Carbon Footprint Evaluation of Melamine-Coated Particleboard Production: A Case Study In Türkiye

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Reducing the carbon footprint is a key objective in global sustainability policies to combat climate change. Wood-based composite panels, which are widely used in the construction and furniture industries, require environmental evaluation due to their production-related impacts. This study quantitatively assessed the carbon footprint of melamine-faced particleboard produced in Türkiye, following a cradle-to-gate system boundary based on the ISO 14067 (2018) standard and the IPCC 2006 Tier 1 methodology. The system boundary included raw material and process input transportation, energy consumption, melamine lamination, and waste management. Primary data were obtained directly from the production facility, while secondary data were sourced from the literature. The functional unit was defined as 1 m³ of melamine-faced particleboard, and emissions were categorized under Scope 1, Scope 2, and Scope 3. Results indicated that 67% of the total emissions originated from Scope 3 activities, with major contributors being raw material transport, electricity consumption, and adhesive production. The carbon footprint of melamine-faced boards was calculated as 462 kg CO_2e/m^3, notably higher than that of non-coated particleboard (299 kg CO_2e/m^3). This study provides valuable data for future carbon footprint assessments of coated wood-based panels and offers a scientific foundation for developing sustainable production strategies in the sector.

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Keywords: Carbon footprint; Melamine-coated particleboard (MFC-PB); Scope emissions; Sustainable production in Türkiye

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INTRODUCTION

While combating climate change remains on the agenda, countries are looking for new and effective solutions to reduce carbon dioxide emissions. In this process, the need to establish a balance between industrial decarbonization and economic growth has gained importance (Gao *et al.* 2021). Türkiye has signed many important international agreements in combating climate change. Türkiye, which joined the United Nations Framework Convention on Climate Change in 2004 and took part in global climate change action, became a party to the Kyoto Protocol in 2009, but did not undertake a binding emission reduction target due to its status as a developing country (UNFCCC 2023). The Paris Agreement, which was adopted in 2015 and signed by Türkiye in 2021, was a turning point for the country's climate goals. This agreement includes Türkiye's commitment to be carbon neutral by 2053 (Paris Agreement 2021).

Carbon footprint (CF) refers to the total amount of greenhouse gases released directly or indirectly into the atmosphere by an individual, organization, product, or activity, and is usually calculated in terms of carbon dioxide equivalent (CO_2-eq) (Wiedmann and Minx 2008; Coşkun and Doğan 2021). In the context of wood-based products, it is essential to distinguish between fossil-based and biogenic carbon. Biogenic carbon refers to the carbon absorbed by trees from the atmosphere during growth and stored in biomass, which can remain sequestered within wood products for decades or longer (Werner and Richter 2007; Hafezi *et al*. 2021). This storage delays the release of CO_2 back into the atmosphere, thereby contributing to climate change mitigation (Peng *et al.* 2022). In contrast, fossil carbon as defined in carbon footprint standards such as ISO 14067 (2018) originates from the combustion or use of fossil fuels and adds to the net atmospheric CO_2 load without a corresponding uptake phase. The approach taken to account for biogenic carbon can significantly influence the calculated carbon footprint of wood-based products, and this methodological choice needs to be stated clearly in any assessment. Figure 1 (San Global Research, 2024) illustrates the distribution of carbon footprint contributions from different activities worldwide. As shown, industry (23%), electricity and heat generation (21%), and agriculture (17%) represent the largest shares of global emissions, followed by road transportation (11%) and land-use change/forestry (10%).

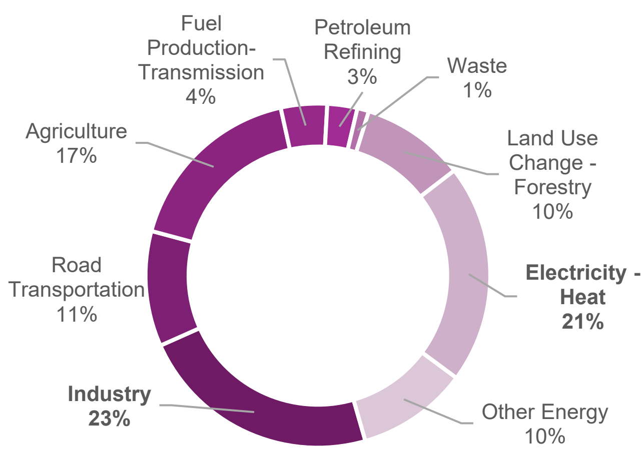


Fig. 1. Carbon footprint distributions by sector on a global scale (redrawn based on San Global Research 2024)

For industrial organizations, carbon footprint is a critical indicator for achieving environmental sustainability and combating climate change. Measuring carbon emissions originating from stages, such as energy consumption, raw material use, and waste management of industrial processes enables these organizations to understand and reduce their environmental impacts. Carbon footprint management can increase the competitiveness of businesses by encouraging energy efficiency practices, circular economy principles, and the use of renewable energy (Yurtay 2025). When looking at carbon emission sources, it is seen that the highest emission producers are heating-electricity and industry-based (Fig. 1.), and in this direction, the importance of industrial organizations determining more environmentally friendly roadmaps is remarkable (San Global Research 2024).

