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Evaluating the sustainability of car mat manufacturing

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ABSTRACT

In recent years, the automotive industry has become increasingly concerned about environmental sustainability. Scant information is available on the environmental impacts of car parts. Therefore, this paper aims to assess the life cycle environmental impacts of one of the most important car interior accessories - rubber car mats - and to identify potential improvements. Sensitivity analysis was performed on alternative raw materials and energy sources used in the production of the rubber mat, as well as different raw material supply transport distances. Rubber and carpet mats for a car have also been compared in terms of environmental sustainability. The inventory is primarily based on primary data, and the evaluation considers a broad variety of environmental impact categories to both human and ecosystem health. The results reveal that the global warming potential of a set of rubber car mats is estimated at 5.9 kg CO_2-eq. The car mat manufacturing is the main contributor to the majority of impact categories (47%–83%) due to the high energy consumption caused by the long mixing time and hot-pressing process. The only exception to this is the depletion of abiotic resources and the ozone layer, which are primarily caused by the production process. The impacts are highly sensitive to the electricity source and types of rubber. The use of carpet mats instead of rubber mats in motor vehicles increased environmental impacts (26%–92% higher) in all categories. The findings of this study will help the automotive industry benchmark the industry and maximize its environmental sustainability. Consumers will be interested in the findings as well, as they will help them identify environmentally more sustainable car parts.

1. Introduction

A key goal on the path to sustainable development is to ensure more sustainable manufacturing, lower energy and material consumption, and the development of new products using various methods and tools in order to maintain global competitiveness and cope with recent challenges [1]. The automotive industry is regarded as one of the most strategic contributors to achieving this goal [2]. This sector is an important driver of economic growth and social welfare; on the other hand, with its vast supply chain, it is frequently a source of negative environmental impacts [2,3]. The greenhouse gas (GHG) emissions of the automotive industry, during production and recycling, accounts for 9% of total annual global GHG emissions in 2018. The twelve major vehicle manufacturers were evaluated and they are responsible for 4.3 gigatons (Gt) of CO_2-equivalent (eq). Extrapolating from this, the entire automotive industry, with 86 million cars sold in 2018, is estimated to have a combined carbon footprint of 4.8 Gt CO_2-eq, accounting for 9% of global GHG emissions. The combined footprint is greater than the European Union's total annual GHG emissions (4.1 Gt CO_2-eq) [4].

In recent years, this sector has become increasingly concerned about environmental requirements. This concern is emerging as a result of not only increased environmental awareness on the industry side but also of increasing regulations and global competitiveness. Previously, the primary focus was on reducing environmental impacts during the use phase of the vehicles, followed by the entire life cycle including the manufacturing of all components and accessories [2]. As a result, decisions about product design and development must take into account environmental factors [5]. Such an evaluation should be aided by appropriate life cycle thinking-based tools, such as the Life Cycle Assessment (LCA).

LCA is an international method that quantifies the environmental impacts associated with goods and services that are manufactured and identifies opportunities for change through the evaluation of the entire product life cycle [6]. Every stage of the life cycle is simulated in this method, which involves the extraction and processing of raw materials, the production process, transportation, usage, reuse or recycling, and final waste disposal. Under the right conditions, the LCA methodology can help to integrate environmental considerations into decision-

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making processes more effectively [7,8].

Mats are an accessory for motor vehicle interior parts that can be bought when the vehicle is purchased or ordered aftermarket. They are likely to be at the top of the list of interior car accessories. In 2017, the global automotive floor mat market was worth US$7.91 billion and will grow at a compound annual growth rate of over 4.8% from 2017 to 2027 [9]. Rising vehicle demand and the growing demand for comfort and protection in vehicle cabins are expected to be key drivers of market growth. Vehicle floor mats are intended to protect the floor from noise, dirt, and corrosion. Mats are made in a variety of materials and shapes. Rubber or carpet are the most common materials used in vehicle mats. There are some differences between these types of car mats. Carpet mats are typically tufted and have a non-slip rubberized backing. Rubber car mats, on the other hand, are more long-lasting and economic [10,11].

In general, all vehicle LCA studies include the various life cycle phases of a vehicle, such as raw material extraction, manufacturing, use, maintenance, end-of-life, and intermediate transports between these phases. Over the years several LCA studies were conducted that considered the environmental sustainability of the entire range of automotive parts and the processes of component design. Methodological topics, life cycle inventory data, as well as environmental impacts, are covered in these LCA papers. Related studies from the automotive industry have analyzed the life cycle environmental impacts associated with tires (e.g. Fiksel et al. [12], Ortíz-Rodríguez et al. [13], Piotrowska et al. [14] and Pavlovic et al. [15]), door components (e.g. Puri et al. [16] and Bushi et al. [17]), composite (e.g. La Rosa et al. [18] and Duflou et al. [19]) and plastic parts (e.g. Smith [20]). Even though LCA is a common technique for determining the sustainability of vehicles, there are no studies on mats or vehicle floor coverings in the literature. Although no studies on the sustainability of car mats have been conducted, studies on floor coverings can be found in the literature. Potting and Blok [21], Jönsson et al. [22], Jönsson [23], Gorrée et al. [24], Minne and Crittenden [25], and Ahmed and Tsavdaridis [26] discussed the environmental sustainability of flooring materials. Other studies discussed the life cycle sustainability of carpets Realff and Saunders [27] and Sim and Prabhu [28]. There are few studies in the literature that look at the environmental effects of using rubber as a floor covering. Li et al. [29] estimated the environmental impact of rubber flooring material made from waste tires over its entire life cycle.

Mats are essential parts of all vehicles. The manufacturing of these products, from raw material extraction to forming, inevitably consumes raw materials and energy and causes various types of environmental impacts [11]. At present, there are no LCA studies of mats for motor vehicles. Therefore, this work aims to evaluate the life cycle environmental sustainability of car mats and identify opportunities for improvements. Several sensitivity analyses have been carried out to test the impact of different assumptions on the results of rubber car mats. The rubber and carpet car mat options are compared via a life cycle assessment. The inventory is based on primary data, and the analysis considers a wide range of impacts to both human and environmental health.

The methodology used in this study is detailed in the next section, including the assumptions and data used in LCA modelling. The results of the modelling of the rubber and carpet car mats are presented and discussed in the Results and Discussion part and conclusions are drawn from the Conclusions part.

