

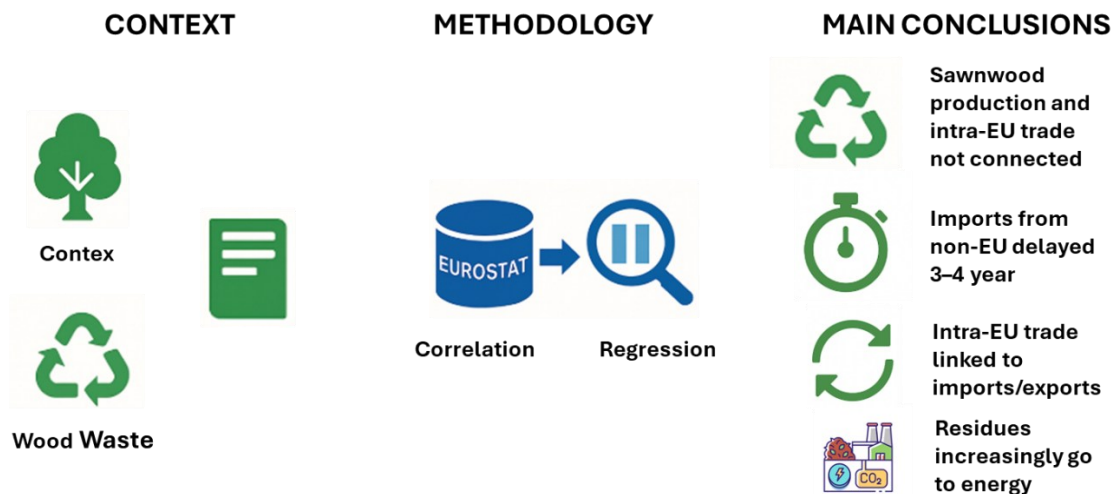
EU Wood Products and Waste Markets: Trends, Trade Dynamics, and Sustainability Perspective

Jelena Crnojević ^a, Andreja Pirc Barčič ^{a,*}, Azra Tafro ^a, Karla Vukman ^a,
Kristina Klarić ^a, Manja Kitek Kuzman ^b and Ivana Perić ^a

*Corresponding author: apirc@sumfak.unizg.hr

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GRAPHICAL ABSTRACT



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Jelena Crnojević ^a, Andreja Pirc Barčič ^{a,*}, Azra Tafro ^a, Karla Vukman ^a,
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The transition to circular bioeconomy in the European Union prioritizes efficient wood resource utilization and waste reduction. This study investigated interrelationships among production of sawnwood and particleboard, as well as intra- and extra-EU wood waste trade from 2004 to 2023 to evaluate alignment with sustainability and climate policy objectives. Eurostat data were analyzed using correlation, cross-correlation, and regression analyses. Sawnwood production peaked at 113.1 million cubic meters in 2007 and declined to 88.3 million cubic meters in 2023. Particleboard production decreased from 80.3 to 52.2 million cubic meters over the same period. Wood waste generation reached 63.1 million tonnes in 2008 and fell to 46.8 million tonnes in 2022, during which time the wood processing sector reduced waste by nearly 68%. No consistent relationship was identified between sawnwood production and internal wood waste trade, nor between internal waste trade and particleboard production. Imports of wood waste demonstrated delayed positive effects on production, and a moderate positive relationship was observed between internal waste trade and waste imports. Using wood residues for energy recovery limits its availability for higher value applications. These findings emphasize the necessity for policies that balance renewable energy targets with long-term material circularity.

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Keywords: Wood waste; Wood products; Market trends; Circular economy; Climate change mitigation; European Union.

Contact information: a: University of Zagreb, Faculty of Forestry and Wood Technology, 10000 Zagreb, Croatia; b: University of Ljubljana, Biotechnical Faculty, Department of Wood Science and Technology, 1000 Ljubljana, Slovenia; *Corresponding author: apirc@sumfak.unizg.hr

INTRODUCTION

The application of circular economy concepts that strive to optimize material resource efficiency and reduce waste generation is crucial for environmental sustainability and climate change mitigation. Furthermore, environmental sustainability and the circular economy are complementary concepts. Environmental sustainability refers to using resources to meet human needs without compromising the health of the ecosystems that provide them (Goldhahn *et al.* 2021), while the circular economy is a model of production and consumption that emphasizes sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products for as long as possible (European Parliament 2023).

The European Union, (European Parliament 2015; European Commission 2020), presented the concept of sustainable development, which introduces a systematic solution

to the issue of environmental protection, sustainable consumption and production, waste management in an environmentally friendly way and the process of informing the public about negative impacts and the production of environmentally friendly products. Furthermore, wood is an important part of the bioeconomy strategy of the European Union (European Commission 2018). More precisely, wood is considered the most important renewable resource for a future sustainable bioeconomy because it can help to realize environmental sustainability. For example, Finland has become a role model on the use of wood for the development of bio-economy and circular economy aiming to carbon-neutral society.

Utilizing and recycling wood waste in wood manufacturing has been associated with both environmental and economic benefits, primarily through waste reduction, resource conservation, and the development of secondary markets for recycled wood products. Wood-based functional materials are often discussed in the literature as potential alternatives to conventional materials derived from fossil feedstocks (Jiang *et al.* 2018; Mi *et al.* 2020; Goldhahn *et al.* 2021). In practice, the implementation of sustainable manufacturing approaches may also support companies in responding to growing demand for environmentally responsible products. In addition, recycling-related activities in the wood sector can create employment in collection, processing, and manufacturing, while the reuse of materials can extend the service life of equipment and machinery.

Efficient use of wood resources is inherently linked to the availability and sustainable management of Europe's forests (Klarić *et al.* 2024). Europe's 227 million hectares of forests cover approximately 35% of its land area, with about 75% available for wood supply. The total growing stock amounts to 34.9 billion m³, 84% of which is in forests accessible for wood supply. Roundwood production has been steadily increasing, amounting to 510 million m³ in 2022, of which about 24 to 25% is fuelwood and the remainder is industrial roundwood (Eurostat 2023). It is also important to note that roundwood production is more than 25% higher than in 2000. Between 2010 and 2020, the average annual carbon sequestration in European forest biomass was 155 million tonnes (Mt) (UNECE/FAO 2020). According to the 2016 European Commission report (Vis *et al.* 2016) on the optimized cascading use of wood, the sustainable technical supply of wood from forests in the EU-28 was estimated at 720.6 million m³ in 2010. Of the 52.3 million m³ of used wood annually, approximately 36.4 million m³ are recovered: 32% for material applications, 37% for energy, and 30% still disposed of without recovery.

Lundmark *et al.* (2014) contend that optimizing Sweden's domestic CO₂ balance requires greater use of wood products, such as sawn timber and wood-based panels. Drawing on Swedish and Finnish case studies, Gustavsson *et al.* (2006) demonstrate that producing wooden building materials generally requires less energy and results in lower CO₂ emissions than concrete materials. They also point out that wood products serve as carbon storage throughout their service life. Therefore, expanding the use of wood in construction is recognized as a strategy for CO₂ emission reduction, despite forest disturbances and other challenges.

Wood should be first utilized in long-lived structural applications where its carbon storage and substitution effects are maximized. Next, following the cascading use principle, it should be downcycled into lower-value products such as panels, and ultimately used for energy recovery (Höglmeier *et al.* 2015; Vis *et al.* 2016). This hierarchy is consistent with recent research indicating that reuse of timber elements represents the most sustainable end-of-life strategy, followed by recycling and energy recovery as the last option (Patrizi *et al.* 2026).

