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ORIGINAL PAPER

Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey

Burçin Atılgan Türkmen[1] · Tuba Budak Duhbacı[2] · Şeyma Karahan Özbilen[2]

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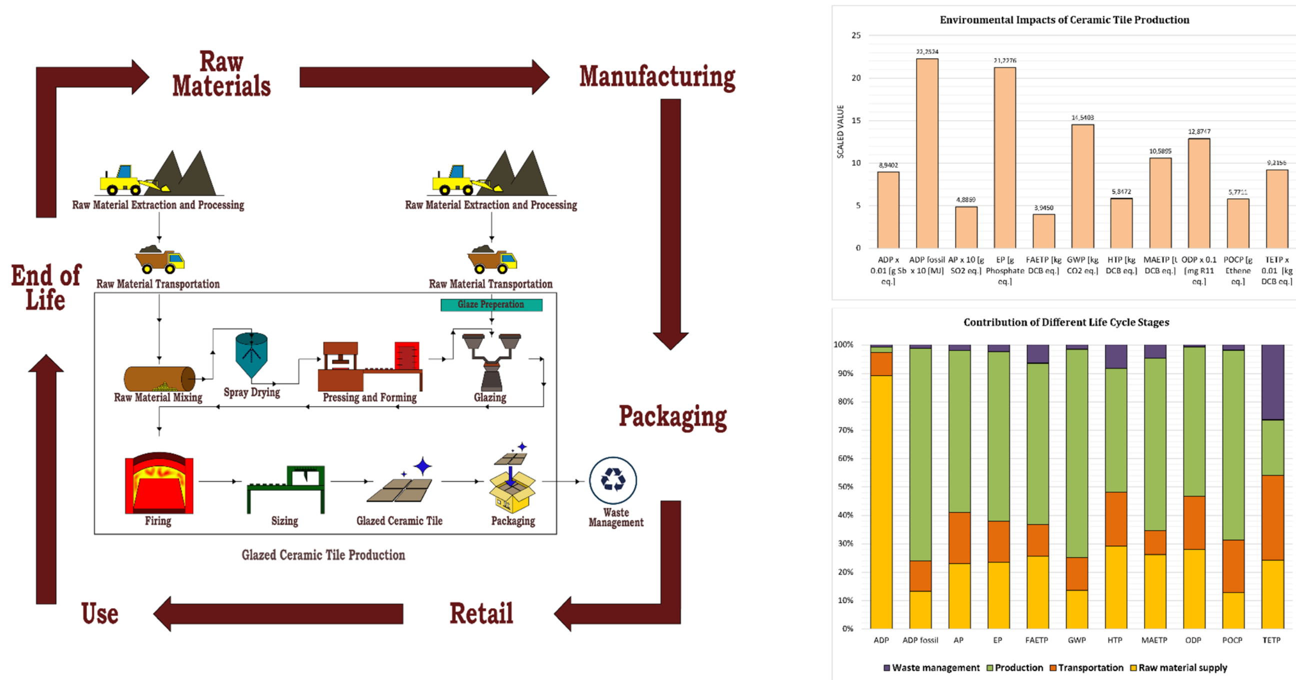
Abstract
The purpose of this study is to analyse the manufacturing of glazed ceramic tiles, from the extraction of raw materials to the packaged product including waste management with the aims of assessing the life cycle environmental impacts and identifying the hotspots. Real and detailed data from a main ceramic tile supplier in Turkey are used in the analysis of the environmental impacts of glazed ceramic tile. Two functional units are considered: 1 m^2 ceramic tile and total annual production of the facility. The environmental impacts have been estimated by conducting Life cycle assessment using GaBi v9.5 software and Ecoinvent database v3.5 with CML 2001 impact assessment method. Sensitivity analysis was carried out to test the robustness of the environmental impacts. The results show that among all environmental impact categories except abiotic depletion potential elements and terrestrial ecotoxicity potential, ceramic tiles production is generating the highest impact on the environment (45.9% for human toxicity potential—73.9% for global warming potential) mainly due to high energy consumption for firing, pressing and forming and drying steps. For abiotic depletion potential elements, raw material supply stage (82.5%) is the biggest contributor while for terrestrial ecotoxicity potential, most of the impact is from raw material transportation stage (31.4%). Annually, 106,195 tonnes or around 5.1 million m^2 of glazed ceramic tiles production from the selected facility emits 74 kt CO_2 eq. on a life cycle basis. As far as the authors are aware, this is the first attempt at such an academic study for the ceramic sector in Turkey. The results of this work demonstrate the importance of the life cycle assessment to improve the sustainability of the ceramic sector.

✉ Burçin Atılgan Türkmen
burcin.atilganturkmen@bilecik.edu.tr

[1] Department of Chemical Engineering, Bilecik Şeyh Edebali University, 11230 Gülümbe, Bilecik, Turkey

[2] The Scientific and Technological Research Council of Turkey, Marmara Research Center, Environment and Cleaner Production Institute, 41470 Kocaeli, Turkey

Graphic Abstract



Keywords Ceramic · Life cycle assessment · Environmental impact · Turkey · Sustainability

Introduction

Resource scarcity and climate change are major global challenges. Global scarcity of resources has become a key policy issue, with forecasts of rising populations, depletion of natural resources, and hunger. Resource scarcity has led people to alternative production methods and the best available technologies. Recently, concepts such as "reduction at source," recycling, recovery, waste reduction, cleaner manufacturing technologies, and industrial ecology have emerged and the need to make the best use of the existing potential has been put on the agenda (Koyuncu et al. 2015). Since industrial production is inevitable, new technologies and methods should be applied to reduce the harmful effects on the environment (Koyuncu et al. 2015).

The scientific world has started to clearly emphasize the serious increase in the level of greenhouse gas (GHG) in the atmosphere and, consequently, the atmospheric temperature in the 1980s. The main source of this increase in GHG emissions from human activities such as industry, energy production and consumption, shelter, and transport (IPCC 2018). Industrial sectors, where significant resources such as energy, raw materials, and water are consumed, have negative environmental impacts. These effects have emerged as global problems such as the depletion of the ozone layer, the greenhouse effect due to the increased atmospheric carbon dioxide (CO_2), and desertification (Koyuncu et al. 2015).

As shown in Fig. 1, the European Union (EU) targets to achieve a 20% reduction by 2020 in total GHG emissions, compared with 1990 levels. In 2017, the EU's GHG emissions were around 4.5 megatonnes (Mt) of carbon dioxide equivalent (CO_2 eq). It was 21.7% lower than 1990 levels. Besides, the EU was 23.2% below 1990 levels in 2018. So remained on track to meet its upcoming target of a 20% reduction in GHG emissions by 2020. It is estimated around a 32% reduction of GHG emissions by 2030, compared with 1990 levels. This reduction is below the 40% target for 2030 (EEA 2020). As of 2017, 19.7% of EU GHG emissions comes from the industrial sector (see Fig. 1). %35 reductions from this sector has been achieved compared with 1990 levels (EEA 2020). In terms of energy and emission formation, the ceramic sector is one of the most important ones among the other sectors of the manufacturing industry (EEA 2020).

The developments in the world economy and construction sector have been directly determining in the ceramic tiles production sector. Considering world ceramic production, in 2018 it was 13.1 billion m^2 with a decrease of 3.6% compared to 2017 and ceramic tile consumption was 12.8 billion m^2. As of 2018, 68.6% of the world ceramic tiles production and 66.4% of the world ceramic