Wood-based panels mainly consist of fresh wood, wood processing waste, forest harvest waste, adhesives, and additives (Zhan *et al.* 2019). They are widely used in areas such as construction, furniture, design, and transportation (Rebollar *et al.* 2007). Türkiye is among the countries leading the wood-based panel sector and is one of the important representatives of the global panel sector. Production, import, and export data of the Turkish wood-based panel sector are given in Table 1. Export data reveal that Türkiye is in a competitive position in the international market in some product groups and that the sector has become an important factor in foreign trade. On a global scale, China became the largest particleboard producer in 2017 with a production exceeding 11 million m^3, followed by Russia with 6.8 million m^3, Germany with 5.4 million m^3, and the USA and Türkiye with 4.2 million m^3 each (Krug *et al.* 2023). Türkiye, which has caught the increasing trend in particleboard production, has the capacity to produce 6.5% of the particleboard produced in the world as of 2020. According to Akbulut and Ayrılmıs (2024) the total installed capacity of facilities producing wood-based panels in Türkiye had reached about 16,300,000 m^3 per year as of 2023. The wood-based panel sector consumes a significant amount of energy in the form of electricity, natural gas, diesel fuel, and biomass in its production processes, and these activities cause carbon emissions. Therefore, increasing sectoral energy efficiency and developing methods to reduce pollution are considered important for the sustainability of the sector in the coming years (Erdil and Yılgör 2020).

In addition to energy use and process-related emissions, another critical environmental aspect of particleboard production concerns the adhesive systems employed in manufacturing. It is important to note that formaldehyde-based resins, such as urea-formaldehyde (UF) and melamine-formaldehyde (MF), differ in their environmental performance. UF resins are widely used in the wood-based panel industry due to their low cost and favorable curing properties, but they are also associated with relatively higher formaldehyde emissions during use. In contrast, MF resins, though more expensive, generally provide better water and heat resistance and tend to release less formaldehyde, thereby contributing to improved indoor air quality and longer service life of coated panels (Yuan and Guo 2017; Chrobak *et al*. 2022). While this study focuses on the carbon footprint of melamine-coated particleboard, such contextual information helps highlight the broader environmental relevance of resin selection.

Table 1. Summary of the Manufacture, Import, and Export of Wood-based Panels from Türkiye in 2022 (FAO 2024)

Process	Volume	PLY/LVL (%)	PB (%)	OSB (%)	MDF/HDF (%)
Manufacture	12570000	4.93	44.75	0.60	49.72
Import	368273	43.25	5.16	9.77	41.82
Export	1828125	6.68	32.56	0.16	60.60

PLY/LVL = Plywood / Laminated Veneer Lumber
PB = Particleboard (coated and uncoated)
OSB = Oriented Strand Board
MDF/HDF = Medium-Density Fiberboard / High-Density Fiberboard

Forest products play an important role in achieving global carbon reduction targets and providing ecological benefits (Peng *et al.* 2022). Although wood-based panels can be considered carbon neutral due to their biogenic carbon content, they are also among the sectors that cause carbon footprints due to emission sources, such as transportation, energy consumption, *etc.*, in the production process (Werner and Richter 2007). Determining and managing the carbon footprint in the production of wood-based panels is also vital for related industries (furniture, construction, *etc.*) (Lao and Chang 2023). The environmental performance of wood-based panels is frequently analyzed through life cycle assessment (LCA) and carbon footprint calculation studies. The LCA is a standardized method that systematically evaluates resource use, emissions, and environmental impacts throughout the product's life cycle (ISO 14044 2006). The carbon footprint calculation quantifies greenhouse gas emissions by focusing on the climate change impact category and is considered a subset of LCA (ISO 14067 2018). However, in wood-based production chains, how environmental impacts will be shared among different outputs constitutes an important methodological debate (Jungmeier *et al.* 2002).

There are studies in the international literature with methodological differences where different CF assessment tools are adopted (Rivela *et al.* 2006; Wilson 2010; Saravia-Cortez *et al.* 2013; Silva *et al.* 2014, 2020; Garcí and Freire 2014; Hussain *et al.* 2018), which makes it difficult to compare the CF results between products (Whittaker *et al.* 2011; Dias and Arroja 2012). However, it is apparent that a majority of studies conducted in academic environments have focused on raw particleboard (uncoated) production (Table 2). In the literature search conducted on limited databases, melamine-coated particleboard CF calculation were not found, and it was seen that various processes (A1–D) were addressed in private sector environmental impact declarations (Pfleiderer 2020; Sonae Arauco 2022). There are also significant differences in carbon footprint calculations across countries (Table 2). This is due not only to technical differences in production processes, but also to factors such as data sources, energy mixes, system boundaries, choice of methodology (CML, IPCC, ISO 14067, *etc.*) and the way biogenic emissions are handled.