Patrizi *et al.* (2026) emphasize that maintaining structural components in use for as long as possible and reusing them in the same or similar applications is the key element of circular approaches in timber construction. That way, timber preserves both its material value and structural function. However, the implementation of such strategies is constrained by challenges related to the assessment of mechanical properties, degradation, and the structural reliability of recovered wood elements (Ranttila *et al.* 2025).

Besides seas and oceans, wood represents one of the most important atmospheric carbon storage resources. However, neither wood product manufacturers nor end consumers are fully aware of their role and potential impact in reducing the environmental footprint of wood-based products. This lack of awareness also affects how wood waste is managed across different stages of the product lifecycle and in various sectors.

Wood waste or wood residues can come from multiple different sectors, of which the construction and demolition section will be addressed and examined. Other sectors and products could be furniture, disposable pallets, wooden packaging, and waste wood from sawmills.

According to Christensen (2023), wood waste generation varies significantly across different global regions. In 2020, the United States generated approximately 55.75 Mt of wood waste. During the 2018–2019 period, Australia reported a total of 2.31 Mt, with the commercial and industrial sector (CandI) contributing 64.3% (1.52 Mt) and construction and demolition waste (CandD) accounting for 25.8% (0.80 Mt). In Hong Kong, around 20.72 Mt of CandD wood waste (CDWW) were produced in 2020. Within the EU-28, wood waste generation was estimated at approximately 50.2 Mt. Germany alone produced around 11.9 Mt in 2015, of which 29.7% (3.53 Mt) originated from construction and demolition activities. In the United Kingdom, 4.5 Mt of wood waste were generated in 2021, with around 0.5 Mt ending up in landfills. Similarly, Sweden reported a total of 14.6 Mt of CandD waste in 2020, of which 0.57 Mt consisted of wood.

Wood products also sequester carbon outside of forests (Johnston and Radeloff 2019); therefore, both the quantity of wood used and the ways in which it is utilized have important implications for forest resource management at national, European, and global levels. As a green, renewable, and biodegradable material, wood represents a valuable resource for the development of more sustainable materials (Goldhahn *et al.* 2021). In practice, wood waste is either used for energy generation or recycled into new material products. According to Knauf (2015), the material use of wood waste focuses primarily on the production of particleboards, with approximately one-third of the European particleboard supply derived from recycled wood. However, the energy use of waste wood often surpasses its reuse. For instance, in Germany only 20% of waste wood is recycled, while the remaining 80% is directly incinerated (Garcia and Hora 2017). For the EU28, the total post-consumer wood potential in 2010 was estimated at 52 million m³, of which 36 million m³ were utilized and 16 million m³ disposed. In comparison, sawmill by-products amounted to 82 million m³, meaning that their use was 2.4 times higher than that of post-consumer wood (Mantau *et al.* 2010; UNECE/FAO 2012).

Already in 2010, Jonsson (2010) predicted that the pressure to reuse larger amounts of waste wood would intensify as wood demand was expected to exceed supply. This anticipated growth in demand underscores not only the urgency of improving wood waste recovery but also the strategic importance of the wood-based sector in supporting Europe's transition to a circular and bio-based economy (Kuzman *et al.* 2024; Vukman *et al.* 2024). Recent studies further highlight that strengthening digital and sustainability competencies, alongside the optimization of primary forest-wood value chains, is essential to safeguard

competitiveness and enable the green transition of the European wood industry (Goropečnik *et al.* 2024; Kropivšek *et al.* 2024; Perić *et al.* 2025). Building on this, other research stresses the need to integrate digitalization, data-driven management, and deeper insights into consumer preferences as key drivers of resilience, innovation, and circular value creation, thereby ensuring the long-term competitiveness of the European wood industry (Pirc Barčič *et al.* 2021; Goropečnik *et al.* 2024; Kropivšek *et al.* 2024; Pirc Barčič *et al.* 2025; Perić *et al.* 2025).

As of 2022, the European wood industry employed approximately 3.6 million people (including 3.2 million employees and 411,000 self-employed), marking a 1.4% increase compared to 2012. This accounted for approximately 10.5% of the total manufacturing workforce. Furthermore, the sector generated a gross value added (GVA) of approximately €136 billion, accounting for approximately 7.2% of the overall manufacturing industry. Despite being largely composed of small and medium enterprises (SMEs), the industry encompasses around 393,000 enterprises, or roughly 19% of all EU manufacturing companies. These figures underscore the continued economic relevance and employment capacity of the wood-based sector, positioning it as a cornerstone of the EU's sustainable industrial and bioeconomy strategies (Eurostat 2022).

Given its economic weight and environmental significance, particular attention has been directed toward improving the efficiency of material use throughout the wood product lifecycle.

In practice, after each product's lifetime, the wood is regained and either recycled for the same kind of product it was used before or further processed to fit into another product. In principle, during this process, the wood pieces decrease in size as the material is disintegrated into smaller components. Solid wood products (*e.g.*, boards) are followed by particle-based products of various sizes (*e.g.*, oriented strand boards, particle boards), which are then succeeded by fibre-based products (*e.g.*, fibre plates, cardboard). In the final stage, the wood can be chemically broken down to extract molecular components before being incinerated for energy production. This cascading use of wood, already applied in sectors such as the pulp and paper industry and energy production, represents a systematic and resource-efficient approach to biomass utilization that maximizes material value across multiple product lifecycles (Keegan *et al.* 2013; Goldhahn *et al.* 2021; Bizjak Govedič *et al.* 2024).

Following the cascading principle, virgin wood should be used first for higher material value applications (*i.e.* construction material), and it could be reused for chemicals after losing its structural properties entirely (Navare *et al.* 2022). However, the reuse of structural wood requires greater efforts both from the technical (careful deconstruction, reconditioning of materials) and logistical side, due to the absence of an established supply chain for reuse (Godina *et al.* 2025). Previous service life, mechanical degradation, and the presence of contaminants (*e.g.*, adhesives, coatings, or mixed-material assemblies) can negatively affect key mechanical properties such as the modulus of elasticity (MOE) and modulus of rupture (MOR). Moumakwa and Hughes (2024) have analyzed experimental evidence to show that the mechanical performance of reclaimed wood can deteriorate significantly due to ageing-related degradation and service-life damage, with elasticity and strength dropping up to 35% compared to virgin wood. The assessment of mechanical properties itself presents a challenge. Salvaged wood can be damaged to various degrees as a result of use and deconstruction, while key information on origin, strength class, and prior treatment is frequently unavailable (Ranttila *et al.* 2025). In the case of cross-laminated wood (CLT) or laminated veneer wood (LVL), the use of recycled material is

further constrained by strict performance requirements (Brandner *et al.* 2016; Ramage *et al.* 2017). Recycled wood is thus typically more suitable for lower-grade applications which do not require careful grading and quality control procedures. In contrast, sawn wood production generates a significant amount of wood residue and waste that can be reused more quickly, with particleboard being the primary cascading option for the recovered wood (Navare *et al.* 2022).

While cascading use improves resource efficiency, growing wood consumption increases the challenge of managing increasing volumes of wood waste. Addressing this growing waste stream is therefore essential for achieving circular economy objectives.

Although previous studies have explored wood waste utilization and trade, the combined effects of sawnwood production, intra- and extra-EU wood waste flows, and particleboard production remain insufficiently understood. This gap limits current knowledge on how material and trade dynamics interact with EU sustainability and circular bioeconomy goals.

The aim of this study was to analyze the relationships between sawnwood production, wood waste trade flows, and the production of boards from particles in the European Union, with a focus on understanding how these interactions reflect evolving material use patterns within the circular bioeconomy framework.