2. Materials and methods

2.1. Life cycle assessment of car mats

This part presents the results of the LCA of the vehicle floor mats. The LCA study has been conducted according to the ISO 14040/14044 standards [30,31]. GaBi v10.5 [32] and Ecoinvent database [33] has been used for the modelling and the background data. The aim and objective of the study are defined below, followed by the detail of the system, assumptions, and inventory data for the rubber and carpet car mats.

2.1.1. Goal and scope of the study

The main goal of the study is to evaluate the life cycle environmental impacts of one of the most common car mats – rubber mats – and to compare them with carpet mats. A further goal is to estimate the life cycle impacts at the facility level, considering the annual manufacturing of rubber car mats in 2020. Several sensitivity analyses have been carried out to test the impact of different assumptions on the results of rubber car mats.

The study is based in Turkey and the results are aimed at the global automotive sector. The functional unit is defined as “1 set of car mat”, the image is shown in Fig. 1. The weight of rubber and carpet mats prepared by the packaging to be sent to the customer is 5.8 and 2.2 kg per functional unit (fu). Moreover, the total annual environmental impacts of the facility have been assessed in our study. The number of rubber mat sets produced at the facility was approximately 73,250 per year.

The scope of the study is from cradle to gate, comprising the production and processing of raw materials (*Raw Material stage*), transportation of the raw materials and distribution of the products (*Transportation stage*), and production of the car mats (*Production stage*). Use and end of life of the car mat stages were excluded due to a lack of data. The construction and decommissioning of the facility are also omitted because the infrastructure impacts per unit of output are negligible over the long life of an industrial plant.

2.1.2. System description, assumptions, and data for rubber car mats

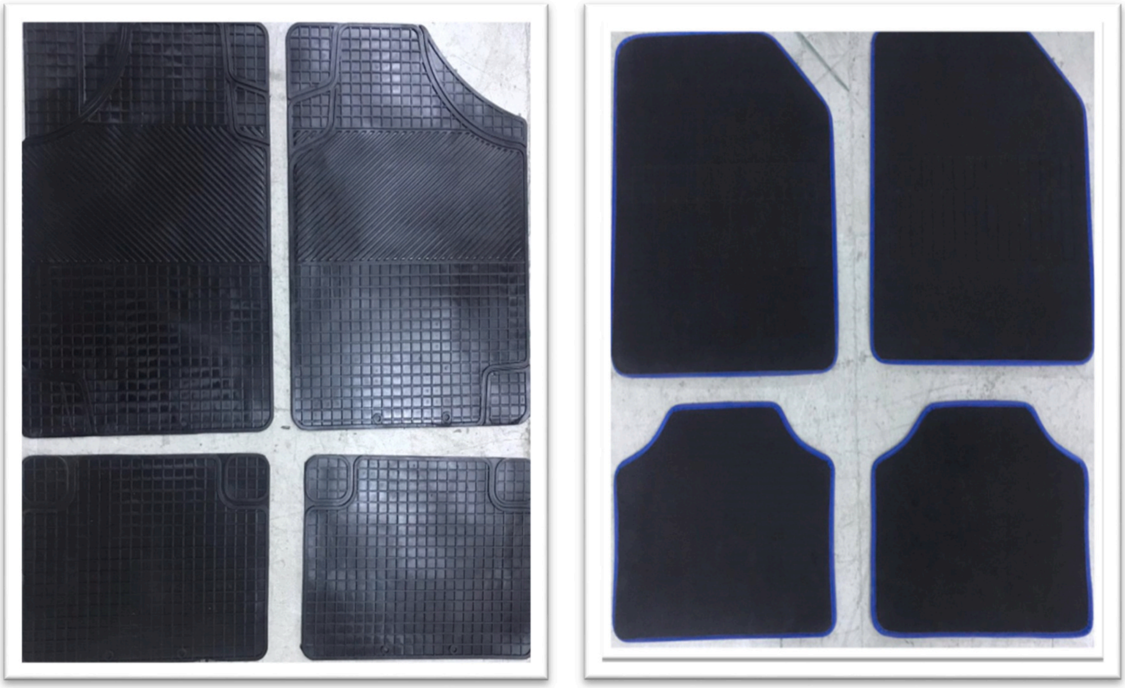
As presented in Fig. 2, the scope of the study is from ‘cradle to gate’, which includes raw material supply, manufacturing of rubber mats, and their distribution. Transportation across the life cycle is also considered. All data on the supply, transportation, and use of raw materials, energy consumption, and packaging material for car mats have been gathered from production data of a factory in Turkey for the year 2020.

Rubber mats are preferred in motor vehicles because they are durable, easy to clean, and economical. While producing rubber mats to provide and improve all of these features, some additives are used in addition to the rubber raw material. Table 1 demonstrates the raw materials and quantities used for the production of rubber mats. The total amount of raw material used in the production and packaging of rubber mats is around 7 kg per functional unit. There are no co-products in this production.

Rubber tile is made up of a uniform blend of rubber, fillers, and additives. Natural rubber is the primary raw material used in the production of mats. It is the main raw material in the formation of the product. Kaolin is a type of clay mineral that is used as an inert filler. The waste rubber mat parts generated in the process are used as a recycling material to reduce costs. Rubber aromatic oil is a non-polar type of mineral oil and is used for the mastication and processing of rubber fillers and rubbers. Zinc oxide acts as an activator to enhance mechanical properties. It is treated with sulphur to harden the rubber and this process is known as vulcanization. The quantities of some additives such as mercaptobenzothiazole (MBT), diphenyl guanidine (DPG), and tetramethyl thiuram disulphide (TMTD) are small (in total <%1), so they have not been taken into consideration for the life cycle modelling.

Raw materials used in the production of rubber mats are transported by lorry or ship. Detailed data on the transport of raw materials used in the production of rubber mats to the production facility are provided in Table 1.