Table 2. Carbon Footprint Studies for Particleboard from Different Countries

Density (kg/ m^3)	Impact Assessments Method	Country	CF (kg CO_2e/m^3)	References
634	CML	Germany	217	Diederichs (2014)
630	CML, USEtox, land use indicators	Brazil	319	Silva *et al.* (2014)
640	ISO/TS 14067, PAS2050, Climate Declaration	Portugal	168-188	García and Freire (2014)
750	IPCC (2013)	Pakistan	975	Hussain *et al.* (2018)
-	IPCC (2007) Tier Method	Türkiye	157.5	Erdil *et al.* (2017)
750	CML, IPCC (2013), USEtox	Japan	444	Nakano *et al.* (2018)
630	CML, USEtox	Brazil	333	Gonzalez-Garcia *et al.* (2019)
640	LCA, ISO/TS 14067	China	348	Lao and Chang (2023)

Türkiye has a high production capacity and technological infrastructure in the wood-based panel industry; however, academic studies on the carbon footprint of this sector remain limited globally (Erdil *et al.* 2017). Considering the economic value of the wood-based panel sector in Türkiye, there is a great need for studies to measure the carbon footprint resulting from production processes. In this study, the carbon footprint of 1 m^3 of coated (melamine decorative paper impregnated) and uncoated particleboard production was calculated, and the emission sources of the production facility were also evaluated according to the scopes. In the light of the findings, the goal was to present suggestions for reducing emissions specific to the relevant sector.

EXPERIMENTAL

Integrated Particleboard Manufacturing Plant Data

In this study, data obtained from an integrated particleboard production facility operating in the Mediterranean region of Türkiye were used. The annual production capacity of the facility is about 456000 m^3 particleboard. A total of 80.7% of the particleboards produced are coated, while 19.3% are offered for sale as uncoated. General content information of the particleboards produced in the facility is given in Table 3. The melamine-coated particleboard production processes and emission sources of the factory are given in Fig. 2.

Table 3. Material Composition of 1 m^3 Melamine-coated Particleboard and Uncoated Particleboard

Raw Material	MFC-PB Weight (%)	PB Weight (%)
Chipboard	90 to 99	90 to 99
Paper	1 to 5	-
Resin	6 to 10	6 to 10
Other additives	1 to 5	1 to 5

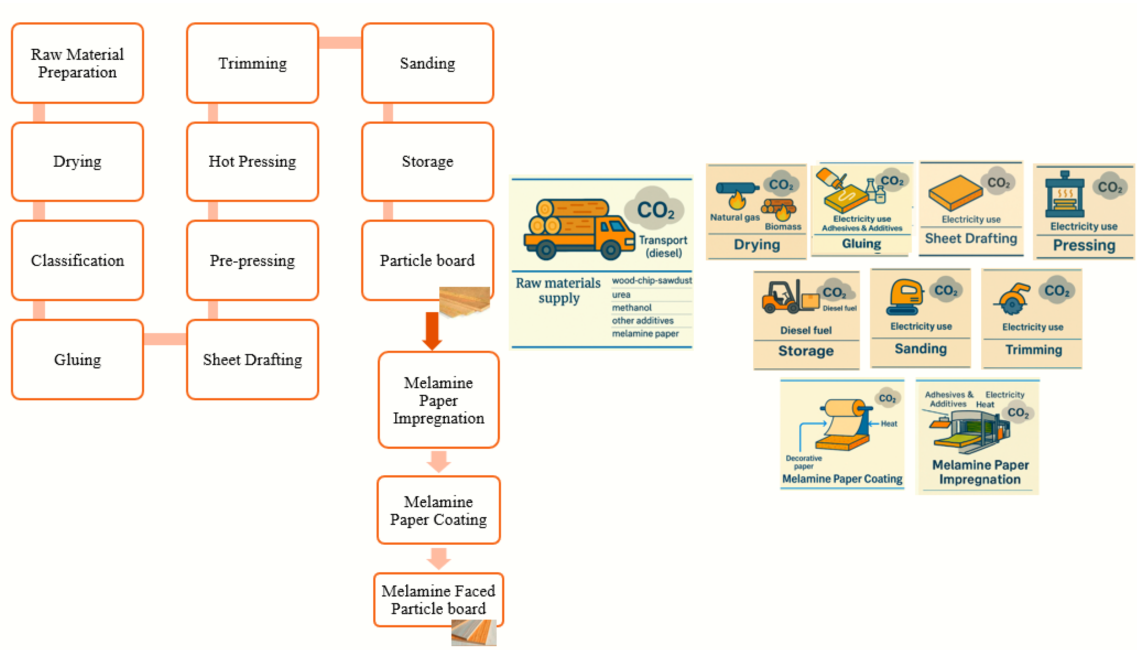


Fig. 2. Particleboard production flow chart and carbon emission source for the company (adapted from melamine-coated particleboard EPD reports produced in Türkiye)

In the production process of the facility, both direct electricity and natural gas are used as energy sources and energy is obtained by burning biomass. Diesel fuel is used in transportation equipment (forklifts) used in the field and vehicles used for raw material supply (trucks, tankers, *etc.*). In carbon footprint calculations, it was assumed that the facility operates 360 days per year. The glues used in the facility, where melamine paper-coated particleboard production is carried out, are produced within the facility. All wood-based wastes that are evaluated as non-hazardous waste and occur in the production processes of the facility are burned and used in energy production, while hazardous wastes are delivered to licensed waste companies and removed. It is assumed that the waste truck travels 3600 km per year and in accordance with the polluter pays principle, the CF associated with transporting hazardous waste to the storage facility was included in the facility's emissions inventory. The data was obtained as a result of face-to-face interviews with facility officials and belongs to 2024. The diesel fuel used by the forklift used in the facility site, natural gas used in production, CFs formed by burning wood-based residues (DEFRA 2023) and CFs formed due to glue production were evaluated in Scope 1, purchased electricity consumption in Scope 2, and transportation activities in Scope 3 as stated in Meza-Lopez *et al.* (2021). Data and emission sources of the particleboard production facility are given in Table 4.