To achieve this aim, the following objectives are defined:

- to analyze trends in sawnwood production, particle board production, and wood waste trade in the EU,
- to assess the relationship between sawnwood production and intra-EU wood waste trade,
- to evaluate the connection between intra-EU wood waste trade and the production of boards from particles,
- to examine the influence of wood waste imports from non-EU countries on board production in the EU,
- to investigate the relationship between intra-EU wood waste trade and imports from non-EU countries,
- to interpret the results in the context of circular bioeconomy and energy use.

This study provides a new perspective by jointly examining long-term trends in primary wood production, waste, and trade flows, thereby improving understanding of the redistribution and use of wood residues in the EU and their role in climate change mitigation and resource circularity.

Research Aim and Hypotheses

This research aim was to analyze market trends and interrelations between the production of sawnwood, the trade dynamics of wood waste, and the subsequent production of boards from particles in the European Union. In particular, the study explored how these flows reflect changing material priorities in light of the EU's environmental and energy policies, including the shift towards renewable energy and the bioeconomy. Additionally, attention was given to the role of imports from non-EU countries and their potential impact on EU-based manufacturing.

One important aspect examined is the potential influence of sawnwood production on the volume of intra-EU wood waste trade. As sawnwood production generates considerable amounts of wood residues, a positive correlation with wood waste trade between EU member states would be expected. However, studies indicate that large

quantities of these residues are often retained and utilized domestically, particularly for energy generation, rather than being circulated through formal trade channels. For example, Borzecka (2018) notes that in many EU regions, wood waste is primarily reused within national borders, limiting its availability for broader market exchange. This trend is reinforced by EU policies promoting renewable energy and circular bioeconomy principles, which increasingly encourage the local valorization of biomass resources. Understanding how this policy shifts reshaping material flows is key to assessing the evolving role of the wood sector in sustainable resource management and climate change mitigation. Therefore, the first hypothesis was formulated as follows:

H1: The production of sawnwood in the EU is linked to the volume of intra-EU wood waste trade.

Furthermore, the production of boards from particles, such as particleboard, OSB, and fiberboard, heavily relies on raw material inputs that often include recycled wood waste. Within the EU, wood waste trade among member states may facilitate the redistribution of residues to regions or manufacturers with higher processing capacities or demand for such secondary raw materials. This trade flow could potentially enhance the supply security for the panel industry, influencing production volumes. However, shifts in energy policies and waste management strategies might redirect wood residues towards bioenergy production rather than board manufacturing. Hence, understanding the role of intra-EU wood waste trade in supporting board production is essential for assessing resource efficiency in the circular bioeconomy (Vis *et al.* 2016; Olsson *et al.* 2016; Jahan *et al.* 2022). Therefore, the second hypothesis was formulated as:

H2: The volume of intra-EU wood waste trade is connected with the production of boards from particles.

The EU imports wood waste from non-EU countries to supplement raw material supplies for wood panel production and other industrial uses. These imports can affect domestic production capacities and the market dynamics for wood residues. However, the influence of imports is complicated by factors such as transportation costs, regulatory frameworks (*e.g.*, the EU Timber Regulation), and certification requirements that may limit the utilization of imported wood waste. Moreover, some imported residues might be destined for bioenergy rather than material uses, affecting the production of boards from particles. Investigating this relationship is key to understanding how global trade flows interact with domestic manufacturing and sustainability policies (Garcia and Hora 2017; de Carvalho Araújo *et al.* 2019). Thus, the third hypothesis was set as:

H3: Imports of wood waste from non-EU countries are associated with the production of boards from particles in the EU.

Trade flows within the EU for wood waste and residues may be closely linked to import dynamics from non-EU countries. A vibrant internal market for secondary wood resources could stimulate or suppress extra-EU imports depending on internal supply-demand imbalances, policy incentives, or cost structures (Olsson *et al.* 2016). For instance, internal redistribution mechanisms among EU member states might influence how much imported material is required to satisfy industrial needs (Barrie and Schröder 2022).

Moreover, when wood waste imports are redistributed across EU borders, this internal trade may amplify the visibility or volume of import flows, even if total external dependency remains stable (Aggestam and Giurca 2022). This interconnectedness between regional (intra-EU) and global (extra-EU) trade dynamics supports the hypothesis that the intensity of wood waste exchange within the EU may influence the volume of imports from non-EU countries. Therefore, the fourth hypothesis was formulated:

H4: Intra-EU wood waste trade is linked to the import of wood waste from non-EU countries.

EXPERIMENTAL

The primary data source for this study was Eurostat, the statistical office of the European Union. Relevant datasets on sawnwood production, production of boards from particles (Eurostat 2025a), as well as on wood waste generation, intra-EU wood waste trade, and imports and exports of wood waste involving non-EU countries (Eurostat 2025b), were retrieved from the Eurostat online database in 2025. The dataset covers the period from 2004 to 2023. Although wood products used in construction, such as LVL, as well as secondary wood products, such as CLT and GLT, are also important in this context, they are not included in the analysis due to the lack of available data in the Eurostat database. Namely, for secondary wood products, data are available only for a two-year period, while for LVL, data are available only for the last three reporting years, which is why it was not possible to include them in the analysis.

This study focused on downstream material flows, including processed wood products and wood waste, while primary raw material inputs (*e.g.*, roundwood) are not included, as the aim is to analyze the circulation and utilization of wood residues within the EU bioeconomy framework. To ensure consistency and comparability of the time-series analysis, only datasets with continuous long-term coverage and a significant contribution to overall waste generation were included.

All analyses and data visualizations were conducted using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) R (Core Team, Vienna, Austria; version 4.5.2). Statistical methods included Pearson correlation analysis, applied to assess the strength and sign of linear relationships between variables, and cross-correlation analysis to explore delayed relationships between import volumes and domestic production figures. Stationarity of the time series was tested using the Augmented Dickey–Fuller (ADF) unit root test. Engle–Granger cointegration tests were conducted for selected variable pairs to address potential spurious correlations arising from non-stationary data. These methods provided insights into short-term associations and potential long-term relationships among wood product manufacturing, wood waste trade, and the utilization of wood residues in secondary production.

RESULTS AND DISCUSSION

Trends and interrelationships in the production, trade, and waste generation of the EU wood sector are analyzed in this section. Emphasis was placed on the production dynamics of sawnwood and boards from particles, the patterns of intra-EU and extra-EU

wood waste trade, and the evolution of wood waste generation across key economic sectors. By combining descriptive market trends with statistical correlation and regression analysis, the study aimed to provide insights into the functioning of circular material flows and their alignment with the EU's environmental and bioeconomic objectives. The discussion was structured according to the key variables relevant to the hypotheses, beginning with production and trade trends, followed by a detailed interpretation of the quantitative relationships between them.

Market Trends of Wood products and Wood Waste in the EU

Understanding long-term production and waste generation trends is crucial for contextualizing the dynamics of wood resource utilization in the European Union. This subsection presents an overview of key developments in the production of sawnwood and boards from particles, as well as in the generation and management of wood waste across the EU between 2004 and 2021. These descriptive insights can serve as a foundation for interpreting changes in material flows and for examining the relationships tested through the formulated hypotheses. By identifying structural shifts linked to economic crises, policy changes, and sustainability goals, this analysis highlighted how the EU wood sector has evolved within the broader framework of the circular economy and bioeconomy transition.

A primary indicator in this context is the production of sawnwood, which revealed notable fluctuations influenced by external economic conditions and internal sectoral developments. During the observed period from 2004 to 2023, EU production of sawnwood (Saw) (Fig. 1.) peaked in 2007 at 113.1 million m³. Following the global financial crisis, production declined sharply to 88.8 million m³ in 2009. After this downturn, the sector gradually recovered, with relatively stable and growing trends recorded between 2012 and 2021. In 2021, production nearly returned to its pre-crisis level, reaching 111.9 Mt. A slight decrease followed in 2022 (109.9 million m³), before a significant drop in 2023, when production fell to 88.3 million m³, the lowest level since 2009. Despite this recent decline, the long-term trend for sawnwood production remains mostly positive, albeit with notable fluctuations in recent years.