Electricity is used as an energy source at the facility. Information on energy use is given in Table 1. This information has been calculated using the total power, efficiency, and time of use of the machine. As presented in Fig. 2, the rubber car mat is manufactured in several stages beginning with the weighting and mixing of the raw materials. First, natural rubber and recycled car mat parts are mixed for about 1.5 min in the mixer (Mixer 1). Then kaolin, aromatic rubber, and zinc oxide are



a) Rubber car mat b) Carpet car mat

Fig. 1. 1 set of car mat chosen as a functional unit.

added and mixed for 12–15 min at 60–70 °C in the second mixer (Mixer 2). The mixture is drawn thickly in the roll (Roll 1). Following that, small and final-stage chemicals are added and mixed for about 15 min, until there is homogeneous participation. The resulting compound is calendared into 0.5 mm thick sheets in the second roll (Roll 2) and cut according to the layouts, generally referred to as preform. The preform is are then placed in the Press and heated for about 3 min at 160 °C. After that, the mats are cleaned and cut to their finished size for packaging. Plastic fittings, cardboard mat labels, nylon mat bags, and cardboard boxes are used as packaging products to package the final product. The weight of the rubber mat prepared by the packaging to be sent to the customer is 5.8 kg. It was assumed that the mats were distributed to Istanbul following the obtained information from the company.

2.1.3. *Sensitivity analysis for the rubber car mats*

In total, four different sensitivity analyses have been conducted to test the impact of different assumptions on the environmental impacts of the rubber car mat life cycle. According to the data received from the company, sensitivity analysis considers the influence on the results of the following key assumptions: transportation distance (S1), synthetic rubber (S2), wind-based electricity (S3), and solar-based electricity (S4). The scenarios are described in detail below. In the Results section, the results are compared to the base case model (Fig. 8) and discussed.

a) Transportation distance (S1)

As indicated in Table 2, natural rubber is transported by sea and road transport to production facilities. According to the information obtained from the manufacturer, alternative routes for the supply of natural rubber have been evaluated. The environmental impact of the life cycle was assessed for the situation in which natural rubber was transported 400 km by road from the national supplier to the facility.

b) Synthetic rubber (S2)

Natural rubber is usually used in the production of rubber car mats in the production facility (Table 1), while in some cases the production of car mats is carried out by the use of synthetic rubber. The use of synthetic rubber was considered in the sensitivity analysis to analyze the impact of this factor on environmental impacts.

c) Electricity supply from wind (S3) and solar (S4) power

The Turkish electricity mix has been considered as an energy source of the selected facility (base case). According to the future investment plans of the company, renewable energy technologies were investigated in this paper. Therefore, two different energy scenarios were developed, with wind turbines and photovoltaic energy sources being used as renewable sources instead of Turkey's electricity mix. In the wind power scenario (S3), the electricity is supplied by onshore wind turbines. The life cycle impacts of Turkey's electricity generation from onshore wind turbines are based on Atılgan and Azapagic [34]. Production, transportation, installation, operation, and demolition of wind turbines are included in the model. In the photovoltaic solar power scenario (S4), the photovoltaic system is based on the global market. The background data is obtained from the LCA software's database [32] for the flat-roof installation. The system's production and service are included in the model.

2.1.4. *System description, assumptions, and data for carpet car mats*

A life-cycle model has been developed for the carpet car mat, which is an alternative to a rubber mat, and the environmental sustainability of these two types of car mats has been compared. System boundaries defined for the production of the carpet car mat are illustrated in Fig. 3. As can be seen from the figure, system boundaries are accepted from cradle to gate to obtain and process raw materials, transportation, raw

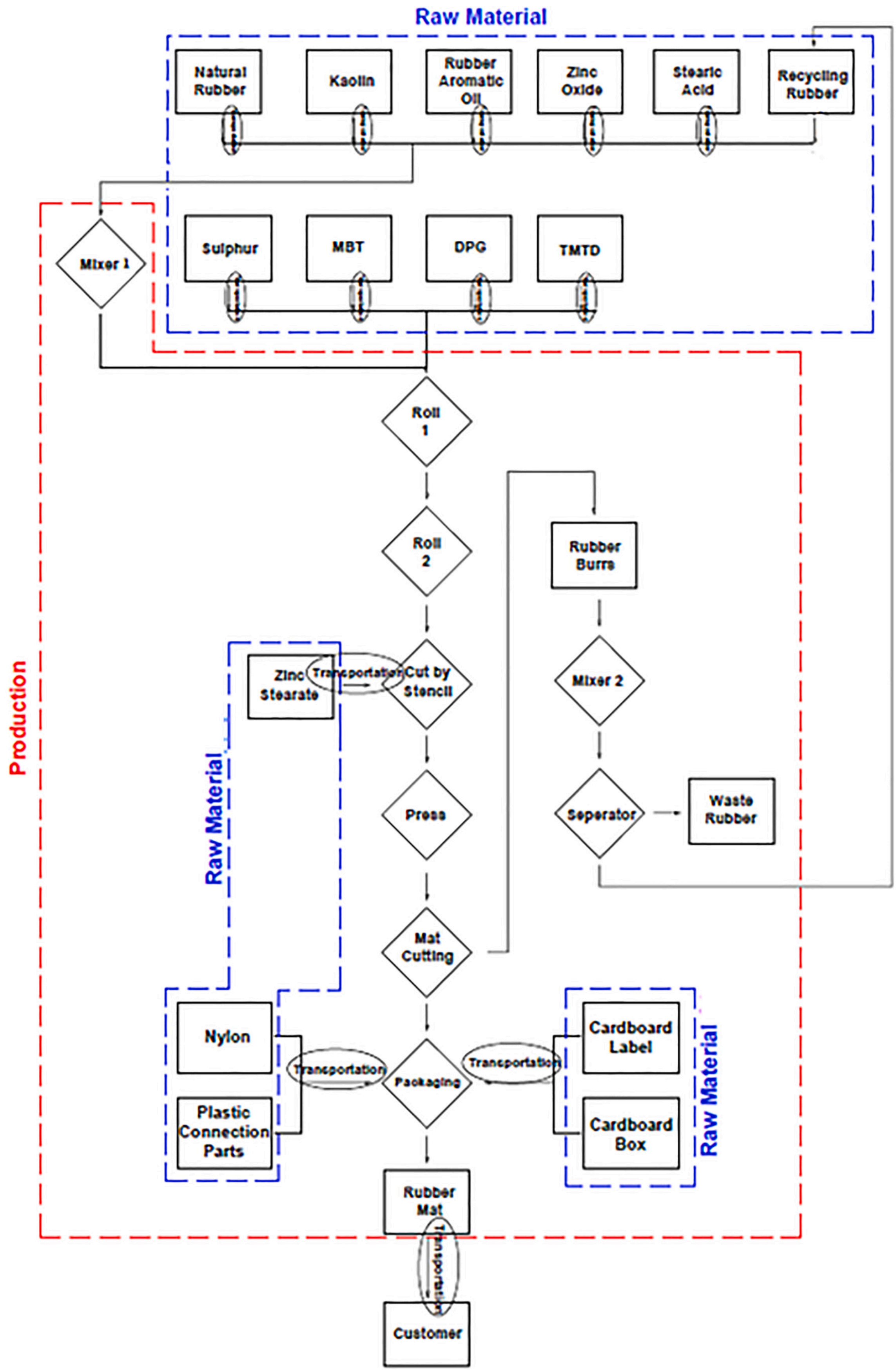


Fig. 2. System boundaries for the rubber car mat.