Table 4. Company Data and Emission Sources

Emission Resource	Consumption Quantities	Unit	Description
Production Quantity	455632	m^3 PB	
	365890	m^3 MFC-PB	
	42300000	m^2 MP	
	4900000	kg UF	
	4660350	kg MF	
Natural gas	10200	m^3/year	heating-production
Diesel	168000	lt/ year	in-production transportation
Diesel	180000	lt/ year	personnel vehicles
Electricity	51000000	kWh/ year	production
Hazardous Waste	479000	kg	glue residue, impregnated paper residue, organic solvents and liquids, waste battery-accumulator-fluorescents, oil filters, *etc.*
Non-Hazardous Waste	25200000	kg	Wood dust
	21600000	kg	Bark
	175000	kg	Mixed packaging waste
Transportation	69434240	tonne/km	Raw material 9566uply (wood based)
	7792168	tonne/km	Adhesive raw material 9566uply (*e.g.*, urea, methanol)
	2097157	tonne/km	MF material supply
	150718	tonne/km	Additives (urea hardener, ammonium sulfate, *etc.*)
PB: particleboard, MFC-PB: melamine faced particleboard, MP: melamine paper, UF: urea formaldehyde, MF: melamine formaldehyde			

Carbon Footprint Calculation

In this study, product-based CF calculations for MFC-PB production were carried out based on the ISO/TS 14067 (2018) standard. The functional unit of the study was defined as 1 m³ melamine coated particleboard. Grid electricity, diesel fuel, glue (UF) chemical additives, and melamine coating materials (MF, decorative paper) are used in the production process. The emission factors required for carbon footprint calculations were obtained from the literature (Table 5) (DEFRA 2019, 2021, 2023; IPCC 2006, 2019; BEİS 2019; Tomberlin *et al.* 2020; Bushi *et al.* 2022).

The CF (for glue production) originating from the in-plant production processes of raw materials and emissions originating from transportation activities were modeled independently of each other and ton/km-based transportation emissions were calculated separately according to DEFRA (2023) data. The activity-based emission factor for the Turkish national electricity grid (0.7108 kg CO_2e/kWh) was taken as the basis (ETKB 2024) and calculated with the help of the following formula (IPCC 2019),

$$CF_{electricity} = E_{kWh} \times EF_{kWh} \quad (1)$$

where E_{kWh} is the amount of electricity consumed (kWh) and EF_{kWh} is the emission factor (kg CO_2e/kWh). The CF resulting from natural gas consumption is calculated with the formula below,

$$CF_{naturalgas} = v \times \rho \times NCV_{kWh} \times EF_{energy} \quad (2)$$

where v is the consumed natural gas volume (m^3), ρ is the natural gas density (kg/m^3) (0.75kg/m^3), NCV is the net calorific value (MJ/kg), and EF_{energy} is the IPCC emission factor (kg CO_2e/MJ).

Because specific local (Türkiye) emission data for UF and MF resins are not available, the current values used in the literature were taken as the basis (Bushi *et al.* 2022). This approach is similar to the method proposed by Hussain *et al.* (2018) for UF resin and other auxiliary inputs.

Table 5. Relevant Emission Factors and Net Calorific Values

Emission Sources	Emission Factors (CO_2/CH_4/N_2O	Unit	Net Calorific Value (NKD) (Tj/Gg)
Natural gas	56100/5/0.1	kgCO_2e/ Tj	48
Electricity	0.7108	kgCO_2/ kWh	-
Diesel fuel	2.68	kgCO_2/lt	-
Transport	0.7468	kgCO_2/ ton·km	-
UF/MF	1.53/5.27	kg CO_2e/kg	-
Decorative paper	1.057	kg CO_2e/kg	-

Material, energy and fuel inputs and outputs per unit product of the melamine coated particleboard production process are presented in Fig. 3.

The CF resulting from raw material transportation was calculated based on the following Eq. 3,

$$E_{GHG_t} = \sum_{i}^{n} M_i \times D_i \times EF_i \quad (3)$$

where M_i represents amount of raw material transported (kg), D_i represents transportation distance of raw material (km), and EF_i is the emission factor of the transportation mode (HGV diesel, rigid > 17t) (kg CO2e/ton·km). This method is compatible with IPCC life cycle assessment standards and allows the determination of emissions from transportation separately according to the distance and amount of transportation of different raw materials (Lao and Chang 2023). The majority of the wood raw material transported to the factory is supplied from state-operated forests within the national borders of Türkiye and especially from forest enterprise directorates close to the factory. Primary data on MFC-PB production were obtained directly from the producer. Raw materials used and one-way transportation distances are given as average values in Table 6.