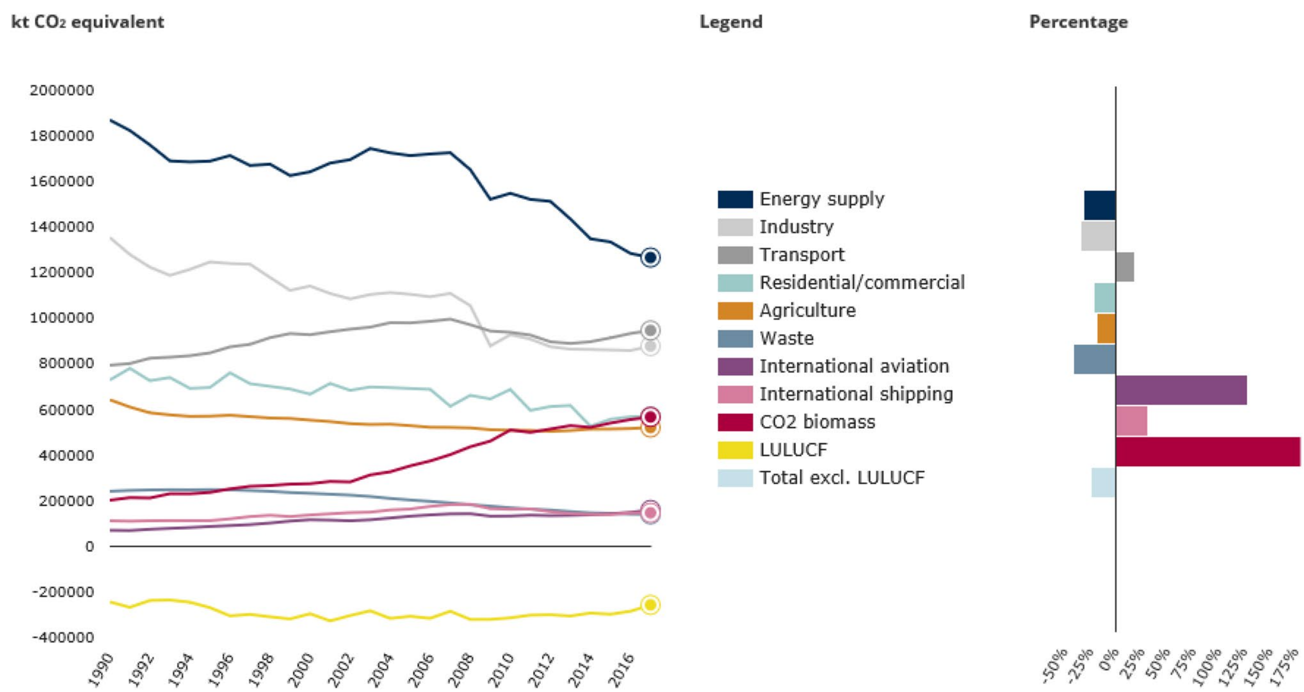


Fig. 1 Greenhouse gas emissions by aggregated sector (EEA 2020)

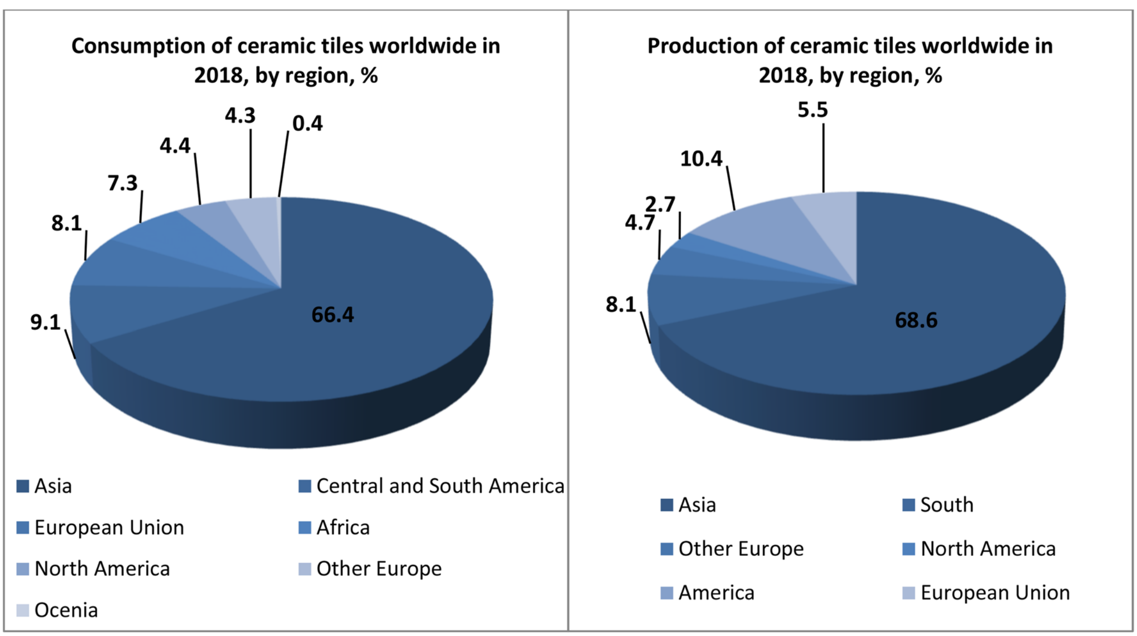


Fig. 2 World ceramic tile consumption and production rates by region (CERSAI 2019)

tile consumption were in the Asian region (Fig. 2). Large capacity and production volume of the Asian region have been formed in production. The share of EU-28 (Turkey included) countries is 11%, while the shares of each of the other regions in production are below 10% (CERSAI 2019).

In 2018, the top 10 countries realized 80.7% of world production. The largest producer is China with 43.4% of world production. The 2nd largest producer is India, followed by Brazil, Spain, and Vietnam. Vietnam has had a significant production capacity in the past 10 years and has become the world's 5th largest producer. Other manufacturers located in the first 10 rows with the production size of Italy, Indonesia, Iran, Turkey, and Egypt. Turkey ranks 9th with a 2.6% share (CERSAI 2019).

According to the 2018 world consumption of ceramic tile manufacturing sector data, the largest consumer is China, and China alone made 37.8% of world consumption. The second largest consumer is India, and the 3rd largest consumer is Brazil. Turkey ranks 8th with a 1.0% share (CERSAI 2019).

The ceramic industry is one of the leading sectors of Turkey in terms of added value. In 2017, the Turkish "ceramic tiles and flags manufacture (23.31 Nace Rev.2)" industry consists of 108 enterprises from small to large size enterprises with an increase of 66% compared to 2009. The production value of "ceramic tile and flags" was 1.8 million US$ in 2016 and 1.6 million US$ in 2017. In addition, the production amount is 334 million m^2 in 2016 and 342 million m^2 in 2017 (MIT 2019).

By 2018, the Turkish manufacturing industry's energy consumption amounts to about 31 million tons of oil equivalent (toe) and 4% belongs to the ceramic industry (MENR 2018). Therefore, the reduction of GHG emissions from the ceramic sector is important for the country to reduce the total GHG emissions from industrial production.

In the reference document prepared for the ceramics industry, the best available techniques for reducing energy are mostly related to kilns and dryers. In particular, shortening the firing time, automatic control of temperature and humidity levels in kilns and dryers, reduction in heat losses in kilns with insulation, recovery of waste heat from furnaces, increase in the temperature distribution by using propellant fans in dryers and application of cogeneration/combined heat and power plants are recommended (EU 2007).

According to the projections made by the European Ceramics Federation based on the year 1990, it is predicted that the total emissions from the brick, tile, coating materials and refractory sectors will decrease by 65% in 2050 (CERAME UNIE 2013). The realization of this prediction is primarily through technologies such as cogeneration applications, process optimization, energy management, raw material modification, renewal of furnace designs, heat exchanger applications in the furnace chimney, recovery of lower furnace waste heat, synthesis gas. It was stated that to achieve this reduction, the sector should be financially supported on various issues such as developing technologies and the use of alternative fuels (CERAME UNIE 2013).

Life cycle assessment (LCA) is used to assess environmental impact during all its life cycle, including raw material extraction, production, transportation, use, and waste management stages. Generally, three areas of protection are considered: ecological and human health, and natural resources. LCA contributes to identifying the potential improvements of the product by examining all the life cycle stages and concerning manufacturing processes in terms of environmental performance. Consequently, resource usage can be reduced by applying the best available techniques in the specific field. Environmental impacts can, therefore, be minimized (EEA 1997; Kellenberger and Althaus 2009; Koyuncu et al. 2015).

Sangwan et al. (2018) conducted an LCA study to assess the environmental impact of the vitrified ceramic floor tile supply chain by using Umberto NXT software with ReCiPe midpoint and endpoint methods. In this case study, the environmental impact has been determined in nine midpoint categories and eight endpoint categories for each stage of the ceramic floor tile supply chain. Also, in this study, all supply chain activities such as raw material extraction, production of ceramic tile, distribution to different regions, implementation of tiles using concrete, and disposal of packaging and construction waste have been considered as a system boundary. The results show that the high environmental impacts such as climate change, human toxicity, fossil depletion, and metal depletion categories were influenced by the red oxide in glazing, electricity used for processes, packaging material production and disposal, concrete used during the installation of tiles, and transportation of tiles.

In addition to the environmental impact assessment of ceramic tiles production, the economic analysis was carried out in a case study by Ye et al. (2018). In this study, the authors suggested reducing the use of coal, electricity, and inorganic chemicals and optimize the transport of raw materials in order to minimize the environmental impacts and economic cost. As a result of the study, marine ecotoxicity, climate change, terrestrial ecotoxicity, human toxicity, and fossil depletion are the most affected environmental impact categories.