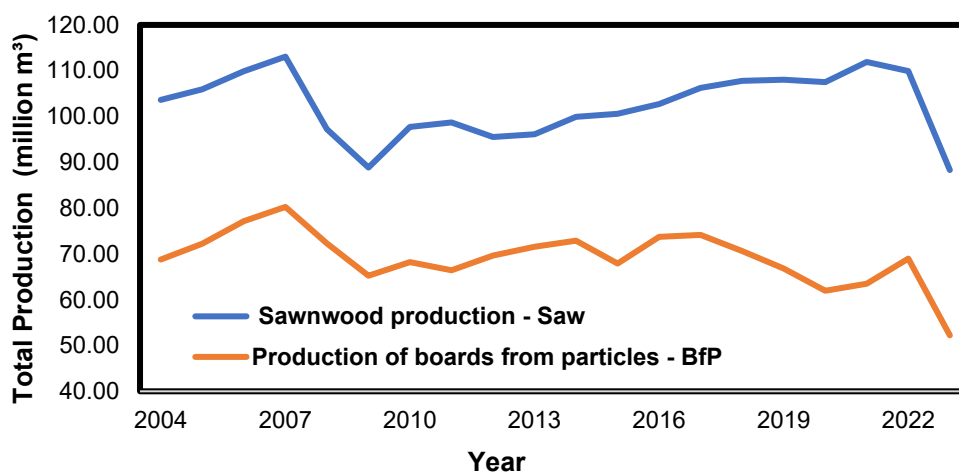


Fig. 1. Trends in sawnwood production and production of boards from particles in the EU 2004–2023 (Authors' calculation based on Eurostat 2025a)

Conversely, the production of boards from particles (BfP) (Fig. 1.), including particle board, OSB, fiberboard, hardboard, and MDF/HDF, also peaked in 2007 at 80.3 million m³, followed by a noticeable decline during the economic downturn. The lowest point was recorded in 2020 with 62.0 million m³. A modest recovery occurred in 2021 and 2022, with values of 63.5 and 69.0 million m³, respectively. However, production declined again in 2023 to 52.2 million m³, the lowest level in the entire observed period. As illustrated in Fig. 1, particle board production showed greater volatility and a more pronounced long-term decline compared to sawnwood.

The most recent declines in 2022 and especially 2023 were largely associated with increased uncertainty and disruptions in global wood markets. In particular, reduced construction activity across Europe, driven by rising interest rates, inflationary pressures, and declining housing investment, has led to lower demand for structural wood products (UNECE/FAO 2023; European Commission 2023, EOS, 2024). At the same time, rising energy costs and broader market uncertainty have affected production conditions and supply dynamics within the wood-processing sector. Recent studies have highlighted that such conditions contribute to short-term supply constraints and demand-side contractions, particularly in construction-related industries (Nepal *et al.* 2024).

Following the analysis of market trends in sawnwood and particleboard production, it was also essential to consider the evolution of wood waste generation, as the volume of waste often reflected fluctuations in industrial activity within the wood processing sector. Assessing the dynamics of wood waste generation provided additional insight into resource efficiency and broader material flows across the EU. As shown in Fig. 2, understanding wood waste trends is key to evaluating the effectiveness of EU sustainability policies.

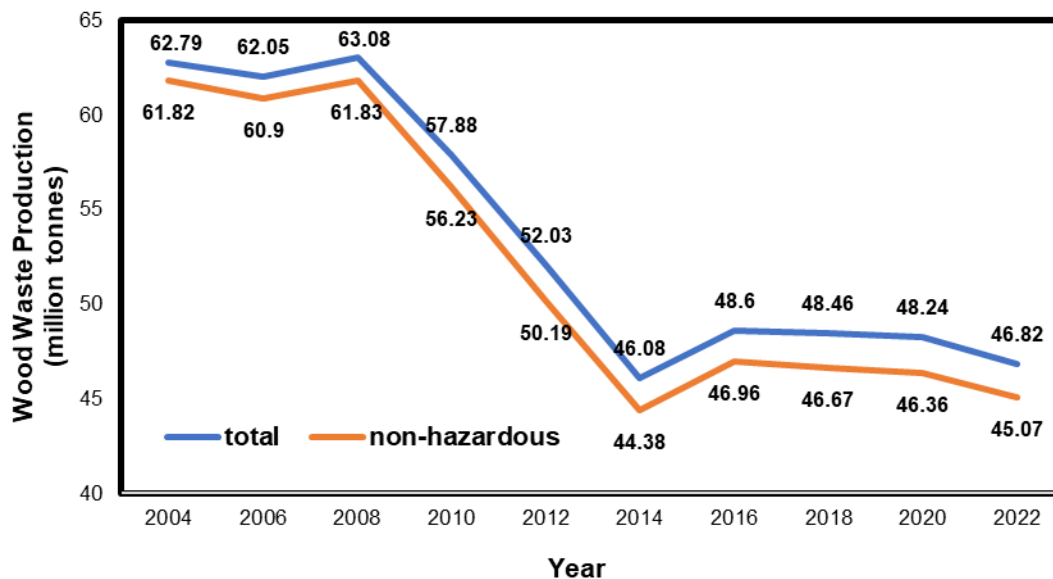


Fig. 2. Trends in wood waste production in the EU 2004–2022 (Source: Eurostat 2025b)

According to Eurostat (2025b), wood waste generation in the EU peaked in 2008 at approximately 63.1 Mt, followed by a steady decline to 44.4 Mt in 2014. Between 2014 and 2020, generation stabilized around 48.0 Mt. However, more recent figures indicated a continuing decrease, with total wood waste falling to 46.8 Mt in 2022, and non-hazardous wood waste reaching 45.1 Mt. These trends suggest ongoing structural changes in

industrial activity and material use within the European wood sector and are consistent with broader EU policy efforts to reduce material intensity and prevent waste generation, as highlighted in the most recent assessment by the European Environment Agency (2024).

In order to contextualize wood waste trends in the EU, it was relevant to identify which economic sectors contributed the most to its generation. Figure 3 illustrates the average shares of wood waste generation by in the EU-27 between 2004 and 2022. More than 89.0% of wood waste during this period was generated by economic activities rather than households. The largest identifiable share originated from the wood processing sector (C16), accounting for 33.8% of total wood waste. This was followed by the construction sector (F) with 15.3%, the paper industry (C17) with 9.7%, and furniture manufacturing (C31) with 4.0%.

An additional 37.2% of wood waste was generated by other sectors and households combined. However, the exact contribution of households within this category was not separately reported in the available data. These results confirm that industrial activities, especially wood processing and construction, are the dominant sources of wood waste in the EU, while also emphasizing the importance of improving data granularity for a more accurate attribution of household-generated waste.