Table 1
Inventory data for rubber car mat.

Data	Rubber Car Mat		Data Source
Raw material	g/set mat		
Kaolin	4350		Manufacturer
Recycled rubber	1204		II
Natural rubber	1032		II
Rubber aromatic oil	344		II
Zinc oxide	43		II
Sulphur	24		II
Zinc stearate	9		II
Packaging	g/set mat		
Cardboard	120		Manufacturer
Label	40		II
Plastic connection parts	35		II
Nylon	25		II
Transportation			
Raw material	**Lorry (km)**	**Ship (km)**	
Kaolin	309	–	Manufacturer
Recycled rubber	–	–	II
Natural rubber	222	10,000	II
Rubber aromatic oil	39	–	II
Zinc oxide and zinc stearate	128	–	II
Sulphur	128	–	II
Packaging	**Lorry (km)**	**Ship (km)**	
Cardboard	30	–	Manufacturer
Label	30	–	II
Plastic connection parts	250	–	II
Nylon	250	–	II
Product	**Lorry (km)**	**Ship (km)**	
Rubber car mat	250	–	Manufacturer
Production	Electricity (kWh/set mat)		
Mixer 1	1.89		Manufacturer
Roll 1	0.77		II
Roll 2	0.42		II
Press	1.20		II
Mixer 2	0.37		II

Table 2
Inventory data for carpet car mat.

Data	Carpet Car Mat		Data Source
Carpet	Carpet usage class 21 and the luxury class 1		GaBi Database [32]
Raw material	**g/set mat**		
Carpet	2612		Manufacturer
Fabric and yarn	0,021		II
Packaging	**g/set mat**		
Cardboard	120		Manufacturer
Label	40		II
Plastic connection parts	35		II
Nylon	25		II
Transportation			
Raw material	**Lorry (km)**	**Ship (km)**	
Carpet	250	–	Manufacturer
Fabric and yarn	750	–	II
Packaging	**Lorry (km)**	**Ship (km)**	
Cardboard	30	–	Manufacturer
Label	30	–	II
Plastic connection parts	250	–	II
Nylon	250	–	II
Product	**Lorry (km)**	**Ship (km)**	
Carpet car mat	250	–	Manufacturer
Production	**Electricity (kWh/set mat)**		
Laser Cutting Machine	0.040		Manufacturer
Laser Cutting Tube	0.003		II
Sewing Machine	0.022		II

materials preparation, laser cutting, binding, and packaging, and distribution of the products. Construction and decommissioning of the production facility, use, and disposal steps after use could not be included within the system limits due to a lack of data. Carpet production does not take place in the facility, so data for this process cannot be provided. Because of this, the background data for the carpet is obtained from the GaBi database [32].

Table 2 lists the raw materials and quantities needed for the life cycle assessment of the manufacturing of a set of carpet mats for motor vehicles. The carpet mat is trimmed so that it can be cut with a laser cutting machine. Bias tape is sewn on the edges of the cut carpet mats before being packed. The total amount of raw material used in the production and packaging of carpet mats is around 2.9 kg per functional unit. The weight of the carpet mat prepared by the packaging to be sent to the customer is 2.2 kg. It is assumed that the manufactured mats were distributed to Istanbul in compliance with the information obtained from the company.

3. Results and discussion

In this study, an environmental sustainability assessment of rubber and carpet mats for motor vehicles has been carried out. The life cycle environmental impacts have been quantified using the CML 2001 impact assessment method [35] using the April 2016 update. All 11 impacts included in this method have been considered: abiotic depletion potential of elements (ADP), abiotic depletion potential of fossil fuel resources (ADP fossil), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity potential (FAETP), global warming potential (GWP), human toxicity potential (HTP), marine aquatic ecotoxicity potential (MAETP), ozone depletion potential (ODP), photochemical oxidants creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

The results for each impact of rubber mats are discussed in the following sections, presents, first for the functional unit related to the manufacturing of a set of rubber car mats (Section 3.1) and then for the annual production of rubber mats in the facility (Section 3.2). This is followed by sensitivity analyses for rubber mats. Finally, the life cycle environmental impacts of the rubber and carpet mats are compared in Section 3.4.

3.1. *Environmental impacts of rubber car mat*

This section presents the life cycle environmental impacts of rubber mats. Fig. 4 shows the environmental impacts of a set of rubber car mats. A detailed description of the contributions within each impact category is given in the following sections. Fig. 5 presents the environmental impact results revealed at the stages of raw materials, transportation, and production, while Fig. 6 demonstrates the distribution of environmental impact from the different stages involved during the production of rubber mat including Mixer 1–2, Roll 1–2, Pressing, and Packaging.

3.1.1. *Global warming potential (GWP)*

As presented in Fig. 4, the GWP for a set of rubber car mats is estimated at 5.9 kg CO_2-eq., with the hotspots being the manufacturing of the rubber mat with an almost 55% contribution. The impact from the manufacturing of the mat is dominated by Mixer 1 followed by the pressing step, contributing nearly 38% and 24% of the total impact from this stage, respectively (Fig. 6). The reason for a high value is that the high energy consumption due to the long mixing time and the hot-pressing process. The step of raw materials, where raw materials are