Almeida et al. (2016) made an environmental impact analysis of four ceramic tile factories in Portugal by using a cradle to grave LCA methodology. The scope of this study included the mining process, transport of the raw material to the manufacturer, the manufacturing process, transport of the ceramic tile to the construction site, use and final disposal. In order to reduce the environmental impact of ceramic tile manufacturing, the suggestions of the authors are as follows: the optimization of electricity, fuel consumption, and raw material transport distance.

Geng et al. (2017) compared the greenhouse gas emissions of wood flooring and ceramic tile overall life cycle stages including raw material acquisition, production, transportation, and final disposal. Also, they analysed the carbon reduction and the cost of avoided emissions for both products. In another study carried out by Souza et al. (2015), the environmental impacts of ceramic versus concrete roofing tiles were compared. In this study, the system boundaries for both products were determined from the raw material extraction, product manufacturing, and transportation to the product's end of life. Besides the authors identified potential improvements for ceramic tile by using the LCA approach. In addition to this study, sensitivity analysis and uncertainty assessment were performed to confirm the robustness of the LCA study. According to the result of the study, it has been noted that the impacts of ceramic tile were less than the concrete tile in terms of water withdrawal, resource depletion, and climate change.

In addition to the studies associated with the assessment of the environmental impacts of ceramic tile products throughout their life cycle, a comparison of manufacturing stages of small and medium-sized ceramic tile enterprises was made by Tikul (2014). This study shows that small-sized enterprise consumes twice as much energy than the medium enterprise to produce 1 m^2 ceramic tile. It has been expressed that small-sized enterprise has larger environmental impacts regarding eutrophication, acidification, and ozone depletion.

Besides, Mezquita et al. (2017) compared the wet and dry methods in the preparation of the raw materials for the forming stage of the ceramic tile production process. This study investigated an alternative technology for the ceramic tile body preparation system for reducing water consumption. By this way, the length of the raw materials drying stage will be reduced and energy saving will be obtained. This study shows that in the dry method, water, electrical energy, and thermal energy are diminished, respectively, by 74%, 36%, and 78%. Due to the reduction in energy consumption, CO_2 direct emissions are reduced by 78% as well.

This case study aims to assess the environmental impact of ceramic floor tile and identify hotspot activities and key substances for improvement. A case study has been performed at one of the major ceramic tile manufacturing plants in Turkey. The manufacturing plant considered in this paper has an annual production of 106,195 tonnes or around 5.1 million m^2 of ceramic tile.

The following section defines the goal and scope of this research, followed by detailed inventory data and assumptions. The results are discussed in "Result and discussion" section, together with sensitivity analysis. At last, the conclusions are drawn in Conclusion section.

Methodology

The life cycle environmental impacts of glazed ceramic tile have been evaluated in this paper. The research has been carried out following the ISO 14,040/14,044 (ISO 2006a, b) According to these standards, there are four main stages of LCA, namely goal and scope, inventory analysis, impact assessment and interpretation of the results.

Primary data on the ceramic tile life cycle stages were collected from a manufacturing plant located in Turkey. GaBi v9.5 (Sphera 2020) was used as the mean to conduct the LCA study. For the environmental impact assessment, the Centre of Environmental Science of Leiden University (CML) impact assessment method (CML 2017) was employed. The methodology, goal and scope of the study and data sources are detailed in the following parts.

Goal and scope definition

This study aims to quantify the life cycle environmental impacts of glazed ceramic tile and to determine hotspots across the supply chain, to identify opportunities for improvement. This study is based on Turkey. A further goal is to estimate the environmental impacts at the facility level, considering the annual production of ceramic tiles production in the selected factory for 2018.

In the scope of this study, making field visits and conducting interviews facilitated the determination of system boundaries and collecting data. Based on the goals of this study, two different functional units are considered:

1. Production of 1 m^2 of glazed ceramic tile, amounting to a total weight of 20.7 kg; and
2. Annual production of ceramic tile from the selected plant (106,195 tonnes or 5.1 million m^2 in 2018).

The scope of the study is from cradle to grave. As presented in Fig. 3, the system boundaries include the following life cycle stages: raw materials extraction and processing, transport, ceramic tiles production stages and waste management. The commonly used ceramic tiles production stages were considered in this study. Ceramic tiles production stages consist of mixing raw materials, spray drying, pressing and forming, glaze preparation, glazing, firing, sizing, and packaging steps. The manufacturing of the equipment used in the facility and construction and decommissioning of the buildings is not included in the system boundary due to lack of specific data. Factory construction, machinery and equipment and decommissioning of the facility were excluded due to a lack of detailed data. This is not considered a major limitation of the research as previous studies showed that their impact contribution is negligible (Metsims 2015a, b; EPD Turkey 2015; Institut Bauen und Umwelt e.V. 2016).

Life cycle inventory

This step consists of data collection, assumptions and mass and energy balance calculations. "Glazed ceramic tile" product has been selected for this LCA study. There are no by-products in the manufacturing of glazed ceramic tiles.

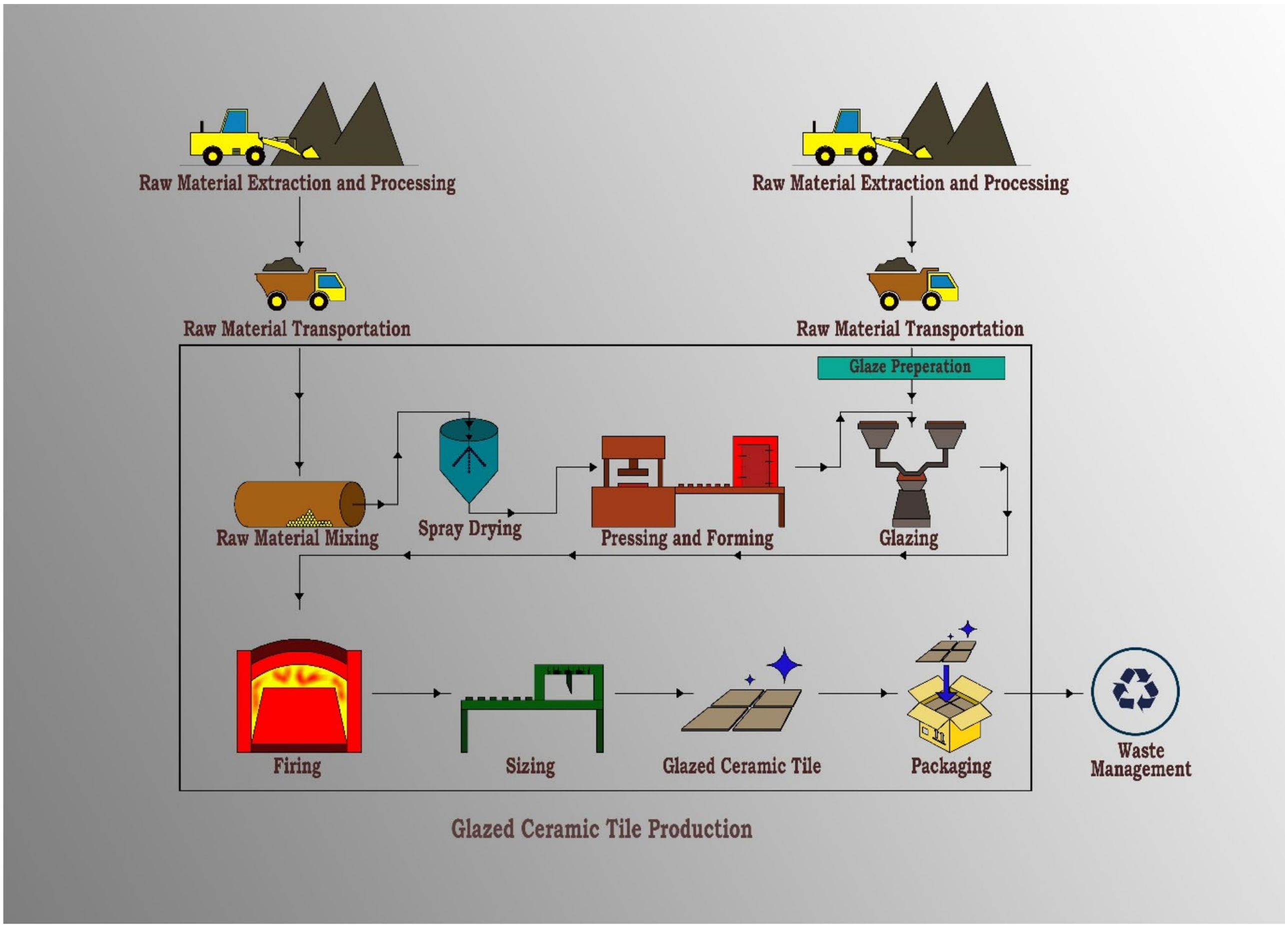


Fig. 3 System boundary and life cycle diagram for ceramic tile

Primary data and information related to the production of glazed ceramic tile were collected from the ceramic company and literature, processed, and evaluated. This study provides a comprehensive life cycle inventory for ceramic and construction sector in Turkey.