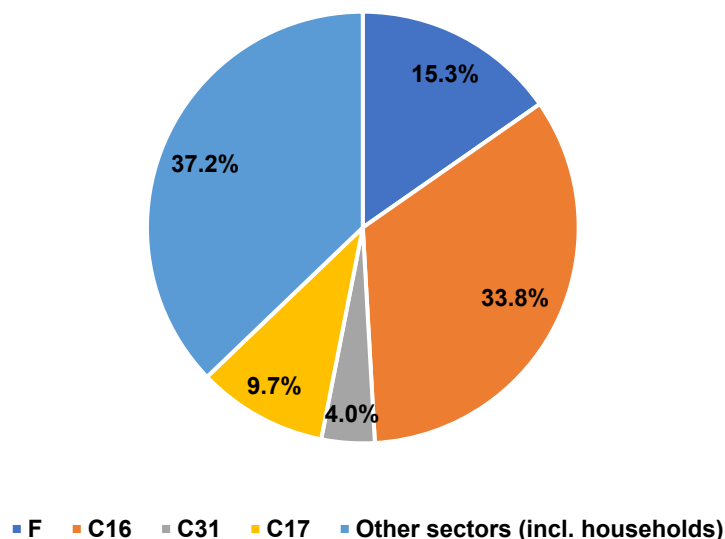


Fig. 3. Sectoral shares of wood waste generation in the EU-27 2004–2022. Sector codes follow the NACE Rev. 2 classification: F – Construction, C16 – Manufacture of wood and of products of wood and cork (except furniture); manufacture of articles of straw and plaiting materials, C31 – Manufacture of furniture, and C17 – Manufacture of paper and paper products. Other sectors include remaining NACE activities and households. (Authors’ calculation based on Eurostat 2025b)

Beyond identifying sectoral shares in total wood waste, examining the absolute quantities generated over time provides a clearer understanding of long-term structural shifts across wood-based industries in the EU. An analysis of wood waste production by the construction sector (F), wood processing (C16), furniture manufacturing (C31), and the paper industry (C17) from 2004 to 2022 reveals distinct sector-specific trends (Fig. 4).

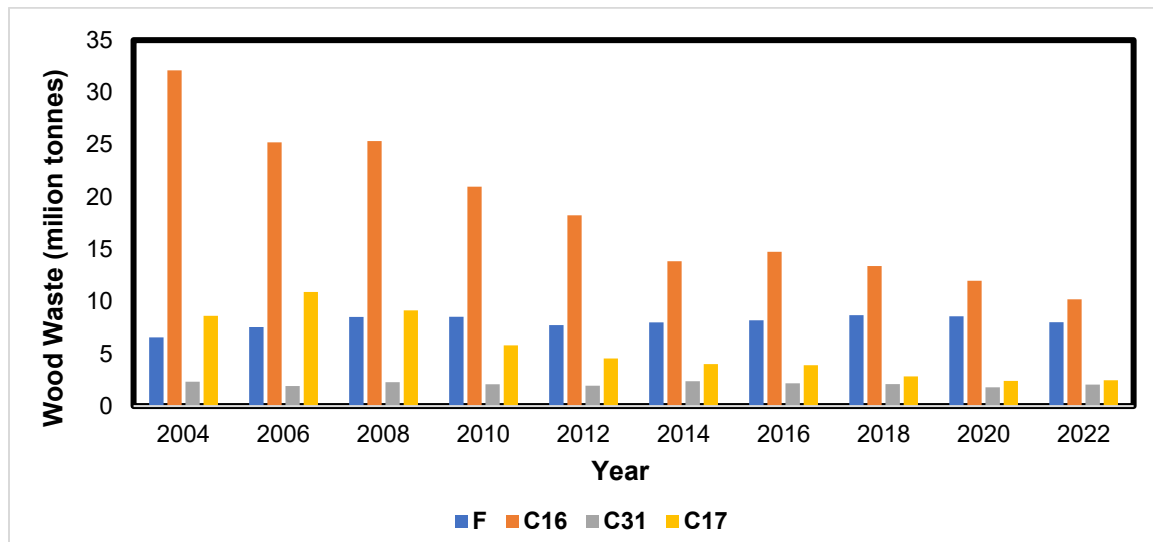


Fig. 4. Wood waste production by sector in the EU 2004–2022. Sector codes follow the NACE Rev. 2 classification: F – Construction, C16 – Manufacture of wood and of products of wood and cork (except furniture); manufacture of articles of straw and plaiting materials, C31 – Manufacture of furniture, and C17 – Manufacture of paper and paper products. (Authors' calculation based on Eurostat 2025b)

Throughout the observed period, the wood processing industry (C16) remained the dominant source of wood waste. Wood waste production exhibited a consistent downward trend, starting at 32.1 Mt in 2004 and dropping to 10.2 Mt in 2022, a reduction of nearly 68%, with occasional fluctuations in 2008 and 2016. This decline may reflect not only improvements in material efficiency and process optimization, but also changes in the utilization of wood residues, as an increasing share is internally used for energy purposes and therefore may not be reported as waste. This interpretation is consistent with previous studies highlighting the growing competition between material and energy uses of wood resources (Mantau 2015; Vis *et al.* 2016).

In contrast, the construction sector (F) maintained relatively stable output, ranging between 6.6 and 8.7 Mt, and even showed a slight upward trend until 2018. In 2022, construction-generated wood waste amounted to 8.0 Mt. This relative stability suggests that improvements in demolition and construction practices have not substantially reduced waste generation over time. At the same time, the potential for diverting this waste into higher-value structural applications remains limited in practice. In the construction context, wood is frequently affected by service-life damage and contamination, which can significantly reduce its mechanical performance (Moumakwa and Hughes 2025). In addition, the lack of reliable information on material origin, treatment, and strength class complicates its structural assessment and reuse (Ranttila *et al.* 2025). Such constraints are particularly critical for applications requiring standardized and predictable mechanical properties, such as CLT and LVL (Brandner *et al.* 2016; Ramage *et al.* 2017).

Furniture manufacturing (C31) and the paper industry (C17) consistently generated significantly lower volumes, rarely exceeding 2.4 Mt annually. While the paper sector showed a clear decline (from 8.6 Mt in 2004 to 2.5 million in 2022), furniture manufacturing remained relatively stable, averaging approximately 2.0 Mt annually with minor year-to-year variation.

These findings align with existing literature that emphasizes the intensive generation of both primary and secondary wood residues, particularly within the

engineered wood products industry (Daian and Ozarska 2009; Ramage *et al.* 2017; Saal *et al.* 2017). A significant portion of these residues are commonly redirected into particleboard manufacturing, forming a critical input stream for this industry. Nevertheless, the potential for expanding the use of recovered wood remains limited. Industry actors cite persistent challenges such as contamination risks, high cleaning and transportation costs, and technical limitations in reprocessing panel waste (Daian and Ozarska 2009; Amarasinghe *et al.* 2024). Furthermore, as Nguyen *et al.* (2023) note, international trade in recycled wood is constrained by classification ambiguities, inconsistent quality standards, and logistical inefficiencies, which together hinder broader circularity goals in the wood sector.

To complement the analysis of wood waste generation, it is also important to consider trade flows, both among EU member states and with non-EU countries, to better understand the dynamics of material circulation within the European wood sector. Available data on intra-EU wood waste trade from 2004 to 2023 reveal significant fluctuations, reflecting broader economic, environmental, and policy-related shifts. These trends are illustrated in Fig. 5, which presents the total annual volume of intra-EU trade in wood waste.