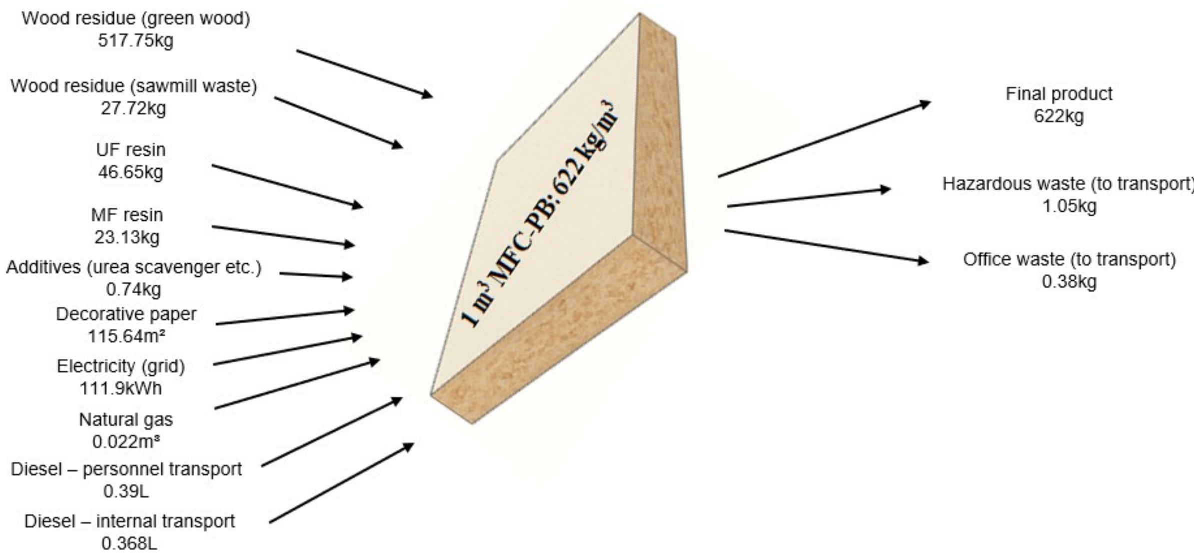


Fig. 3. Inputs and outputs to produce 1.0 m³ of MFC-PB

Table 6. Raw Materials and One-way Transport Distances

Material	Delivery Distance (km)
Wood residue (green wood)	296
Wood residue (from sawmill)	20
Urea (UF raw material)	450
Methanol (UF raw material)	450
Other additives (*e.g.*, wax, catalyst)	450
Decorative paper	600
Melamine formaldehyde resin (MF)	450

In the study, CF from biomass combustion was calculated based on the following equation (IPCC 2006),

$$CF_{bio} = E \times \left(EF_{CH_4} \times GWP_{CH_4} + EF_{N_2O} \times GWP_{N_2O}\right) \quad (4)$$

where CF_{bio} represents the total carbon dioxide equivalent (CO_2e) emission amount (kg CO_2e/year) from biomass combustion. *E* represents the total annual energy consumption (GJ/year) during biomass combustion. $EF_{(CH_4)}$ and $EF_{(N_2O)}$ show the emission factors (kg/GJ) used per energy for methane (CH_4) and nitrous oxide (N_2O), respectively. $GWP_{(CH_4)}$ and $GWP_{(N_2O)}$ express the 100-year global warming potential (GWP) of the relevant gases. With this method, the contributions of greenhouse gases other than direct CO_2 as a result of biomass combustion in terms of CO_2 equivalent are also included in the total emission calculation. According to the IPCC (2006) Tier 1 methodology, CO_2 from biomass combustion is considered biogenic and carbon neutral, while CH_4 and N_2O emissions are included in the carbon footprint.

Cut-off Criteria

In this study, emission factors for UF and MF resins cover processes, such as production of raw materials used in the resin production process, transportation to the resin production facility, and energy consumption in the production process. Because MF resin is supplied externally, the use of cradle-to-gate EF is suitable for these processes that occur outside the production facility. In addition, emissions resulting from the transportation of MF resin to the board plant are also included in the calculations. Because UF resin is produced on-site at the board production facility, a cradle-to-gate comprehensive EF was not used; instead, emissions were calculated separately based on electricity, heat, and chemical inputs used in resin production. Thus, the energy used for UF production was not double-counted in the carbon footprint calculations made over the total energy consumption of the facility. This approach ensured consistent modeling of energy consumption within the system boundaries. The system boundary covers production processes including raw material transportation, energy consumption, glue, melamine coating, additives, and waste management. Energy losses that may occur in the facility during the period from the entry of the raw material to the final product formation have been neglected, and the supply of wood raw material (harvesting of fresh wood from the forest) and the distribution and transportation of the final product produced in the facility have not been included in the calculations.

RESULTS AND DISCUSSION

The CF values calculated in the study and their sources are given in Table 7.