Primary data, including the type and amount of materials, energy consumption, water consumption, and transport data for materials as well as details of the production process, have been directly obtained from a main ceramic tile supplier in Turkey for the period year of 2017 and 2018. Data for 2017 have been used for the sensitivity analysis. The background life cycle inventory data (i.e. waste management, raw material extraction) has been sourced from Ecoinvent database v3.5 (Ecoinvent 2018).

Transportation

This stage covers all relevant raw material and packaging material transport to the factory and internal transportation within the plant via conveyor belt. Transportation in the factory is carried out by the conveyor belt system. It is about 1 km long.

Transport distances from raw material sites to manufacturing sites were obtained from the manufacturer. The facility is located at Eskişehir, Turkey. The data comprise the extraction site locations, transportation distances, and types of transport used. The details related to transportation are presented in Table 1. The raw materials are extracted and processed and then transported by road and by sea to the factory where they are stored and used.

Raw materials

Data related to raw materials were obtained directly from the manufacturer. Background data have been sourced from the Ecoinvent v3.5 database (Ecoinvent 2018).

The main raw materials used to produce the ceramic tile body considered in this study are mineral-based materials readily available in nature, such as clay, sand, and feldspar. Frit, aluminium oxide, calcite, zinc, zirconium oxide, boric acid, and dolomite are used as auxiliary products. The raw

Table 1 Data for transportation distances

Material	Distance (km)	
	Lorry	Ship
Clay	249	–
Kaolin	105	–
Feldspar	251	–
Additives	185	3340
Aluminium oxide	352	2415
Calcite	10	–
Bentonite	800	–
Dolomite	44	–
Zircon	170	2264
Zinc	200	–
Silica sand	256	–
Magnetite	50	
Sodium silicate	400	–
Sodium chloride	45	–
Boric acid	150	
Packaging: Carton boxes and the others	185*	–
Packaging: Plastics	240	–

*100 km for carton boxes and 85 km for the others

Table 2 Data for ceramic tile preparation raw materials for 1 kg glazed ceramic tile

Material	Amount (g)
Clay	386
Kaolin	145
Feldspar	556
Silica sand	0.2
Sodium silicate	12
Magnetite	8
Bentonite	5
Water	600
Raw waste	21

material supply stage includes raw material extraction and pre-processing processes.

The raw materials for ceramic tile body production are loaded into hoppers to obtain the composition given in Table 2. The quantities of colourants used in ceramic tile body are small, so they have not been taken into consideration for the life cycle modelling. Most scrap and waste, produced before the firing stage, is recycled back into the product. Data for raw materials and water consumption are collected directly from the company.

The main raw materials to produce glaze are frit, feldspar, clay, sand, kaolin, and zircon (see Table 3). The quantities of colourants used in glaze preparation are small, so they have not been considered in the life cycle modelling. The amount of water used for glaze is 0.017 kg/kg glaze.

Table 3 Data for glaze preparation raw materials for 1 kg glazed ceramic tile

Material	Amount (g)
Aluminium oxide	1.22
Limestone	0.03
Feldspar	5.33
Dolomite	1.16
Magnetite	0.01
Zircon	2.28
Zinc	0.01
Sodium silicate	0.63
Frit	27.72
Kaolin	4.41
Calcium silicate	0.54
Silica sand	3.08
Clay	4.29
Sodium chloride	0.01
Water	17.23

Table 4 Data for frit preparation raw materials for 1 kg glazed ceramic tile

Material	Amount (g)
Aluminium oxide	0.45
Limestone	2.28
Feldspar	2.23
Dolomite	0.65
Zircon	0.48
Zinc	1.12
Boric acid	0.58
Silica sand	5.79
Soda	0.34
Magnetite	0.09
Water	0.79

Frit is also produced in the facility. All the primary data related to the frit production are obtained from the company. The raw materials to produce frit are given in Table 4.

Manufacturing

The manufacturing process for ceramic tile consists of several stages. The first stage is to weigh and mix up the raw materials to get slurry. The slurry is important for the production of physically and chemically homogenous material in order to form better. Water is used for batch enhancement and fine grinding. The slurry is then fed into a spray dryer, and dried to be powdered. It is sent to pressing to be tiled where it is pressed and formed. The ceramic tiles which are formed are fed to the vertical dryer to remove moisture and then to the glazing unit. Glazing is performed on dried tile surfaces. Ceramic tiles discarded before firing are ground and re-produced in the factory. Glazed ceramic tile products are fired at suitable temperatures (1200–1210 °C) in ovens, resulting in a hard body. Then the tiles are cut and squared at the desired size. After sizing, the ceramic tiles are packaged which have passed the quality control stage. Cardboard box, plastics, and styrofoam are used in the production of glazed ceramic tiles as packaging material.

Electricity and natural gas are consumed during the production of glazed ceramic tiles. The type and amount of the used energy for each production stage are presented in Table 5. Primary data of the manufacturing of glazed ceramic tile have been directly obtained from the manufacturer. The background inventory data for the production stage have been obtained from the Ecoinvent database v3.5 (Ecoinvent 2018).

Waste management

This step includes wastewater treatment and solid waste disposal. All the activities related to the waste management stage have been modelled using Ecoinvent database v3.5 (Ecoinvent 2018). The amount of wastewater produced from glazed ceramic tile is 19.5 kg per kg glazed ceramic tile. Sizing is the processing stage at which over 90% of process water is used in ceramic manufacturing.

Most of the production waste is recycled in the process. In the production stage, a 2.5% loss of fired ceramic tile has been assumed. These are sent to one of the cement factories close to the production facility, and this step is not included in this study.

Impact assessment

The environmental indicators are estimated using LCA (ISO 2006a, b) and the CML 2001 impact assessment methodology (CML 2017). CML uses a midpoint approach for calculating 11 environmental impacts. The following impact categories are considered: abiotic resource depletion elements (ADP), abiotic resource depletion fossil (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 oxidation creation potential (POCP) and terrestrial ecotoxicity potential (TETP).

Table 5 Data for energy consumption during the production for 1 kg glazed ceramic tile

Production stage	Electricity (kJ/kg product)	Natural gas (kJ/kg product)
Raw material mixing	168	–
Glaze preparation	49	–
Frit preparation	0.9	24
Spray dryer	113	1200
Pressing and forming	163	450
Glazing	34	–
Firing	221	2360
Sizing	98	–
Packaging	116	–
Waste management	22	–

Results and discussion

The impact assessment aims at evaluating the significance of potential environmental impacts using the results of the inventory analysis. This part presents and analyses the environmental impacts of glazed ceramic tiles. The research is carried out in two steps. In the first step, the life cycle environmental impacts are estimated based on the functional unit defined as ‘1 m^2 glazed ceramic tiles production’. Secondly, the functional unit is the ‘annual production of the facility’ to the total annual impacts. The comparison of the findings with the literature is presented in the following section. A sensitivity analysis has been performed to explore the effect of changing some of the parameters.

The estimated results for each environmental impact category are described in the following sections, first for the functional unit related to the production of 1 m^2 glazed ceramic tiles and then the annual production of glazed ceramic tile from the selected factory in 2018. Further details on the results of each environmental impact category can be found in Appendix.