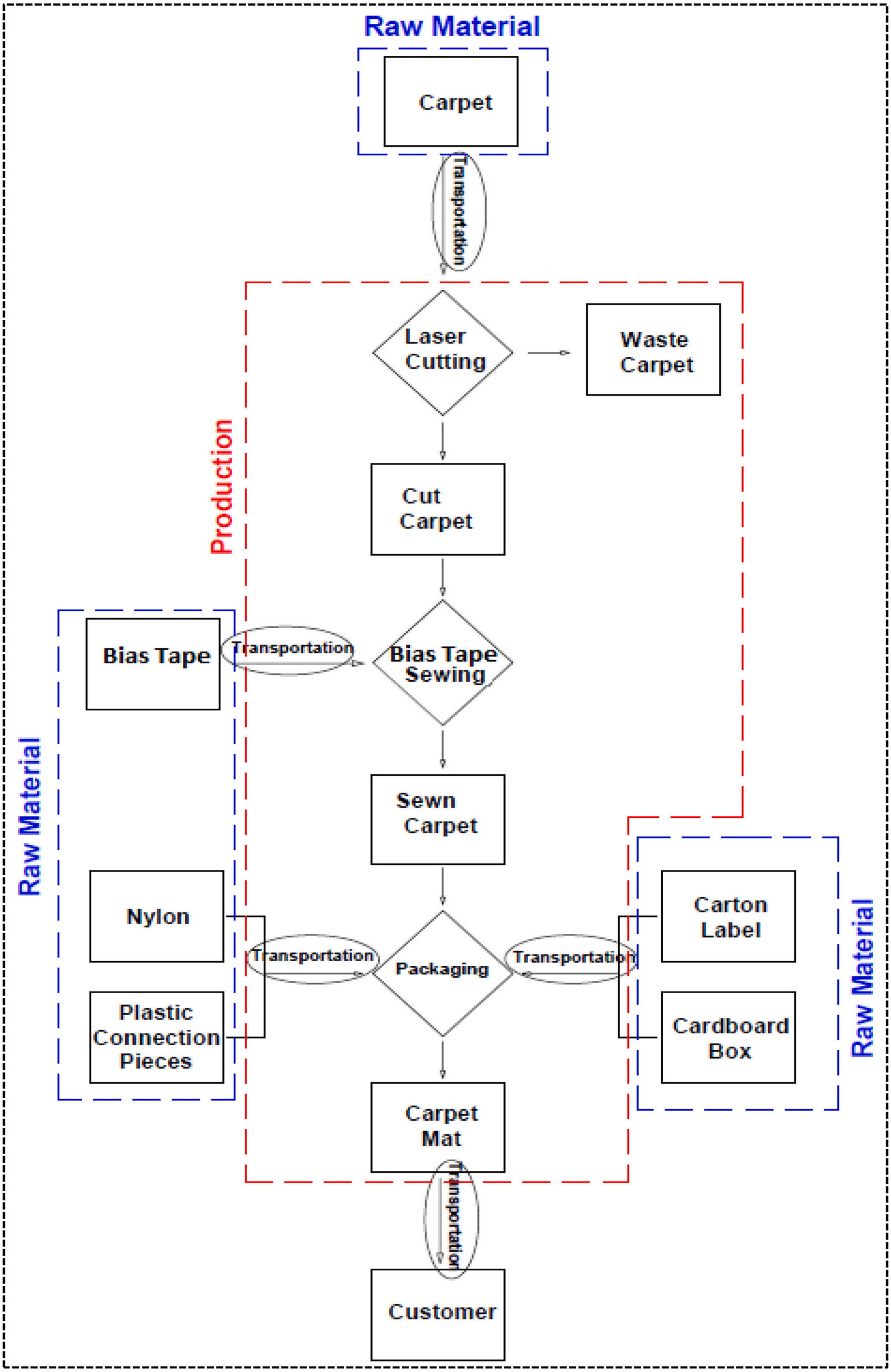


Fig. 3. System boundaries for the carpet car mat.

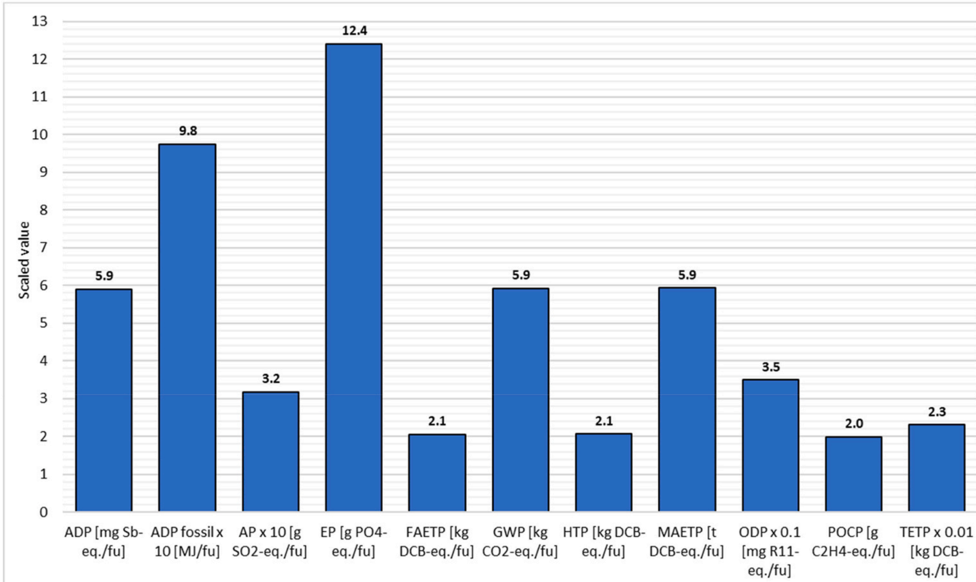


Fig. 4. Life cycle environmental impacts of a set rubber car mat. [fu: functional unit. The values for some life cycle environmental impacts have been scaled to fit.]