Table 7. Carbon Footprint Values for 1.0 m^3 of Particleboard and 1.0 m^3 of Melamine-Faced Particleboard

Input	PB CF (kg CO_2e/m³)	MFC-PB CF (kg CO_2e/m³)
Wood raw material (transport)	114.45	114.45
Electricity	63.58	63.58
Electricity (impregnation)	-	14.85
Natural gas	0.054	0.054
In-plant transport	0.99	0.99
Personnel vehicles	1.05	1.05
UF production	71.37	71.37
UF (transport)	12.52	12.52
MF glue consumption	-	121.90
MF consumption	-	4.28
Additives consumption	32.81	32.81
Additives (transport)	0.25	0.25
Decorative paper consumption	-	13.18
Decorative paper (transport)	-	5.70
Hazardous waste (transport)	2.50	2.50
Office waste (transport)	0.0057	0.0057
Wood burning (excluding CO_2)	2.34	2.34
TOTAL	**299.41**	**461.84**

In the MFC-PB production, CF markedly increased compared to uncoated particleboard due to the use of MF glue and decorative paper specific to the impregnation line. This finding demonstrates that surface coating processes (impregnation) substantially increase the environmental impact. The highest contributions in both products come from transportation, electricity consumption, and processes belonging to the glue production chain.

The distribution of carbon footprints of MFC-PB production processes at scope 1, scope 2, and scope 3 levels and their proportional contributions according to detailed sources are presented in Fig. 4.

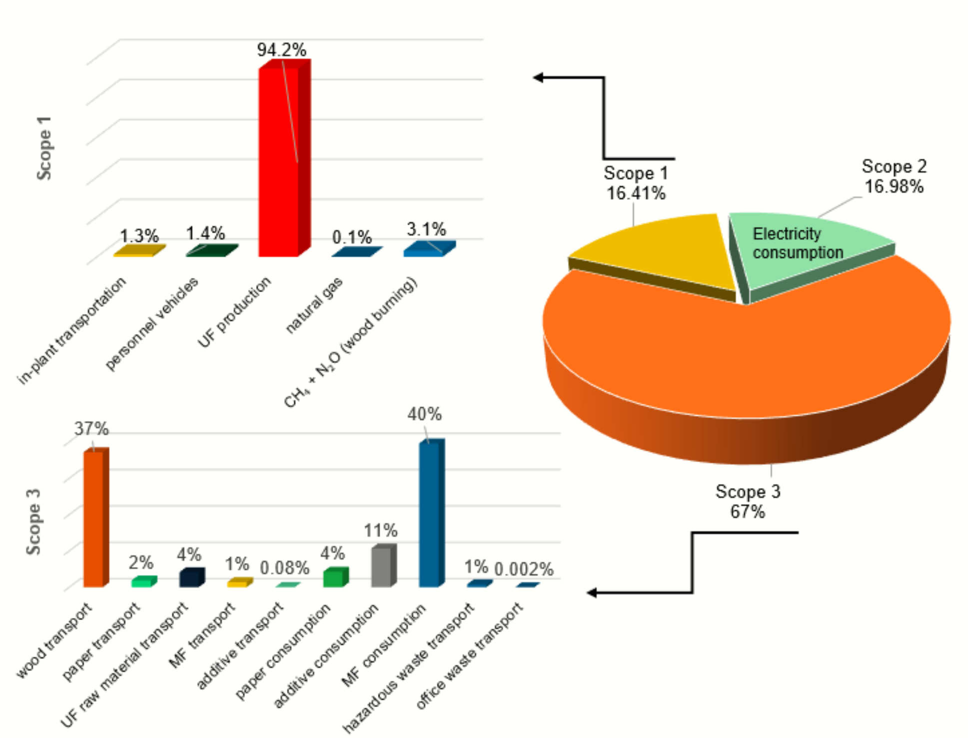


Fig. 4. Distribution of scopes and emission sources included in the scopes

The study found that raw material transportation had a major impact on the total CF (29.85%). A similar study reported that the raw material supply stage had the largest impact (55% to 81%) for four types of wood-based panels (Lao and Chang 2023). However, it is emphasized that raw material supply and transportation contribute significantly to the CF in wood products, including wood-based composites (Lao and Li 2023).

For the CF calculated within the scope of the study, the glue chain makes a notable contribution (UF: 25.32%, MF: 27.32%). Similarly, Hussain *et al.* (2018) reported that fossil fuel consumption and glue production chain constitute a large part of the total emissions. Kuntar and Hill (2014) stated that UF glue used in MDF production contributes to 28.5% to the total carbon footprint. Similarly, in studies on particleboard production processes, it is stated that urea formaldehyde (UF) resin contributes approximately 29% to the CF calculation (Lao and Chang 2023). In studies on oriented particleboard production processes, it is stated that glues contribute 38% of the total CO_2 emissions (Ferro *et al.* 2018).