Environmental impacts per m^2 of glazed ceramic tiles production

This part discusses the results of all aspects of the glazed ceramic tile. The results per m^2 of glazed ceramic tiles production are presented in Fig. 4, and the details related to hotspots are given in Fig. 5 and Fig. 6. Among all environmental impact categories except ADP and TETP, ceramic tiles production represents the life cycle stage with the largest impact (Fig. 5) mainly due to high fossil fuel-based energy consumption for firing and spray drying stages (Fig. 6). For ADP, the raw material supply stage is the biggest contributor, while for TETP, most of the impact is from raw material transportation stage. The results of this study show that the environmental impact results for the case study are well within the range found in the literature, reports or database

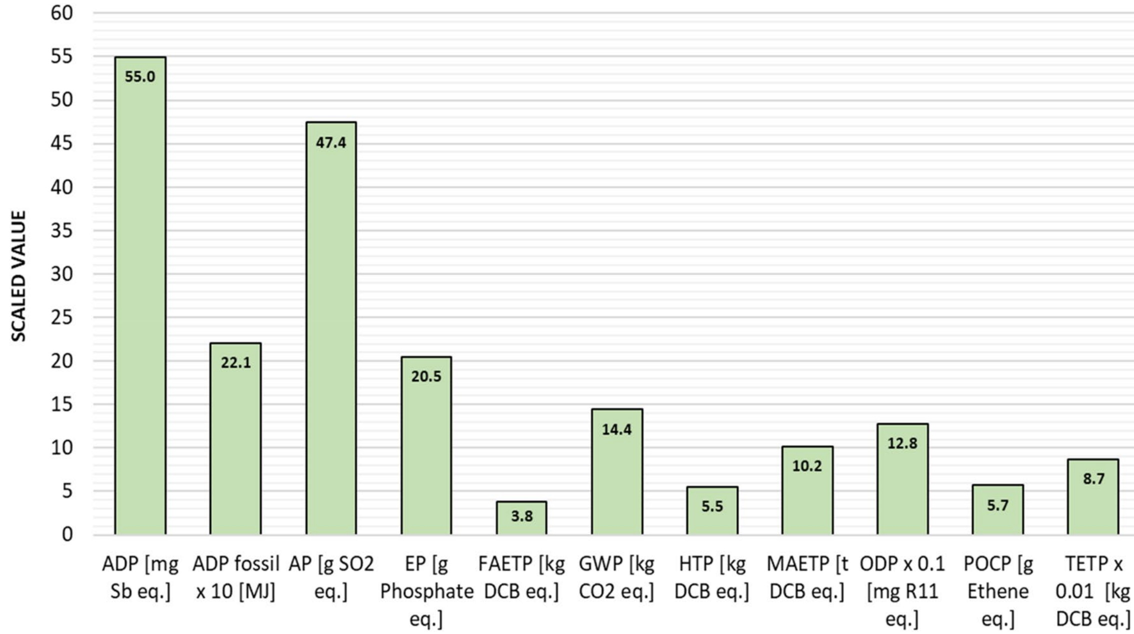


Fig. 4 The environmental impacts of producing 1 m^2 ceramic tile in Turkey [The values for some impacts have been scaled to fit.]

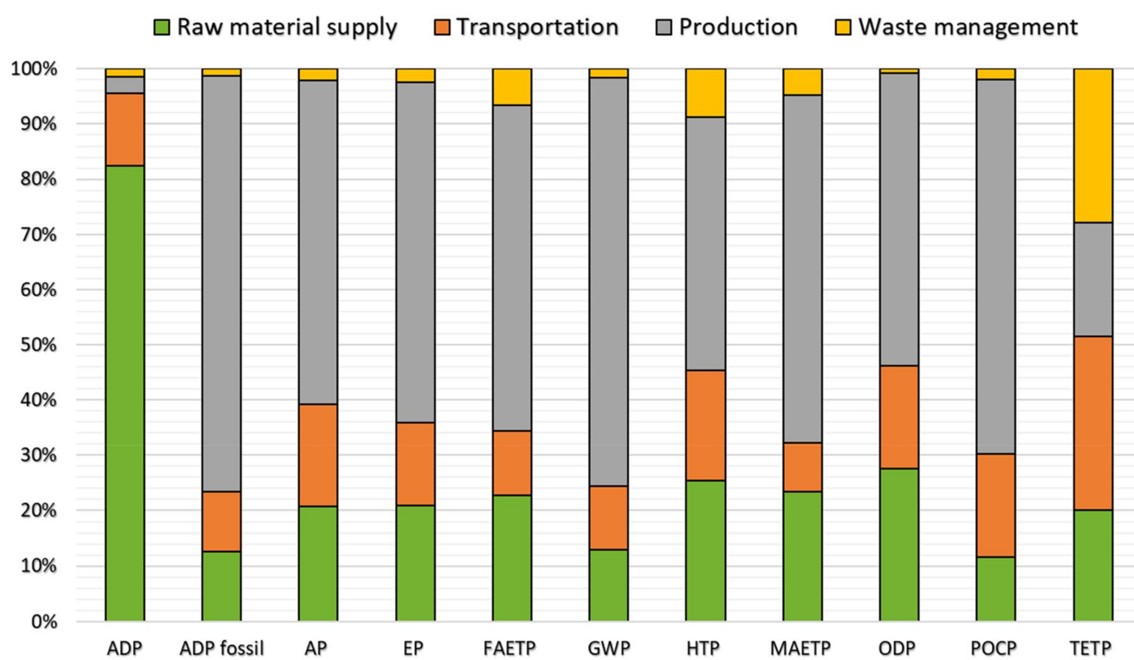


Fig. 5 Contribution of different life cycle stages to the environmental impacts for the ceramic tile

for ceramic tile. The results are discussed for each environmental impact below.

Abiotic depletion potential elements (ADP)

Total ADP of the glazed ceramic tiles production is about 55 mg Sb/m^2 (Fig. 4). The largest contribution within this impact category comes from the raw material supply stage which includes raw material extraction and processing. This stage accounts for 82.4% of the total ADP (see Fig. 5).

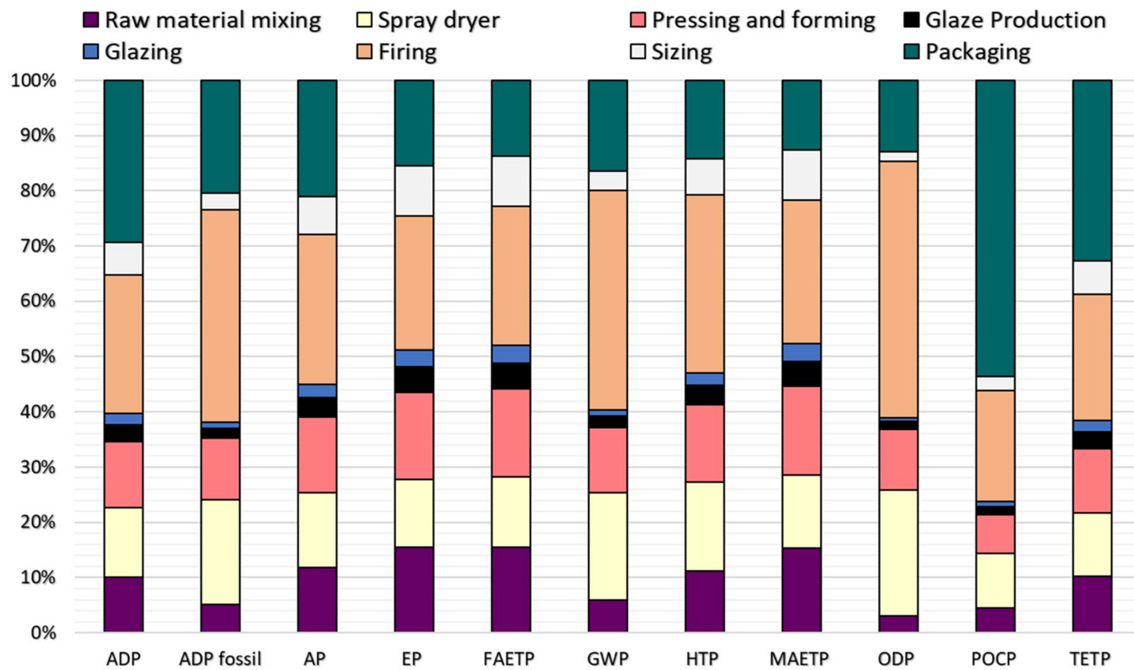


Fig. 6 Contribution of different manufacturing stages to the environmental impacts from production

Abiotic depletion potential (ADP fossil)

Total ADP fossil is estimated at 221 MJ per m^2 ceramic tile (Fig. 4). As seen from Fig. 5, the largest contribution within this impact category comes from the production stage (75.3%). Raw material supply contributes 12.6% to a total of 221 MJ/m^2. Burdens from raw material transportation are the third largest contributor to this impact, accounting for 10.9% of the total.

Acidification potential (AP)

As shown in Fig. 4, the total AP is equal to 47.4 g SO_2 eq./m^2. This is due to the emissions of sulphur dioxide (60.2%) and nitrogen oxides (27.2%) emissions to air. The main source of AP is the ceramic tiles production stage contributing 58.8% to the total AP, mainly due to the firing and spray drying; and pressing and forming stages (see Fig. 6). Raw material supply and raw material transportation stages contribute 20.8% and 18.4% to the total, respectively.