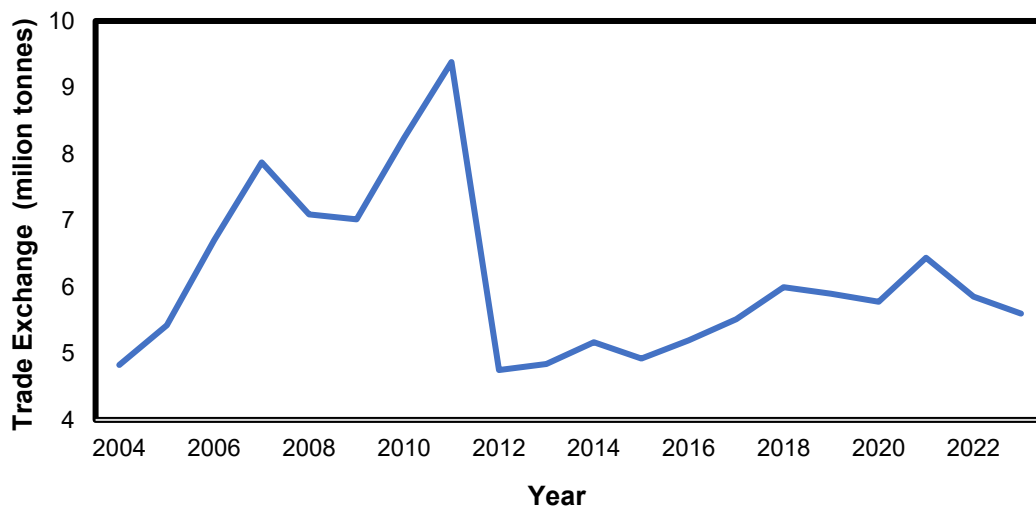


Fig. 5. Total intra-EU trade in wood waste 2004–2023 (million tonnes) Note: Total intra-EU trade was estimated as the average of exports and imports. The strong correlation between these variables ($r = 0.817$, $p < 0.001$) confirms the reliability of this approximation. (Authors' calculation based on Eurostat 2025b)

From 2004 to 2011, total intra-EU trade in wood waste, measured as the average of exports and imports among member states, displayed a continuous upward trend, rising from 4.8 Mt in 2004 to a peak of 9.4 Mt in 2011. This period was marked by market expansion and increasing integration of secondary material flows. However, in 2012, the trade volume dropped sharply to 4.8 Mt, nearly a 50% decrease, indicating a structural shift in market behaviour.

Following that decline, intra-EU trade stabilized and experienced moderate growth. Annual volumes ranged between approximately 4.8 and 6.5 Mt from 2013 to 2023. In 2021, the volume reached 6.4 Mt, followed by a slight decrease to 5.6 Mt in 2023. Although the trade level recovered relative to 2012, it remained consistently lower than the peak recorded before 2011.

This pattern is consistent with observed transitions toward regionalized waste management and resource valorization strategies. As noted by Amarasinghe *et al.* (2024), the growing focus on localized wood waste processing within EU countries may reduce the need for cross-border transport, as materials are increasingly used in proximity to where they are generated. In parallel, Borzecka (2018) highlights that EU bioeconomy policies emphasize regional value chains in order to minimize emissions from transport and enhance circularity within local systems. These strategic shifts offer a plausible explanation for the sustained moderation in intra-EU wood waste trade volumes observed since 2012.

To further elaborate on the structure of international wood waste trade, this section examines the total import of wood waste from non-EU countries to the EU, as well as exports from the EU to non-EU countries. As shown in Fig. 6, during the observed period (2004 to 2023), the total volume of wood waste imports from non-EU countries to the EU was about 5.4 times higher than the total volume of exports from the EU to non-EU countries. Notably, in 2011 both import and export volumes peaked: wood waste imports from non-EU countries into the EU reached 4.7 Mt, while exports from the EU to non-EU countries amounted to only 0.64 Mt.

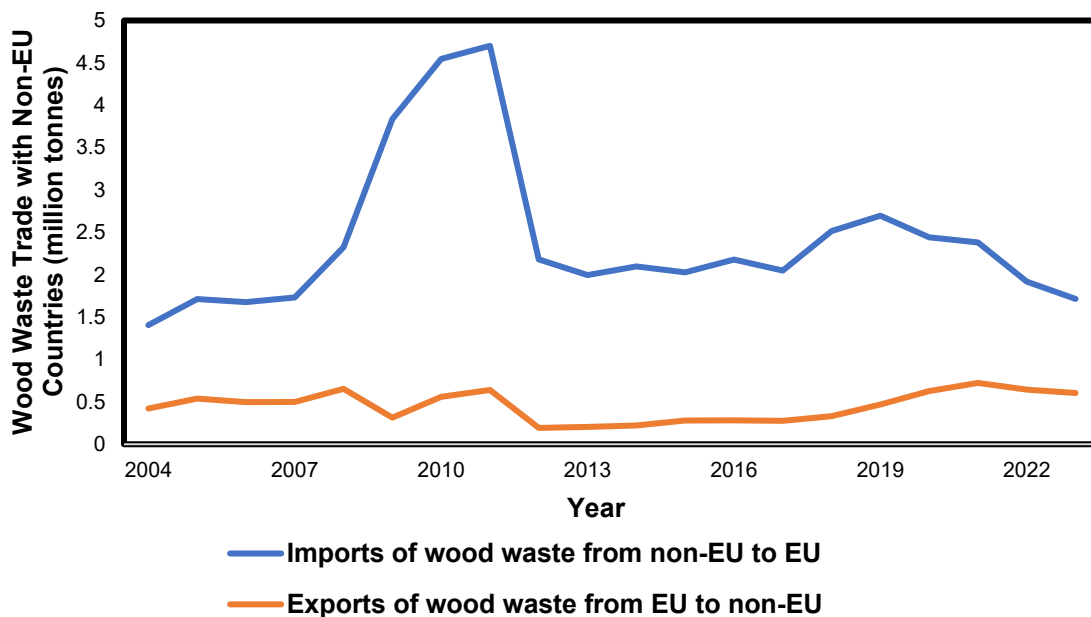


Fig. 6. Total imports and exports of wood waste between the EU and non-EU countries 2004–2023 (million tonnes) (Source: Eurostat 2025b).

After peaking in 2011, imports declined sharply and stabilised at considerably lower levels, whereas exports displayed a slow but steady growth trend, reaching their maximum in 2021 (0.72 Mt). This divergence suggests that the EU has gradually reduced its reliance on external wood waste inputs while modestly increasing outbound flows. Nevertheless, the structural imbalance remains, as imports continue to outweigh exports by more than fivefold, underscoring the EU's position as a net importer of wood waste. This structural imbalance in trade volumes reflects underlying regulatory, economic, and logistical dynamics. One of the primary contributing factors is the EU's strict regulatory environment concerning the trade of timber and wood-based materials. For instance, the EU Timber Regulation (EUTR) was introduced to combat the import of illegally harvested wood and imposes due diligence obligations on all operators placing timber on the EU

market. While its primary objective is sustainability and legality assurance, the EUTR has also led to reduced trade flows from countries with weaker governance frameworks, especially in the Global South (Kim *et al.* 2024).

In addition to legality requirements, phytosanitary measures significantly affect the feasibility of transboundary wood waste trade. As outlined by the Forestry Commission (2017), wood and wood products entering the EU must comply with strict biosecurity protocols, including treatment (*e.g.*, heat treatment or methyl bromide fumigation), removal of bark, and provision of official phytosanitary certificates. These requirements are derived from international standards such as ISPM 15 and the EU Plant Health Law, which aim to prevent the spread of pests and diseases but can simultaneously increase the cost and complexity of imports and exports (European Commission 2024).

These biosecurity measures pose particular challenges for the export of wood waste from the EU, where waste streams often include mixed or contaminated fractions that do not meet the standards for international shipment. As a result, the EU's internal waste management policies, circular bioeconomy strategies, and environmental regulations are increasingly focused on local or regional valorisation of wood waste, which further limits the motivation or feasibility for export (Borzecka 2018). This aligns with observed trends of regionalization in the circular economy, where wood residues are processed and reused close to their point of origin to reduce transport emissions and maintain traceability (Amarasinghe *et al.* 2024).

Overall, the analysis highlights a persistent structural imbalance in the EU's international wood waste trade, with imports consistently and substantially exceeding exports. While regulatory frameworks and biosecurity requirements have curbed both flows, they have particularly constrained exports, reinforcing the EU's role as a net importer. At the same time, growing emphasis on circular bioeconomy strategies points toward increasing regionalisation, suggesting that future trade dynamics will be shaped less by global exchange and more by local valorisation and reuse of wood residues.