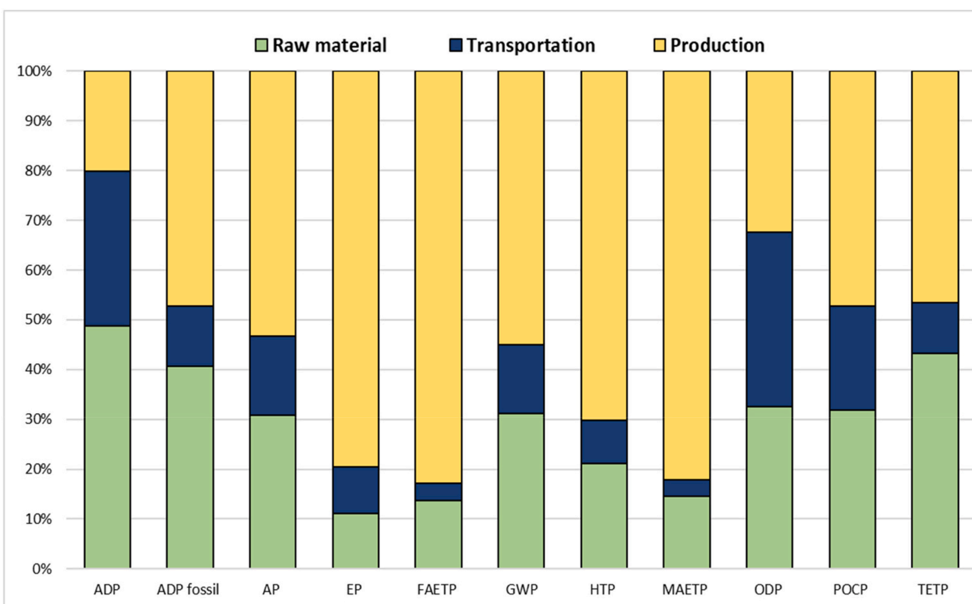


Fig. 5. Environmental impacts of the rubber car mat, showing contributions of different life cycle stages.

extracted and ready for production, is another life cycle step that has a high potential for this impact (31%). The majority of the effects from this step are due to a large amount of kaolin and rubber material in the product. The CO_2 emissions account for about 92% of the total GWP while CH_4 contributes a further 5%.

3.1.2. Other environmental impacts

For a set of rubber mats, the ADP is at 5.9 mg Sb-eq. with the raw materials (49%) being a major contributor to this impact, see Fig. 5. This impact is caused by the use of gold (29%), lead (18%), copper (16%), and rock salt (15%) in the process of obtaining and processing raw materials.

The results in Fig. 4 show that the ADP fossil for the rubber mat is estimated at nearly 98 MJ/fu, most of which comes from the energy use in the production processes. Oil, natural gas, lignite, and coal consumption account for 38%, 31%, 17%, and 14% of ADP fossil, respectively. This effect is caused by Turkish electricity generation from fossil fuels [36].

The AP for the rubber car mat is 32 g SO_2-eq./fu mainly due to the emissions of sulphur dioxide and nitrogen oxides to air. The results are shown in Fig. 5 present that the production stage causes the majority (53%), largely due to the mixers (in total 45%) and press (25%) due to the high energy consumption. Raw materials contribute 31% to the total AP.

As presented in Fig. 4, the EP for a set of rubber mats is 124 g PO_4-eq. with most of the impact related to energy use in the mat production stage (nearly 80%). The emissions of phosphate (71%) and nitrogen oxides (15%) are the main burdens contributing to this impact.

The total FAETP from the rubber mat is estimated at 2.1 kg dichlorobenzene (DCB)-eq./fu. As shown in Fig. 5, this impact is caused by

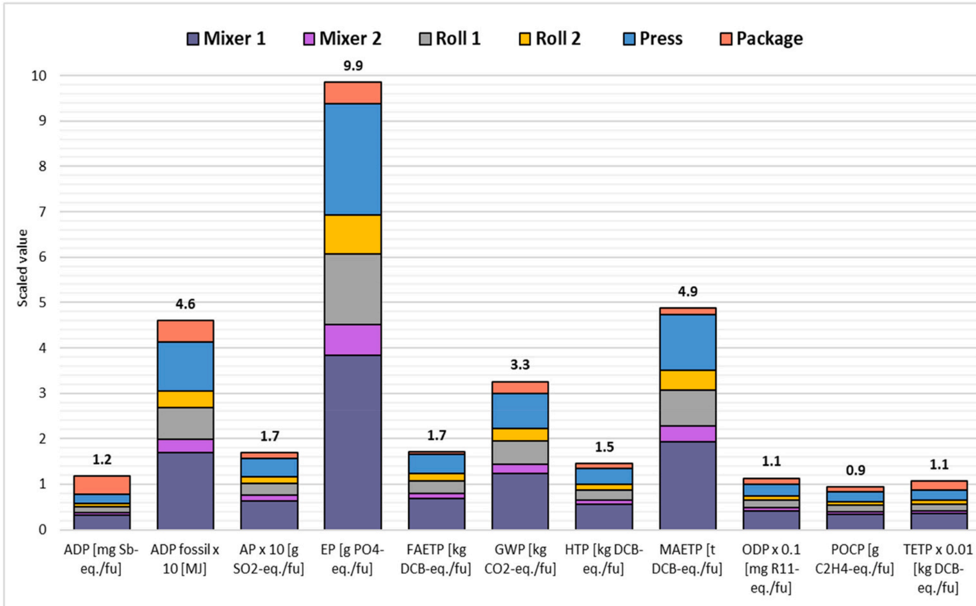


Fig. 6. Environmental impacts of the rubber car mat, showing contributions of different production steps. [fu: functional unit. The values for some life cycle environmental impacts have been scaled to fit.]

manufacturing (83%). Nickel (%34), beryllium (%20), vanadium (%14), cobalt (%10) and copper (%8) emissions to freshwater are the major burdens. The raw material supply stage accounts for 14% of the total FAETP.

The presented in Fig. 4, the rubber car mat has a total impact of 2.1 kg DCB-eq./fu, dominated by the production of the mats (more than 70%). This is mainly due to the energy used for the mixers and the press in the facility, Fig. 6. This impact is comprised of hydrogen fluoride and heavy metal emissions into the atmosphere, as well as selenium, thallium, and vanadium emissions into the water.

The results show that a set of rubber car mats has a MAETP of 4.9 t DCB-eq. The main hotspot is production (82%) and followed by raw materials (15%). Within this, the biggest contributing burdens are from Mixer 1, Roll 1, and press. This impact is mostly due to the emissions of beryllium (40%), hydrogen fluoride (31%), and nickel (8%) emissions.

The total ODP is 0.35 mg R11-eq./set rubber mat, with the transportation of the raw materials, packaging materials, and distribution of the products accounting for 35% of the total. This impact is primarily due to halon 1301 (70%) and halon 1211 (24%) emissions into the atmosphere. The long-distance transportation of imported natural rubber is the key cause of these emissions. Raw materials and mat production account for 33% and 32% of total ODP, respectively.

Total POCP is equal to 2.0 g ethane-eq./fu. As shown in Fig. 5, the largest contributor is the production stage (47%) mainly due to the emissions of sulphur dioxide, nitrogen oxide, carbon monoxide, and methane. Raw material supply is the second-largest contributor, adding 32% of the total of this impact.