Eutrophication potential (EP)

Total EP fossil of the ceramic tiles production is estimated at 20.5 g phosphate eq./m^2 glazed ceramic tile. As seen from Fig. 5, this impact is mainly due to the production of the ceramic tile stage which contributes 61.7% to the total mostly from firing, mixing and pressing, and forming production steps. Burdens from raw material supply and transportation are the other largest contributors to this impact, accounting for 20.9% and 15.0%, respectively.

The emissions to the freshwater of phosphate (61.8%) and air of nitrogen oxides (10.5%) are the major burdens contributing to this impact.

Freshwater aquatic ecotoxicity potential (FAETP)

This impact is estimated at 3.8 kg dichlorobenzene (DCB) eq. per m^2 produced ceramic tile. As presented in Fig. 5, the largest contribution to FAETP comes from the ceramic tiles production (mostly from firing, mixing and; pressing and forming) and raw material supply stages accounting for 59.0% and 22.8% of the total, respectively.

The most significant burdens are emissions to freshwater, mainly nickel (32.9%), beryllium (19.2%), vanadium (15.3%), cobalt (10.1%), and copper (9.7%).

Global warming potential (GWP)

As shown in Fig. 4, the estimate for the GWP is 14.4 kg CO_2 eq./m^2 ceramic tile. The CO_2 emissions account for about 92.1% of the total of this impact; CH_4 contributes further 7.0%.

The main contribution to this impact category comes from the production stage (Fig. 5), which accounts for 73.4% of the total GWP mainly due to high energy consumption for firing and spray drying stages. Burdens from raw material extraction and processing are the second largest contributor to GWP, accounting for 12.9% of the total. Transportation of the raw materials is the next main contributor with 11.5%.

Human toxicity potential (HTP)

The total HTP from ceramic tiles production is estimated at 5.5 kg DCB eq./m^2 glazed ceramic tile. As shown in Fig. 6, this impact is caused by ceramic tiles production, raw material supply, and raw material transportation stages which contribute 45.9%, 25.4%, and 20.0%, respectively.

Emissions to air, mainly chromium (17.8%) and arsenic (10.1%) and freshwater, mainly selenium (19.5%) and barium (6.5%) are the major burdens.

Marine aquatic ecotoxicity potential (MAETP)

Figure 4 shows that the MAETP of the ceramic tiles production is 10.2 t DCB eq./m^2. Around 63.0% of this is from the ceramic tiles production stage (Fig. 5) mostly due to firing, pressing and forming and raw material mixture stages. Another 23.5% of the total MAETP is from raw material supply stage due to the emissions from raw material extraction and processing.

The emissions to the freshwater of beryllium (40.5%), nickel (8.3%), cobalt (4.6%), vanadium (5.2%), and selenium (4.6%) and air of hydrogen fluoride (28.4%) are the major burdens contributing to a total of 10.2 t DCB eq./m^2.

Ozone layer depletion potential (ODP)

Ceramic tiles production has an ODP of 1.3 mg CFC-11 eq./m^2 which is mainly caused by the production stage (52.9%), Fig. 5. Burdens from raw material supply and raw material transportation stages are the other major contributors to this impact, accounting for 27.5% and 18.8%, respectively.

The key contributors to this effect are emissions of non-methane volatile organic compounds (NMVOC) to air, such as halon 1301 (55.6%) and halon 1211 (24.3%) due to the natural gas consumption for the heat production.

Photochemical oxidant creation potential (POCP) A majority (67.8%) of the 5.7 g ethane eq./m^2 ceramic tile photochemical oxidant creation potential is from the ceramic tiles production stage due to the emissions of sulphur dioxide, nitrogen oxides, carbon monoxide and methane from the production stage. The packaging stage is one of the main contributors to POCP mainly from the life cycle of polystyrene foam (Fig. 6). Another 18.6% and 11.7% of the total are from the raw material transportation and raw material supply stages, respectively.

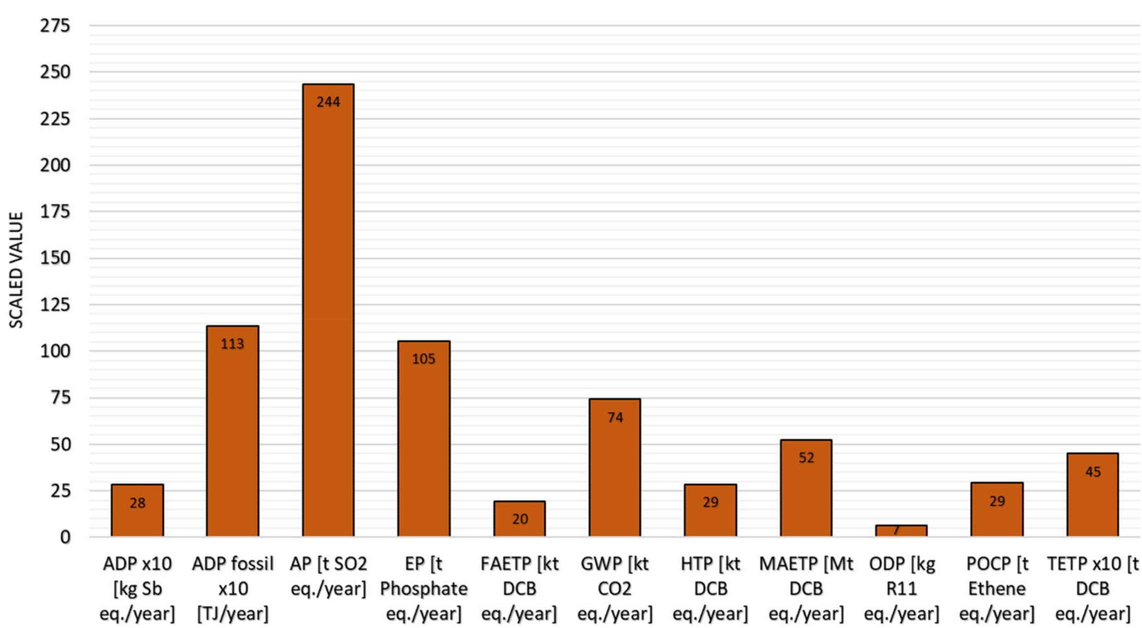


Fig. 7 The total environmental impacts of glazed ceramic tile annual production [The values for some impacts have been scaled to fit]

Terrestrial ecotoxicity potential (TETP) As shown in Fig. 4, total TETP amounts to 87.3 g DCB eq. per m^2 ceramic tile. This is mainly due to the emissions of chromium to air (46%) and soil (18.4%), and mercury to air (34.3%). Raw material transportation stage (31.4%) is the key contributor to this impact. The waste treatment stage accounts for 27.8% of the total. The production stage is the third largest source, accounting for 20.6% of the overall TETP.

Annual environmental impacts

The total annual environmental impacts from glazed ceramic tiles production in Turkey have been estimated using the impacts of 1 m^2 discussed in the previous section. The total glazed ceramic tile that year (106,195 tonnes or 5.1 million m^2). The total annual environmental impact results are displayed in Fig. 7. For example, the total life cycle GWP is estimated at 74 kt CO_2 eq./year. The total energy consumption of the facility is 1130 TJ per year to produce 106,195 tonnes of glazed ceramic tile.

Comparison of results with literature

The results estimated in this study are compared to similar studies in the LCA database (Ecoinvent 2018), literature (Ibáñez-Forés et al. 2011, 2013), and Environmental Product Declaration (EPD) documents e.g. (Metsims 2015a, b; EPD Turkey 2015; Institut Bauen und Umwelt e.V. 2016). Figure 8 presents the results for 8 out of 11 environmental impacts per kg produced ceramic tile. The results obtained from the reports and literature do not include the ecotoxicity impacts.

There is a large variation in the considered environmental impact categories in the literature, as the impacts depend on the different parameters such as raw materials, transportation distances, and energy mix.

The specific weight of the ceramic tiles of the literature is ranging from 14.0 to 24.3 kg per m^2. Thus, results have been calculated for 1 kg glazed ceramic production for comparison as the ceramic tiles has different specific weight (kg/m^2).

As can be seen from Fig. 8, for environmental impact categories, a wide range of values has been obtained from the literature, reports, or database. This is primarily due to the different types of ceramic tile (wall or floor type), production techniques such as dry or wet milling, geographical and transport variations, profiles of grid electricity or heat generation sources, background data, the scope of the study and assumptions. In this paper, CML 2001 updated January 2016 has been used for the calculation of the results.

All the impacts calculated in the current study are well within the ranges documented in the literature, reports or database. For example, the GWP reported in the literature ranges between 137 and 1,044 g CO_2 eq./kg ceramic tile, compared to the value of 698 g CO_2 eq./kg ceramic tile obtained in this paper. The main contribution to GWP comes from the natural gas consumption for firing and spray drying stages.