In recent years, research on alternative resins and hardeners that do not contain formaldehyde has gained importance in the production of wood-based panels. In particular, the focus is on substitutes that can be used instead of formaldehyde in amino and phenolic resins (Chrobak *et al.* 2022; de Carvalho *et al.* 2025). It is stated that lignin-based binders can be used to reduce the environmental impacts caused using glue in the production processes of green wood composites and can be considered as an alternative to traditional glues from an environmental perspective (Yuan and Guo 2017). Jia *et al.* (2019) recommend using pyrolysis bio-oil instead of phenol as an alternative to UF glue in plywood production. These studies show that glue production processes are critical processes in reducing environmental impacts and carbon emissions in wood-based panel production.

Another process that is critical in terms of environmental impacts in the particleboard production process is the production stages that use energy intensively. In this study, the contribution of electricity consumption, which is the primary energy source of the facility, to the total CF was calculated as 17%. In addition, the melamine impregnated paper coating line (particularly hot pressing and impregnation processes) accounts for 33.70% of the total carbon footprint. Similar studies on the subject in the literature also state that drying and hot pressing processes in particular cause significant carbon emissions due to high energy consumption (Puettmann and Wilson 2005; Wilson 2010).

In addition, it is apparent that there are considerable differences in carbon footprint values according to countries (see Table 2). The reason for this difference is not only due to technical differences in production processes, but also to factors such as data sources, energy mixes, system boundaries, methodology preference (CML, IPCC, ISO 14067, *etc.*), and the way biogenic emissions are handled. Therefore, methodological transparency and consistent system boundary definition are crucial for ensuring comparability across products. In particular, the amount of energy used in production and the source of this energy (renewable or fossil fuel-based) play a decisive role in many environmental impact categories. For example, preferring renewable energy sources in MDF production creates lower greenhouse gas emissions and environmental burden compared to fossil fuels (Yılmaz 2024). In this study, the necessary steam and heat in the plant processes (with the use of natural gas for the first ignition) are provided entirely by burning wood-based residues. It is seen that the CF value of the uncoated particleboard obtained in this study is within the range specified in the literature (see Table 2).

Biogenic Carbon Content Assumption

The amount of biogenic carbon has been assessed in accordance with the GHG Protocol, PAS 2050 standard and it has been calculated that 1,038.65 kg CO_2e carbon is stored per 1 m^3 melamine coated particleboard. When this value is compared with the total emission of 462 kg CO_2e/m^3 resulting from the production process, it is seen that the net carbon footprint of the product is -577 kg CO_2e/m^3. However, this net effect is based on the assumption that the carbon will remain constant throughout the product's life cycle without being released into the atmosphere. It should be noted that the treatment of biogenic CO_2 as neutral depends on the assumption that the biosphere can continue to absorb carbon at its current rate. However, as Liu *et al.* (2018) points out, this assumption can introduce bias in LCA studies if ecosystem carbon performance changes over time. Furthermore, Matuštík and Kočí (2022) emphasizes that climate change and elevated atmospheric CO_2 may reduce the biosphere's capacity, making the neutrality assumption increasingly tenuous. The amount of biogenic carbon stored in the product is calculated with the following formula according to the PAS 2050 (2011) standard,

$$C = CC\ x\ W\ x\ 3.67 \tag{5}$$

where CC represents the carbon content in the dry mass of wood (0.50) and W represents the amount of dry matter per 1 m³ of product (566 kg/m³). According to the calculation, the amount of biogenic carbon stored in the MFC-PB product is calculated as 1,039 kg CO_2e/m³. This value can be evaluated as an emission reduction according to PAS 2050 in case the product is used for 100 years or more (PAS 2050 2011; EN 16485 2014) (Fig. 5). Whether or not biogenic carbon is included in the life cycle assessment leads to differences in the total CF. Garcia and Freire (2014) calculated negative CF values (-913 kg CO_2e/m³, -939 kg CO_2e/m³) due to the effect of biogenic carbon according to the GHG Protocol and PAS 2050, and positive CF values (188 kg CO_2e/m³, 168 kg CO_2e/m³) in the ISO/TS 14067 methodologies, and drew attention to the CF values that vary depending on the methodology used.

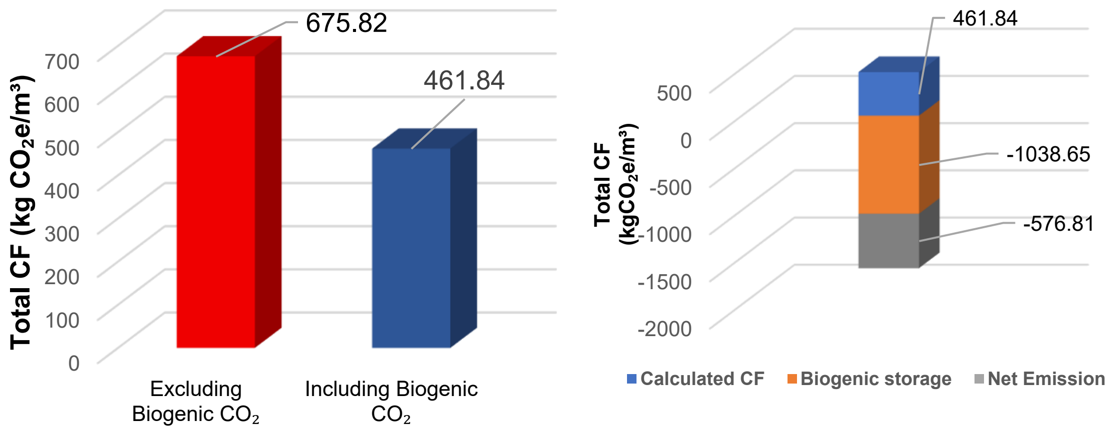
Different Scenarios for Biomass Combustion