Rubber car mat life cycle has a TETP of 23.1 g DCB-eq. per set of mats. The production stage contributes 47% to the total POCP (see Fig. 5); this is due to the emissions to air primarily due to the emissions of chromium (35%), mercury (22%), and vanadium (12%). The raw material supply stage contributes 43% to the total TETP.

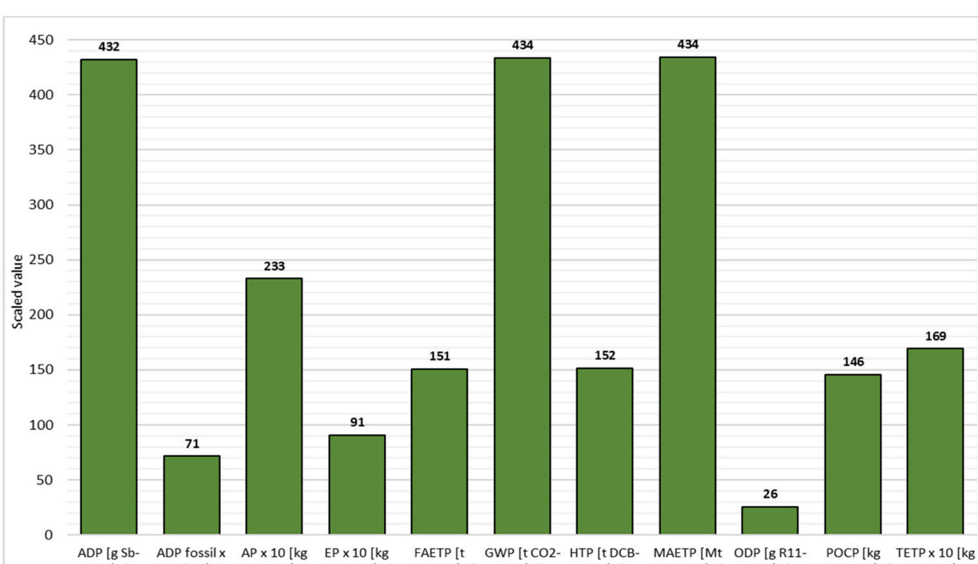


Fig. 7. Total annual environmental impacts of the rubber car mat. [yr: year. The values for some life cycle environmental impacts have been scaled to fit.]

3.2. Total annual environmental impacts for rubber car mat

The annual environmental impacts from rubber car mats have been estimated based on the impacts per set of rubber car mat presented in Fig. 4 and discussed in Section 3.1 and the total annual rubber mat manufactured in 2020 by the selected facility. The total annual environmental impacts from the total number of rubber mats manufactured by the selected facility are given in Fig. 7.

According to the information provided by the company, a total of 0.7 TJ of energy is consumed in this facility for the production of 73,250 mats. The total GWP of the annually manufactured rubber car mats is 434 tons of CO_2-eq. A round-trip economy flight from Istanbul to Berlin emits 0.29 tons of CO_2-eq. GHG emissions per passenger [37]. The total annual GWP is approximately the same as 1500 round-trip flights from Istanbul to Berlin.

3.3. Sensitivity analysis for rubber car mat

The sensitivity analysis investigates the effect of alternative rubber type (S1) and energy sources (S3 for wind and S4 for solar power) used in the production of the rubber mat and on transportation distance for the rubber supply (S2). The results of the sensitivity analysis are summarised in Fig. 8 and discussed below for each considered parameter in turn.

The car mat made of natural rubber, or tree-derived rubber, was found to be more environmentally friendly than the mat made of synthetic rubber, or oil-based, as shown in Fig. 8. The change has the greatest impact on the ADP (70%), followed by the ODP (65%). The other environmental impacts also increase, if synthetic rubber is used, but less significantly (43%–17%).

As presented in Fig. 5, the contribution of transportation of the raw materials and packaging materials and distribution of products ranges from 3% to 35% across the impact categories. The situation of supplying rubber from our country to the facility was assessed, and an LCA model for natural rubber transportation over a 400-km road was developed. Only the ADP increased (nearly 2%) in this case, while the other ten environmental impact categories decreased (0.5% for FAETP - 7% for AP). The decrease in the distance is the primary reason for this. According to the findings of this stage of the research, if transportation by sea is preferred over transportation by road, environmental impacts will be reduced.

The results indicate that replacing the grid mix with the onshore wind (S3) or solar power (S4) can reduce environmental impacts (29%–80% for S3 and 10%–70% for S4) over the life cycle, except the ADP for both wind turbine and photovoltaic. As presented in Fig. 5, the use of natural resources during photovoltaic and wind turbines has a significant negative impact on the ADP due to the use of metals and other non-renewable materials such as gold, silver, and copper.

3.4. Comparison of environmental impacts of rubber car mat and carpet car mat

The life cycle environmental impacts of rubber and carpet car mats are compared in Fig. 9. When carpet mats were used in the vehicle instead of rubber mats, the environmental effect increased. Although the carpet mat is lighter than the rubber mat, the carpet mat's environmental effects are greater due to the energy and raw material density used in the manufacturing process. While the process of making a carpet mat is simpler than that of manufacturing a rubber mat, the process of processing raw materials for carpet mats is more complicated. This demonstrates that using carpet mats rather than rubber mats increases (26%–92%) the measured environmental impact groups.

4. Conclusion

Companies are considering the concept of sustainability and its applications in the automotive sector due to the increased demand. This sector is characterized by high consumption of raw materials and energy, primarily from fossil sources. It is, therefore, important to direct the development of this sector towards environmentally sustainable approaches, addressing the challenges of raw materials and energy use, climate change, and other environmental impacts. For this reason, appropriate choices are required for the entire life cycle of each motor vehicle's part, and LCA is properly accepted as a valid tool for this purpose. Therefore, this study assesses the life cycle environmental impacts of car mats.

The GWP for a set of rubber car mats is calculated to be 5.9 kg CO_2-eq., with the manufacturing of the rubber mat accounting for nearly 55% of the total. The high energy consumption caused by the long mixing time and hot-pressing phase is the explanation for the high value.