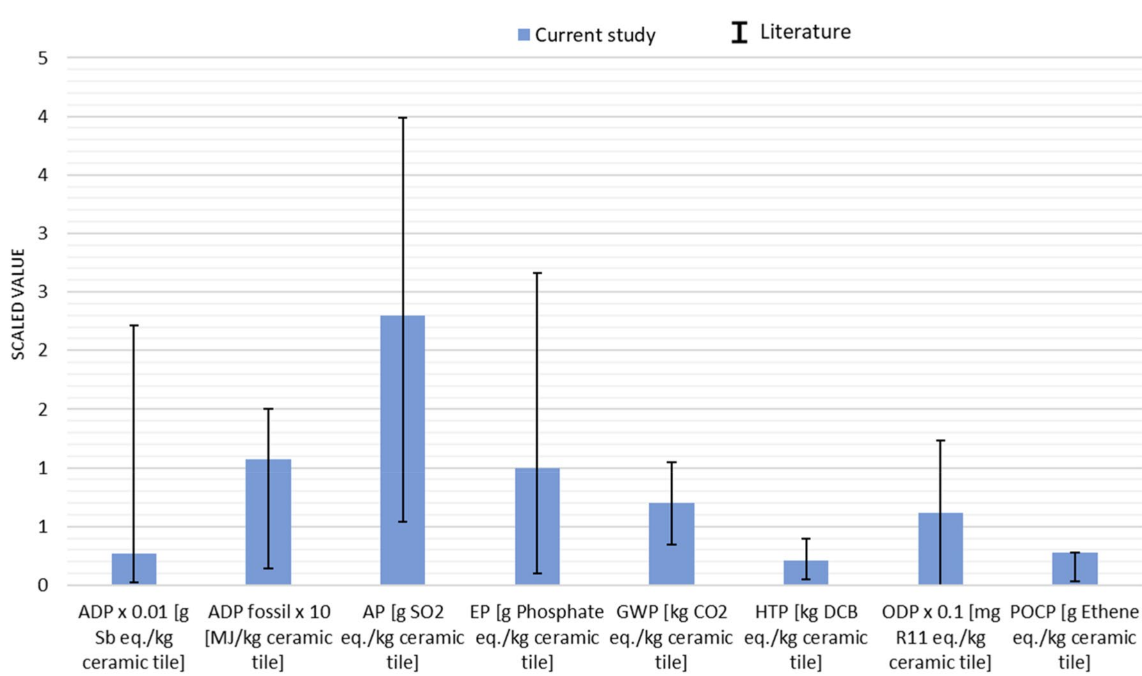


Fig. 8 Comparison of the results with literature

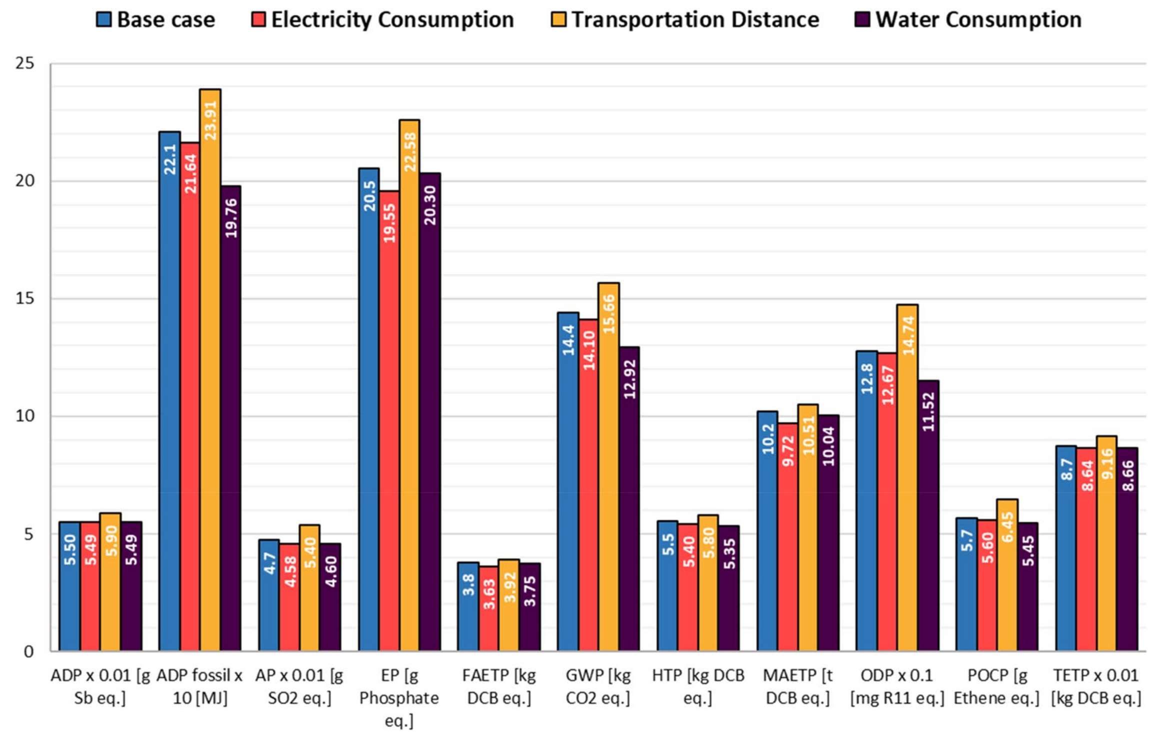


Fig. 9 Results for the sensitivity analysis

As shown in Fig. 8, the POCP of this study is higher, since this impact is mainly due to the energy consumption of the production process and the process in the packing materials.

Sensitivity analysis

The sensitivity analysis investigates the effect of the following parameters on the environmental impacts of glazed ceramic tiles:

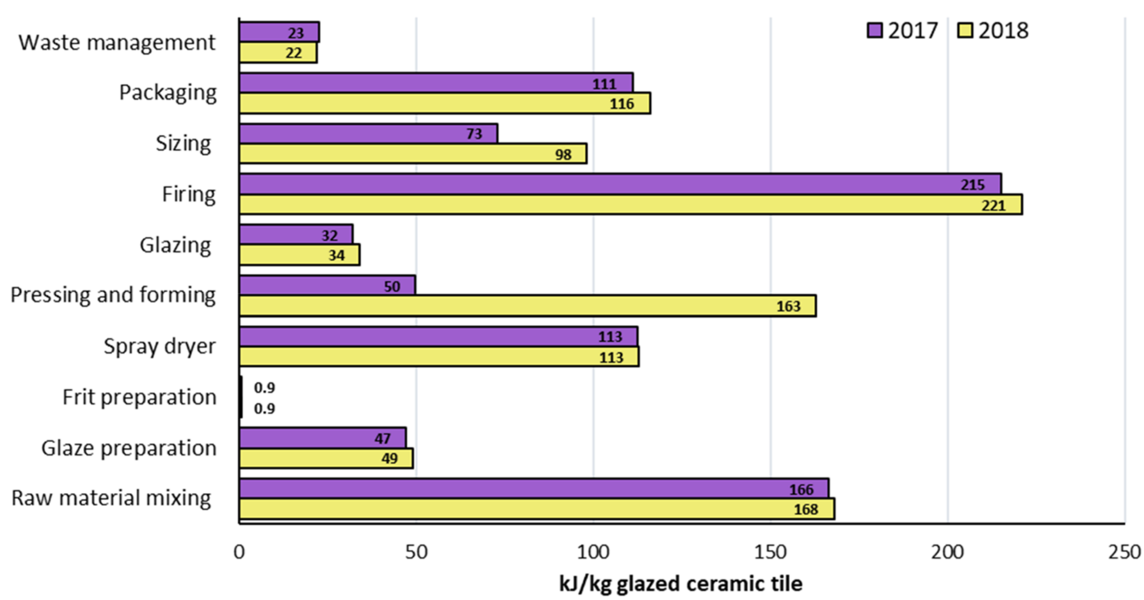


Fig. 10 Comparison of the electricity consumption in ceramic tile production for 2017 and 2018

- The electricity consumption in the production of glazed ceramic tile system,
- Transportation distances for the raw material supply to the facility,
- Reduction of the water used for mixing the raw materials.

The results of the sensitivity analysis are summarized in Fig. 9 and discussed below for each considered parameter in turn.

