysis of biomass accumulation suggests that there is still untapped potential in the use of these resources and that high accumulation may indicate inefficient management, which underlines the need for policies to stimulate more efficient use of accumulated biomass to maximize economic and environmental benefits [7,9,71].

Emissions from biomass use have remained relatively stable, but keeping these emissions under control is important for the long-term sustainability of bioenergy and it is essential that the European Union invests in more efficient and cleaner technologies to minimize environmental impacts [8,9,72].

The positive and growing biomass balance in the European Union indicates progress in securing the domestic resources needed to support bioenergy production. This trend is helping to reduce import dependency and increase energy sequestration while providing energy price stability, and the efficiency of biomass use has increased, which is essential to ensure the sector's environmental and economic sustainability [73]. This increased efficiency helps to reduce production costs and limits the need for additional imports, thus strengthening the long-term sustainability of bioenergy in the European Union.

The European Union has made significant progress in the utilization and management of biomass resources for bioenergy production; in particular, the steady increase in processed biomass and the positive biomass balance suggest that the European Union has become increasingly capable of managing its internal biomass resources to meet its energy needs [10,28,34,44,62,74]. However, net imports of biomass, although relatively stable, still indicate a dependence on external resources; although this may be manageable at present, a reduction in this dependence would be beneficial in the longer term, especially in the context of possible geopolitical tensions or global economic changes that could affect the availability of these resources [68].

The use of biomass for bioenergy needs to take into account environmental impacts, as although it is a renewable source, inappropriate use can lead to deforestation, soil degradation and greenhouse gas emissions [75]. The European Union has managed to maintain a balance between the efficient use of biomass and environmental protection, but this balance needs to be strengthened in the long term; at the same time, as demand for bioenergy increases, it is essential that policies include measures to protect soil and biodiversity, and increasing recycling capacities and efficient use of agricultural and forestry waste can reduce pressure on primary biomass resources, contributing to sustainability [69,76].

The economic outlook for the use of biomass for bioenergy underlines the importance of developing a strong industry that can create jobs, stimulate innovation and contribute to the energy security of the European Union; thus, a stable and well regulated market for biomass can encourage investment in infrastructure and new technologies, ensuring price stability and long-term competitiveness, while government support, in the form of subsidies and incentives, is crucial to make bioenergy competitive and promote the development of efficient and sustainable technologies.

Despite progress, the bioenergy sector faces significant challenges, such as competition for resources, where biomass is in demand in multiple industries, making fair and efficient allocation of these resources essential; climate change also poses risks that may affect biomass availability, and ensuring environmental sustainability by preventing ecosystem degradation and net carbon emissions is a major challenge, but also an opportunity to promote sustainable practices and certification of biomass resources.

6. Conclusions

Agricultural biomass in the European Union has significant potential to contribute to the energy transition and to achieving climate neutrality objectives. However, the challenges of import dependency and ensuring environmental sustainability require well-coordinated policies and strategic investments, so bioenergy, together with advanced technologies and a supportive regulatory framework, can become a central element of the EU's sustainable energy mix. The development of agricultural biomass self-sufficiency in the EU between 2012 and 2021 has seen a slight increase over the period under review, as a result of policies geared towards the development of sustainable agriculture and bioenergy. Improved management of natural resources, increased local biomass production and the integration of more efficient technologies have contributed to this development; however, climate change, droughts and international market fluctuations have negatively influenced the stability of self-sufficiency in certain periods.

The EU continues to rely to some extent on imports of agricultural biomass, especially for advanced biofuels and the specific resources needed for bioenergy production. This dependence affects long-term energy security and sustainability, increasing vulnerability to external market fluctuations and disruptions in supply chains, and imports can have indirect effects on food security, as some agricultural biomass is obtained from crops that compete with food production. Gross inland consumption of agricultural biomass grew steadily between 2012 and 2021, fueled by demand for biofuels and bioenergy. Although this contributed to greenhouse gas emission reductions and increased self-sufficiency, it also underlined the EU's vulnerability to imports needed to meet additional demand, and self-sufficiency increased, but not at the pace needed to completely eliminate import dependence. The trade balance for agricultural biomass remained negative, reflecting a significant ratio of imports to exports, underlining the need to strengthen domestic production to reduce import dependence and improve long-term sustainability. Overall, there is a direct correlation between import dependence and the EU's vulnerability to global market disruptions, and a positive trade balance would contribute to bioenergy security and resilience in the region.

In order to improve the sustainability of agricultural biomass, the EU should implement more rigorous policies that encourage sustainable local biomass production, supporting farmers and the bioenergy industry through financial incentives and advanced technologies. Promoting regenerative agriculture, recycling and the circular economy will help optimize gross inland consumption and reduce waste. Future strategies should include developing coherent policies to integrate bioenergy into the EU's energy and environmental plans, stimulating research and innovation to develop more efficient and cleaner technologies, promoting a circular economy through the full and efficient use of biomass and organic waste, and ensuring a legal framework that protects ecosystems and prevents deforestation or other forms of environmental degradation. Bioenergy thus has the potential to become a central element of the energy transition in the European Union, if

managed sustainably. Promoting a circular economy should focus on implementing strong legislation to encourage waste reduction and sustainable resource use, extending extended producer responsibility (EPR) to encourage sustainable product design and promoting sustainable materials such as biodegradable plastics and low-carbon building materials. To strengthen climate and energy policies, future strategies should focus on the successful implementation of the European Union's Green Pact, which aims to make Europe the first climate-neutral continent by 2050, and on reforming the European Union Emissions Trading System (ETS) by tightening the emissions cap and expanding the sectors covered. Adaptation and resilience planning are also essential to protect communities and ecosystems from the impacts of climate change, and to encourage sustainable agriculture and responsible land use, future strategies should promote climate-smart agricultural practices that reduce emissions and enhance carbon sequestration, such as precision farming, agroforestry and regenerative agriculture. In addition, sustainable forest management needs to be improved to increase carbon sequestration and preserve biodiversity, through reforestation initiatives and protection of existing forests. Reducing agricultural emissions should be supported by policies that encourage the use of alternative fertilizers and improved manure management.

The European Union has made significant progress in reducing emissions and making the transition to a sustainable economy, but achieving the ambitious targets of the Green Pact will require continued efforts in areas such as the uptake of renewable energy, electrification, the circular economy, innovation and sustainable agriculture, and biomass is poised to play a key role in the European Union's energy and climate strategy to 2030, serving as a key component in the transition to a sustainable and low-carbon energy system, contributing to energy security and carbon neutrality. One of the main limitations of this research is the dependence on available data, which, although covering an extended period (2012–2021), may not fully reflect recent developments in the energy market and policies. Also, the lack of detailed local-level data on the impacts of biomass on ecosystems, biodiversity and soil may limit a full understanding of the environmental effects of bioenergy use. Additionally, the analysis focused on quantitative indicators and could be complemented by qualitative research on the perceptions of key industry stakeholders.

Future research should focus on assessing the impact of emerging technologies on energy efficiency and emissions from biomass utilization, such as carbon capture and storage (BECCS). It would also be useful to investigate the geopolitical impact on the biomass market, given international tensions and fluctuating energy prices. Other research directions could include exploring the relationship between bioenergy and the circular economy to identify solutions to reduce unutilized biomass storage and benchmarking between EU member states to identify the most effective policies and practices.

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