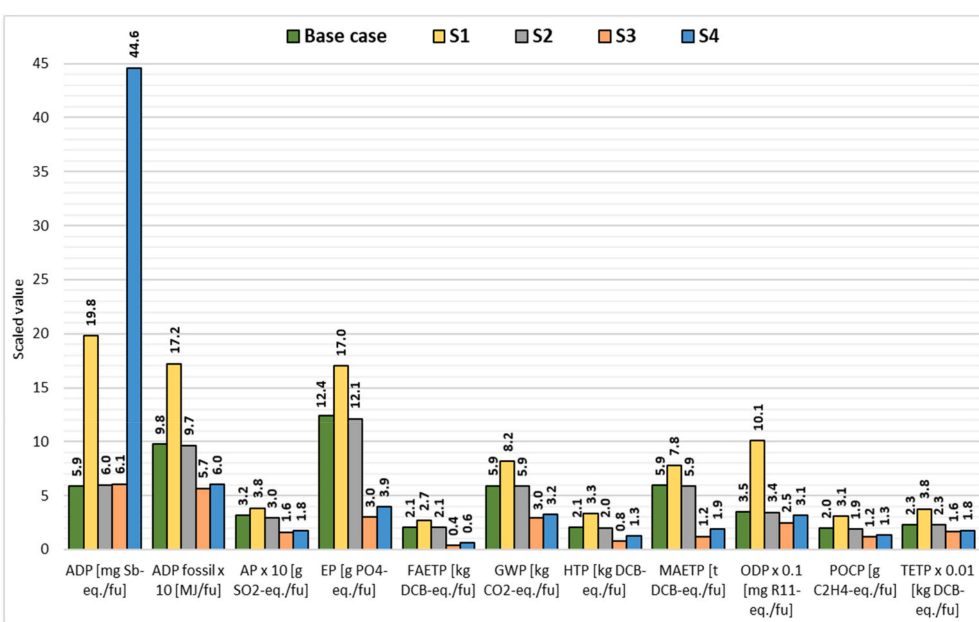


Fig. 8. Results for the sensitivity analysis. [fu: functional unit. The values for some life cycle environmental impacts have been scaled to fit.]

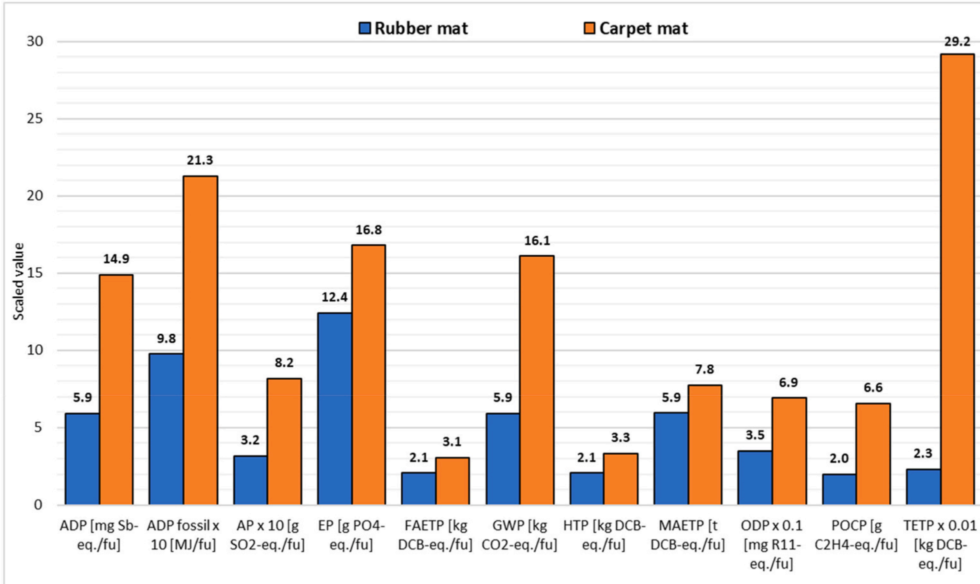


Fig. 9. Comparison of the environmental impacts of rubber and carpet car mats. [fu: functional unit. The values for some life cycle environmental impacts have been scaled to fit.]

CO_2 emissions account for approximately 92% of the total of this impact. GWP of rubber car mats is very sensitive to using synthetic rubber, increasing the impact by 38% and using renewable-based electricity, decreasing up to 50%.

When the environmental impacts of the rubber car mat are examined throughout its life cycle, it is found that the majority of environmental impacts (47% for ADP fossil and %83 for FAETP), except the depletion of abiotic resources and the ozone layer, are primarily caused by the production process. The main reason for this is the high energy consumption in production steps such as mixing and pressing due to the long mixing time and the hot-pressing process. Another life cycle step that has an impact on the environment is the raw material supply (11% for EP and 49% for ADP). Because of the large amount of kaolin and rubber in the product, the majority of the effects come from this step. The transport step has the greatest impact on ozone depletion potential (49%). The main reason for this is halon emissions caused by the transportation of rubber imported from other countries. Annually, the manufacturing of 73,250 rubber car mats emits 434 t CO_2-eq. on a life cycle basis.

Results are sensitive to assumptions on location, electricity mix, and types of rubber. The car mat made of natural rubber was found to be more environmentally friendly than the mat made of synthetic rubber as shown in Fig. 8. The change has the greatest impact on the ADP (70%), followed by the ODP (65%). The other environmental impacts also increase, if synthetic rubber is used, but less significantly (43%–17%). Only the ADP increased (nearly 2%), while the other ten environmental impact categories decreased (0.5% for FAETP-7% for AP) when rubber was supplied from Turkey. If synthetic rubber is used instead of natural rubber, the environmental impact increases (17%–70%). Except for the ADP for both wind turbine and photovoltaic, replacing the grid mix with onshore wind or solar power can reduce environmental impacts (29%–80% for S3 and 10%–70% for S4).

As far as the authors are aware, there are no other sustainability studies of vehicle car mats. The results of this work will be of interest to policymakers, car producers, and customers, helping them to make more informed decisions towards sustainability of the motor vehicles. Future LCA studies on car mats should look into different materials and extend the system boundaries of the LCA study including use, and end-of-life stages. Furthermore, the environmental sustainability indicators considered for car mats should be integrated with economic and social sustainability indicators. Forthcoming LCA studies on car mats should address futuristic materials and production trends and their opportunities to lower the environmental impacts.

CRediT authorship contribution statement

Ertuğrul ÖRÜCÜ: Investigation, Resources, Software, Visualization, Writing – review & editing. **Burçin Atilgan TÜRKMEN:** Supervision, Conceptualization, Methodology, Software, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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