Sensitivity analysis of electricity consumption

This parameter has been selected due to the annual electricity consumption differences. As presented in Fig. 10, consumed electricity for the production of 1 m^2 glazed ceramic tile is different for the years 2017 and 2018. Therefore, the sensitivity analysis considers a decrease of 15% for the total electricity consumption to explore the potential effects on the environmental impacts.

As indicated in Fig. 9, reducing the total electricity consumption by 15% reduces the life cycle environmental impacts. The greatest reductions are found for EP (4.7%), FAETP (4.5%) and MAETP (4.8%). The effect of this parameter is small across the other environmental impacts (0.2%-3.4%).

Sensitivity analysis of transportation distance

The details related to transportation are presented in Table 2. The contribution of transportation of the raw materials and packaging materials ranges from 8 to 30% across the impact categories, see Fig. 5.

Transport distances for each raw material and packaging materials from raw material sites to manufacturing area were obtained from the manufacturer. However, there are alternative clay and feldspar suppliers in Turkey. For sensitivity analysis, lorry transportation distances are increased to 500 km only for clay and feldspar. As presented in Fig. 9, all the environmental impacts are affected by lorry transportation distances, increasing by between 3.2% and 15.4%. This is due to the raw materials and packaging materials supplied from longer distances increased energy consumption and emissions.

These results show that the use of local or national raw materials and packaging materials to decrease the distance of transport can play an important role in reducing the impacts of the ceramic sector.

Sensitivity analysis of water consumption

Water is an important input for ceramic tile production. The manufacturer uses a wet process to prepare its raw materials. According to our data from the manufacturer, the water consumption for the raw material mixing process to produce 1 m^2 of glazed tiles is different for the years 2017 and 2018. Water usage for the raw material mixing process is around 10% higher in 2017 than in 2018. Owing to the use of more water, the natural gas used in the spray dryer and pressing and forming stages are %8 and 5% higher in 2017 and 2018, respectively.

Reducing the water amount in the mixing process affect the environmental impacts, decreasing them from 0.2 for ADP to 10.5% for ADP fossil (see Fig. 9). The results indicate that the dry milling process would reduce some of the environmental impacts compared with the wet milling process.

Conclusions

This paper has discussed the environmental sustainability of glazed ceramic tiles production. Life cycle assessment method has been used to assess the environmental impacts from the glazed ceramic tile production supply chain, following the ISO 14,040/14,044 series guidelines. This study provides a comprehensive Life cycle inventory for ceramic and construction sectors in Turkey. In total, eleven environmental impacts have been estimated using the CML 2001 method. Moreover, to test the robustness of the results sensitivity analysis has been performed.

The findings indicated that for the generation of 1 m^2 ceramic tile, the total energy requirement is 221 MJ. The GWP is estimated at 14.4 kg CO_2 eq. to produce 1 m^2 glazed ceramic tile. Due to high energy consumption, ceramic tiles production stage is the main hotspot for nine out of eleven environmental impacts categories, contributing 45.9% for HTP—%73.9 for GWP. For ADP, raw material extraction and production stage (82.5%) are the biggest contributors, while for TETP, most of the impact is from the transportation stage (31.4%). The total energy consumption of the facility is 1130 TJ per year to produce 106,195 tonnes of glazed ceramic tile. Annually, glazed ceramic tiles production from the selected facility emits 74 kt CO_2 eq. on a life cycle basis.

This study is expected to be useful for the ceramic industries to recognize hotspots and to find environmentally friendly solutions. Based on the obtained results, some actions for improving the environmental sustainability of the whole life cycle of ceramic tiles can be suggested to decrease the life cycle environmental impact of the identified hotspots. The impact of the ceramic tile production mainly deriving from the firing, spray drying, and pressing and forming processes, could be reduced using measures in the whole production system that lead to decreased heat and electricity consumption. Also, natural gas is used for heat production and the electricity supply in Turkey is dominated by coal and natural gas. Replacing natural gas by biogas or supplied electricity from renewable sources would minimize the environmental impacts by burning of fossil fuels from the production stage. Other options would be adding a cogeneration system or using waste heat in the production process. The manufacturing process is an intensive user of raw materials. The development of compositions that include alternative materials or waste from other industries to replace conventional raw materials would decrease the environmental impacts from the raw materials supply stage. Moreover, as discussed in the sensitivity analysis, the local acquisition of raw materials, decreasing the use of electricity and water would reduce the impacts notably.

Hence, it is proposed that further work be carried out to improve the environmental sustainability of the ceramic sector including the different scenarios modelled by real and detailed data and taking into consideration that the manufacturer's plans and investments.

Table 6 Life cycle impact assessment results for each life cycle stage

Environmental impact	TOTAL	Raw material supply	Transportation	Production	Waste management
$ADP_{elements}$ [kg Sb-eq]	8.9E − 05	8.0E − 05	7.3E − 06	1.6E − 06	8.0E − 07
ADP fossil [MJ]	2.2E+02	2.9E+01	2.4E+01	1.7E+02	2.7E+00
AP [kg SO_2-eq]	4.9E − 02	1.1E − 02	8.8E − 03	2.8E − 02	9.7E − 04
EP [kg PO_4-eq]	2.1E − 02	5.0E − 03	3.1E − 03	1.3E − 02	5.1E − 04
FAETP [kg DCB-eq]	3.9E+00	1.0E+00	4.4E − 01	2.2E+00	2.5E − 01
GWP [kg CO_2-eq]	1.5E+01	2.0E+00	1.7E+00	1.1E+01	2.4E − 01
HTP [kg DCB-eq]	5.8E+00	1.7E+00	1.1E+00	2.5E+00	4.8E − 01
MAETP [kg DCB-eq]	1.1E+04	2.8E+03	9.0E+02	6.4E+03	4.9E+02
ODP [kg R11-eq]	1.3E − 06	3.6E − 07	2.4E − 07	6.8E − 07	1.0E − 08
POCP [kg C_2H_4-eq]	5.8E − 03	7.4E − 04	1.1E − 03	3.9E − 03	1.1E − 04
TETP [kg DCB-eq]	9.2E − 02	2.2E − 02	2.7E − 02	1.8E − 02	2.4E − 02

Table 7 Life cycle impact assessment results for each production stage

Impacts	Total impact of production stage	Raw material mixing	Spray dryer	Pressing and forming	Glaze production	Glazing	Firing	Sizing	Packaging
$ADP_{elements}$ [kg Sb-eq]	1.6E − 06	1.6E − 07	2.0E − 07	1.9E − 07	4.9E − 08	3.3E − 08	4.0E − 07	9.5E − 08	4.8E − 07
ADP fossil [MJ]	1.7E+02	8.6E+00	3.1E+01	1.8E+01	3.0E+00	1.7E+00	6.4E+01	5.0E+00	3.4E+01
AP [kg SO_2-eq]	2.8E − 02	3.3E − 03	3.8E − 03	3.8E − 03	9.8E − 04	6.6E − 04	7.6E − 03	1.9E − 03	5.8E − 03
EP [kg PO_4^{3-}-eq]	1.3E − 02	2.0E − 03	1.6E − 03	2.0E − 03	5.7E − 04	4.0E − 04	3.1E − 03	1.1E − 03	2.0E − 03
FAETP [kg DCB-eq]	2.2E+00	3.5E − 01	2.9E − 01	3.6E − 01	1.0E − 01	7.0E − 02	5.7E − 01	2.0E − 01	3.1E − 01
GWP [kg CO_2-eq]	1.1E+01	6.3E − 01	2.1E+00	1.3E+00	2.2E − 01	1.3E − 01	4.2E+00	3.7E − 01	1.8E+00
HTP [kg DCB-eq]	2.5E+00	2.8E − 01	4.1E − 01	3.6E − 01	8.7E − 02	5.7E − 02	8.2E − 01	1.7E − 01	3.6E − 01
MAETP [kg DCB-eq]	6.4E+03	9.9E+02	8.5E+02	1.0E+03	2.9E+02	2.0E+02	1.7E+03	5.8E+02	8.2E+02
ODP [kg R11-eq]	6.8E − 07	2.1E − 08	1.5E − 07	7.5E − 08	9.0E − 09	4.2E − 09	3.1E − 07	1.2E − 08	8.7E − 08
POCP [kg C_2H_4-eq]	3.9E − 03	1.7E − 04	3.8E − 04	2.7E − 04	5.6E − 05	3.5E − 05	7.7E − 04	1.0E − 04	2.1E − 03
TETP [kg DCB-eq]	1.8E − 02	1.8E − 03	2.1E − 03	2.1E − 03	5.5E − 04	3.7E − 04	4.1E − 03	1.1E − 03	5.9E − 03

Appendix

Environmental impact results based on CML impact method

See Tables 6, 7.

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