Relations between Sawnwood Production, Wood Waste Trade Dynamics, and Production of Boards from Particles in the EU

To advance the analysis of wood sector dynamics in the EU, particular attention was given to the interplay between sawnwood production, the manufacture of boards from particles, and wood waste trade flows. Building on the research hypotheses, the section applies correlation analysis and trend interpretation over a twenty-year period to uncover statistically relevant relationships. The analysis focuses on sawnwood production (Saw), intra-EU wood waste trade, production of boards from particles (BfP), and import/export flows of wood waste with non-EU countries.

Results of the analysis are presented in Table 1. As a preliminary step, all variables were tested for stationarity using Augmented Dickey–Fuller unit root tests, which indicated that none of the series were stationary in levels. To address the potential issue of spurious correlations arising from non-stationary time series, the authors conducted Engle–Granger cointegration tests for all variable pairs. The results indicate that among the pairs with statistically significant Pearson correlations, intra-EU wood waste trade and wood waste imports were cointegrated in both specifications, suggesting a stable long-run relationship. In addition, sawnwood production and production of boards from particles, as well as intra-EU wood waste trade and EU exports to non-EU countries, exhibit evidence of cointegration in one direction. These findings support the validity of the corresponding correlation results, indicating that they are not driven solely by common trends. For other

variable pairs, correlations were not statistically significant, and thus concerns regarding spurious relationships were less relevant for the interpretation of results.

The correlation analysis showed no statistically significant relationship between sawnwood production and intra-EU wood waste trade. For the full period (2004 to 2023), the correlation was almost zero ($r = 0.02$). A historical comparison reinforced this weak association, with a slightly negative correlation between 2004 and 2011 ($r = -0.20$, $p = 0.64$) and a positive one between 2012 and 2023 ($r = 0.68$, $p = 0.014$, but no cointegration). The sample was divided into two subperiods (2004–2011 and 2012–2023) to account for structural changes associated with the global financial crisis and its aftermath. The results demonstrate that the relationship between sawnwood production and intra-EU wood waste trade was unstable and did not exhibit a consistent long-term association. While short-term correlations may emerge in specific subperiods, the lack of cointegration evidence indicates that these do not constitute a persistent structural connection. This finding should be considered within the broader context of wood waste management dynamics in Europe. Previous research has shown that wood waste is allocated across multiple recovery pathways, particularly recycling and energy recovery, with distribution influenced by factors such as residue quality, contamination levels, sorting practices, and national regulatory frameworks (Pazzaglia and Castellani 2023). Furthermore, only a small proportion of processed wood remains in long-term products, reflecting limited material retention within the system (Zbieć *et al.* 2022). Therefore, increases in primary production do not necessarily result in a proportional rise in secondary raw material availability for manufacturing or intra-EU trade. Instead, wood residues are often redistributed among competing pathways, which weakens the direct connection between sawnwood production and intra-EU wood waste trade. As a result, Hypothesis H1 was rejected.

Table 1. Pearson Correlation Matrix of Selected Wood Sector Indicators in the EU 2004–2023

Variable	Saw	BfP	Trade exchange	Import	Export
Saw	1	0.464* ($p=0.039$)	0.023 ($p=0.924$)	-0.334 ($p=0.150$)	0.274 ($p=0.242$)
BfP		1	0.057 ($p=0.812$)	-0.218 ($p=0.355$)	-0.352 ($p=0.128$)
Trade exchange			1	0.723*** ($p<0.001$)	0.548* ($p=0.012$)
Import				1	0.181 ($p=0.444$)
Export					1

Note: Values represent Pearson's correlation coefficients (r). * = $p \leq 0.05$; ** = $p \leq 0.01$; *** = $p \leq 0.001$. Saw = sawnwood production; BfP = boards from particles production; Trade exchange = intra-EU wood waste trade (average of exports and imports); Import = wood waste imports from non-EU countries; Export = wood waste exports to non-EU countries.

The analysis further showed no significant relationship between intra-EU wood waste trade and the production of boards from particles ($r = 0.057$; $p = 0.812$). A breakdown by sub-periods yielded only weak and statistically irrelevant results, with a slightly negative correlation between 2004 and 2011 ($r = -0.1$, $p = 0.82$) and a negative one between 2012 and 2023 ($r = -0.36$, $p = 0.24$). These findings suggest that intra-EU waste trade did not exhibit a systematic association with particleboard production during the observed

period. This outcome implies that wood residues are not consistently allocated to material use within the EU, although the specific drivers cannot be identified from the current analysis. Nevertheless, this pattern aligns with broader structural trends in wood waste utilization. Previous research indicates that a significant proportion of wood biomass in Europe is used for energy purposes, often exceeding 50% of processed material (Zbieć *et al.* 2022), which may constrain the availability of residues for material applications such as particleboard production. As a result, Hypothesis H2 was rejected.

While some relationships in the correlation matrix (Table 1) were statistically significant at the 5% or 1% level, it is important to recognise that statistical significance does not automatically imply practical or economic relevance. For example, Pearson correlation coefficients below 0.5 indicate only weak to moderate associations, which may not be strong enough to support robust conclusions or policy actions. Therefore, these findings should be interpreted with caution, considering both statistical and practical implications. Previous studies suggested that wood waste imports could play an important role in sustaining EU particleboard production, especially in light of growing demand and regional shortages of raw materials (de Carvalho Araújo *et al.* 2019; Junginger *et al.* 2019). Yet, the present analysis did not confirm this assumption. Instead, the regression results indicated a weak and negative relationship: $BfP = 72,660.2 - 0.00143 \times Import$ ($R^2 = 0.048$, $p = 0.355$). This finding implied that higher import volumes were not associated with increased production of particle-based boards. Although the negative slope suggested a substitution effect, the relationship was statistically insignificant and explained only a very small share of the variance in production. This pattern is consistent with previous research showing that imported residues are often unsuitable for panel manufacturing or are redirected toward bioenergy due to contamination, traceability concerns, or quality mismatches (Olsson *et al.* 2016; Garcia and Hora 2017). In addition, high transport costs, the prioritization of local biomass, and regulatory requirements such as the EU Timber Regulation (EUTR) and phytosanitary measures (ISPM-15) further restrict the use of imported wood waste in material applications (Forestry Commission 2017; Aggestam and Giurca 2020; Amarasinghe *et al.* 2024; Kim *et al.* 2024).

To explore potential delayed effects, cross-correlation analysis was also applied (Table 2). While the contemporaneous correlation was negative ($r = -0.218$), stronger positive associations emerged at longer lags, particularly at +3 years ($r = 0.481$) and +4 years ($r = 0.474$). It is important to note that these correlations are not entirely reliable due to the non-stationarity of the data. However, this suggests that part of the imported material eventually contributes to board production, but only after regulatory processing, sorting, or storage delays.

Table 2. Cross-Correlation Coefficients (r) between Wood Waste Imports from Non-EU Countries and Board Production at Different Lags

Lag (years)	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
r	0.196	0.064	0.028	-0.173	-0.232	-0.218	-0.318	0.198	0.481	0.474	0.194
Note: r -Pearson correlation coefficient											

In summary, these findings suggest that imports of wood waste from non-EU countries did not provide an immediate boost to particleboard production and may even have competed with material uses when redirected to bioenergy. However, the lagged correlations indicated that part of the imported material eventually found its way into production cycles, albeit with considerable delays. This highlights the importance of regulatory and logistical factors in shaping how international trade flows are integrated into EU manufacturing systems, and explains why Hypothesis H3 was only partially supported. After analysing the relationship between wood waste imports and particleboard production (H3), the next step was to explore how intra-EU wood waste trade related to international trade flows.