The process heat and steam needs of the facility are met by burning biomass wastes, such as wood dust and bark, resulting from production. In this study, biogenic CO_2 emissions were included in the carbon cycle and were excluded from the calculation; however, CH_4 and N_2O emissions formed during the combustion process were evaluated in terms of CO_2 equivalent over their global warming potential (GWP) (IPCC 2006). Calculations were made considering that a total of 46,800,000 kg of biomass (wood dust and bark) is used annually and the lower heating value (LHV) of these fuels is assumed as 18.6 MJ/kg. Accordingly, total energy production was found to be 870,500 GJ. According to IPCC Tier 1 emission factors, CH_4 and N_2O emission factors for stationary combustion systems are 0.015 kg CH_4/GJ and 0.003 kg N_2O/GJ, respectively. According to these data, annual total CH_4 and N_2O emissions were calculated as 13,100 kg and 2,610 kg, respectively. With the conversion made using IPCC AR6 GWP values (CH_4: 27.2, N_2O: 278), total greenhouse gas emissions were calculated as approximately 1,070,000 kg CO_2e/year, and the emission value per m^3 product was calculated as 2.34 kg CO_2e/m³ and added to the total CF value.

In this study, biogenic CO_2 emissions from biomass combustion were considered carbon neutral in accordance with the IPCC Tier 1 methodology and therefore were not included in the carbon footprint calculations (only CH_4, N_2O were included). However, in an alternative sensitivity analysis, it was calculated that if the CO_2 emissions from biomass combustion were also considered, an additional 214 kg CO_2e/m³ load would be added to the total carbon footprint for 1 m³ of melamine-faced particleboard (see Fig. 5). This comparison reveals the decisive influence of the way biogenic carbon is assessed on the final results. In addition to illustrating the influence of biogenic carbon assumptions, the results presented in Fig. 5 may also serve as a starting point for future cradle-to-grave studies to examine the implications of an extended service life of melamine-coated particleboard, since a longer lifetime could substantially reduce replacement frequency and associated emissions.

Moreover, although the present study did not quantify toxic gas emissions from the burning of wood-based residues, it is important to note that melamine-formaldehyde (MF) resins generally exhibit greater thermal stability and tend to release less formaldehyde than urea-formaldehyde (UF) resins under combustion conditions (Myers 1984; Chrobak *et al.*

2022). Tatàno *et al.* (2009) further demonstrated that the burning of engineered wood wastes analogous to coated particleboard under non-ideal conditions may generate additional toxic byproducts such as pyrroles, amines, phenolic and nitrogen-containing compounds, as well as carbon monoxide, NO_x, and fine particulate matter (PM_1). These findings highlight that, beyond formaldehyde release, burning of coated wood products can lead to a broader spectrum of environmental and health impacts, which should be addressed in future cradle-to-grave studies.



a) Effect of biogenic CO_2e accounting on total CF **b)** Impact of biogenic carbon storage on net emissions

Fig. 5. Effect of biogenic CO_2 accounting and biogenic carbon storage on the carbon footprint of MFC-PB production

CONCLUSIONS

This study provided a comprehensive carbon footprint evaluation of melamine-faced particleboard (MFC-PB) production in Türkiye, following ISO 14067 (2018) and IPCC 2006 Tier 1 methodologies. The findings offer valuable insights into emission hotspots and strategic opportunities for reducing environmental impacts in the sector.

1. The total carbon footprint of MFC-PB was calculated as 462 kg CO_2e/m^3, which was notably higher than that of uncoated particleboard (299 kg CO_2e/m^3). Surface coating processes—primarily melamine impregnation and hot pressing—were shown to substantially increase the product's environmental impact.
2. Scope 3 emissions contributed the largest share (67%) of total emissions, driven by raw material transportation and adhesive production. Scope 1 and Scope 2 emissions were mainly associated with on-site energy use (biomass combustion, natural gas, and electricity).
3. The adhesive production chain (UF and MF resins) alone accounted for over 52% of the total carbon footprint of MFC-PB. This underscores the critical importance of exploring low-carbon adhesive alternatives, such as bio-based or formaldehyde-free systems.
4. The use of biomass-based process heat considerably affected the facility's carbon profile. The inclusion or exclusion of biogenic CO_2 emissions and the adoption of

alternative energy substitution scenarios led to substantial differences in net emissions, highlighting the sensitivity of carbon footprint results to methodological choices.

The findings of this study suggest that renewable energy integration, reducing raw material transport distances, and promoting eco-innovations in adhesive formulations have the potential to yield considerable emission reductions. Implementing these strategies could align with global sustainability targets and support Türkiye's commitment to achieving carbon neutrality by 2053.

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