Focusing on the period 2004 to 2023, the initial correlation analysis (Table 1) revealed two statistically significant simultaneous relationships: a strong positive correlation between intra-EU wood waste trade and imports from non-EU countries ($r = 0.723$; $p < 0.001$), and a positive correlation between intra-EU trade and EU exports to non-EU countries ($r = 0.548$; $p = 0.012$). These results are consistent with previous studies, such as Junginger *et al.* (2019), who observed that EU member states with strong internal flows (e.g., Germany, Sweden) also tended to rely on extra-EU imports to balance regional shortages, and Aggestam and Giurca (2022), who emphasized the interconnectedness between regional and global residue markets.

To test Hypothesis H4 in greater detail, cross-correlation analysis was conducted to examine potential lagged effects. The results (Table 3) showed that intra-EU trade was most strongly associated with imports at lag 0 ($r = 0.723$), with an additional positive relationship at lag -1 ($r = 0.465$). This suggested that increases in internal trade volumes may have preceded import growth by about a year, which echoes earlier findings that domestic redistribution often amplified the need for external supply when local imbalances arose (Barrie and Schröder 2022).

Table 3. Cross-correlation Coefficients (r) - Intra-EU Wood Waste Trade vs. Imports from Non-EU Countries

Lag (years)	-5	-4	-3	-2	-1	0	+1	+2	+3	+4	+5
r	-0.192	0.110	0.308	0.339	0.465	0.723	0.315	-0.142	-0.489	-0.526	-0.431

Note: r -Pearson correlation coefficient

Finally, regression analysis was applied to quantify the strength of these associations. For imports (Fig. 7), a moderate positive relationship was identified ($y = 0.262x - 802,059$; $R^2 = 0.523$), indicating that a moderate proportion of the variation in imports can be explained by intra-EU wood waste trade volumes. Although export flows were also examined, the relationship with intra-EU trade was weaker ($R^2 = 0.36$) and therefore not central to the testing of Hypothesis H4. Overall, these findings suggest that intra-EU exchange may act as a contributing factor in shaping import patterns from non-EU countries, rather than a dominant driver of global trade patterns, reflecting processing capacity imbalances, policy incentives, and redistribution mechanisms (Kellenberg 2012; Olsson *et al.* 2016).

These findings provide a deeper understanding of evolving material flows in the EU wood sector and underscore the growing influence of environmental regulation, energy policy, and logistical factors on wood residue utilization. Hypotheses H1 and H2 were not

supported, indicating that neither sawnwood production nor intra-EU wood waste trade showed a systematic effect on material circulation. Hypothesis H3 was only partially supported, as imports from non-EU countries displayed weak or delayed effects on particleboard production, suggesting that imported residues were often diverted toward energy uses or affected by regulatory barriers. Hypothesis H4 was moderately supported, as intra-EU trade volumes showed a measurable but not dominant association with external trade flows. These findings also suggest practical implications for wood waste management, particularly the need for clearer import standardization and stronger domestic waste collection systems, in order to reinforce circular economy objectives and reduce dependency on external supply.

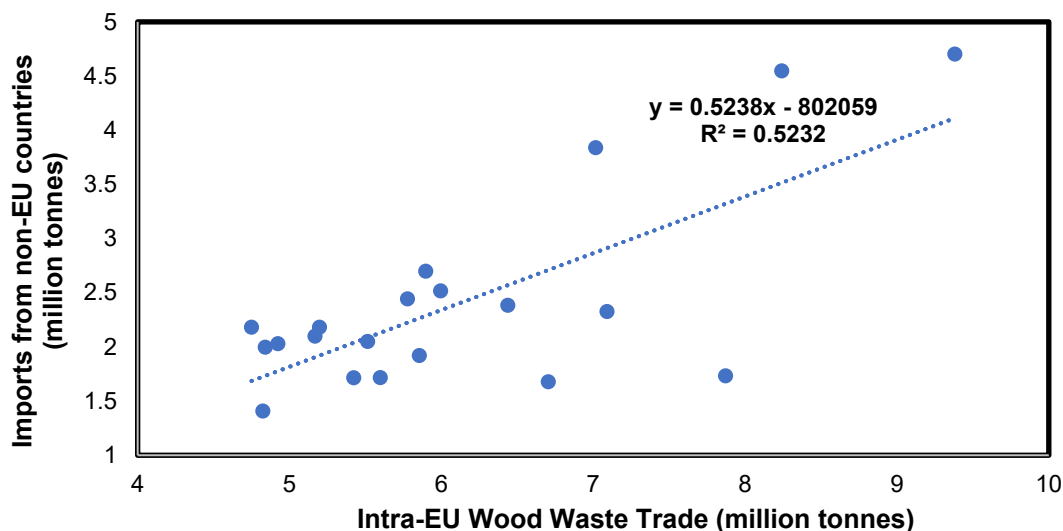


Fig. 7. Association between intra-EU wood waste trade and imports from non-EU countries 2004 to 2023

Practical Implications

The findings of this study carry several practical implications for EU wood waste management and circular economy policies.

First, the moderate association between intra-EU and international wood waste trade suggests the importance of harmonized standards and improved traceability systems to ensure that secondary materials can be more effectively utilized in manufacturing rather than energy recovery.

Second, the observed dominance of bioenergy valorization suggests a potential policy trade-off: while renewable energy targets are advanced, material circularity objectives may be undermined. Policymakers and industry stakeholders should therefore prioritize investments in technologies and infrastructure that enable higher-quality recycling of wood residues.

Finally, the declining contribution of key industrial sectors to wood waste generation highlights the growing importance of post-consumer wood streams, particularly from households as well as construction and demolition activities. However, these streams are not systematically captured in current statistical systems, and historical data remain very limited, which restricts their inclusion in long-term empirical analyses. This represents an important limitation for assessing the potential of post-consumer wood for higher-value applications, including structural reuse.

Limitations and Future Directions

While this study has provided valuable insights into the dynamics of sawnwood production, wood waste generation, and trade flows in the EU, several limitations should be acknowledged. The reliance on aggregated EU-level data, primarily from Eurostat, may obscure important national or sectoral differences. A further limitation relates to the limited availability and lack of long-term, disaggregated data on post-consumer wood waste, particularly from construction and demolition activities, which restricts its inclusion in the analysis.

Future research could benefit from country-level or firm-level datasets and the application of econometric techniques capable of testing causality more robustly. Moreover, integrated approaches such as life cycle assessment (LCA) and material flow analysis (MFA) would enable a more comprehensive evaluation of the climate and resource-efficiency impacts of wood waste utilization within the EU.

CONCLUSIONS

1. Sawnwood production and intra-EU wood waste trade were not significantly or systematically connected. Correlation analysis across 2004 to 2023 showed no significant relationship between these variables, nor between intra-EU trade and particleboard production, indicating that residues from primary processing were largely retained domestically, often for bioenergy use.
2. Imports of wood waste from non-EU countries played only a limited and delayed role in EU particleboard production. Immediate correlations were weak or negative, but lagged analysis revealed positive associations after three to four years, suggesting that imported residues may eventually enter material cycles following regulatory processing or storage.
3. Intra-EU wood waste trade was moderately associated with international trade flows, particularly imports from non-EU countries. Both correlation and regression analyses indicated positive but not strong relationships, while cross-correlation suggested that internal trade may precede changes in import volumes, reflecting the interdependence of regional and global residue markets.
4. EU wood waste management is shifting from material recycling toward energy valorisation. This transition aligns with renewable energy targets but may challenge long-term circular economy goals, underlining the need for policies that balance energy use with material reuse in order to strengthen sustainability outcomes.

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Use of Generative AI

No AI tools were used in the construction or writing of the manuscript.

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