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Research article

Improving the sustainability of ceramic tile production in Turkey

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ABSTRACT

The concept of environmental sustainability and its applications in the ceramic industry has been raised due to the environmental issues related to the construction sector. This study evaluated and compared the environmental impacts of ceramic tiles manufactured by the current production technologies. Four different cleaner scenarios are applied based on cradle-to-gate life cycle assessment. Scenario A refers to the energy recovery to supply heat for the drying process. Scenario B is related to efficient combustion. Scenario C relates to reducing the thickness of ceramic tiles to minimize energy consumption and save raw materials. Scenario D is a combination of the other scenarios. According to the results, the tile production stage is the main hotspot for all the impact categories except abiotic depletion and terrestrial ecotoxicity potential for all the cases. Scenario D has a 22% reduction in ozone layer depletion. The greenest option for glazed ceramic tile production is Scenario D. This scenario has the lowest global warming potential, being 21% lower than the base case. The findings of this paper could assist the government and ceramic producers in developing robust strategies for improving the sustainability of the Turkish construction sector and contributing to the country's greenhouse gas emission reduction targets.

1. Introduction

The construction sector and, accordingly, the building materials industry continue to occupy an important place in the global economy. The construction sector is continuously growing due to increasing population and urbanization, infrastructure requirements, improvement, and transformation needs. Moreover, buildings with higher standards, such as energy efficiency, are required. Finally, smart buildings, cities, and systems are coming to the forefront as digitization continues. The technology density of the construction and building materials industries is increasing (IMSAD, 2019).

The construction sector in Turkey is one of the most important sectors supporting economic growth (Özden et al., 2019). In Turkey, the construction and building materials industry has increased in recent years. Many factors such as mega projects of public institutions, urban transformation, and infrastructure investment continue to accelerate the construction sector (IMSAD, 2019). The construction sector contributes to the development of many sub-sectors that provide inputs and significantly affect the capacity for job creation in the country. It is also observed that government policies, economic and political decisions, and developments in foreign markets directly influence the sector (Özden et al., 2019). In 2019, the Turkish construction sector consumed a total of 646 thousand tonnes of oil equivalent (toe) energy (MENR, 2021).

The production of the Turkish building materials industry grew by 9.1% in 2020 compared to the previous year. Due to the conditions that emerged with the outbreak of COVID-19, the industrial production of building materials decreased by 8% in the second quarter of the year. On the other hand, in the third and fourth quarters, with the demand created by the support of the construction sector, the industrial production of construction materials ended the year with very high growth. Among the subsectors, the highest increase in production in 2020 was realized in the subsector "parquet and floor coverings" with 35.5%. "cement manufacturing" increased by 28.4%, "ready-mixed concrete manufacturing" by 25.9%, and "ceramic tiles and flags manufacturing" by 25.4% (IMSAD, 2021).

Construction materials imports increased by 3.5% in 2020 compared to 2019 and reached US$7.03 billion while exports decreased by 1.5% in 2020 to US$21.16 billion. Imports and exports of construction materials shrank significantly in the first and second half of the year respectively due to the COVID-19 outbreak (IMSAD, 2021).

Turkish ceramic industry is one of the largest ceramics producers in the world in the last 50 years (TURKSTAT, 2020). The lo-

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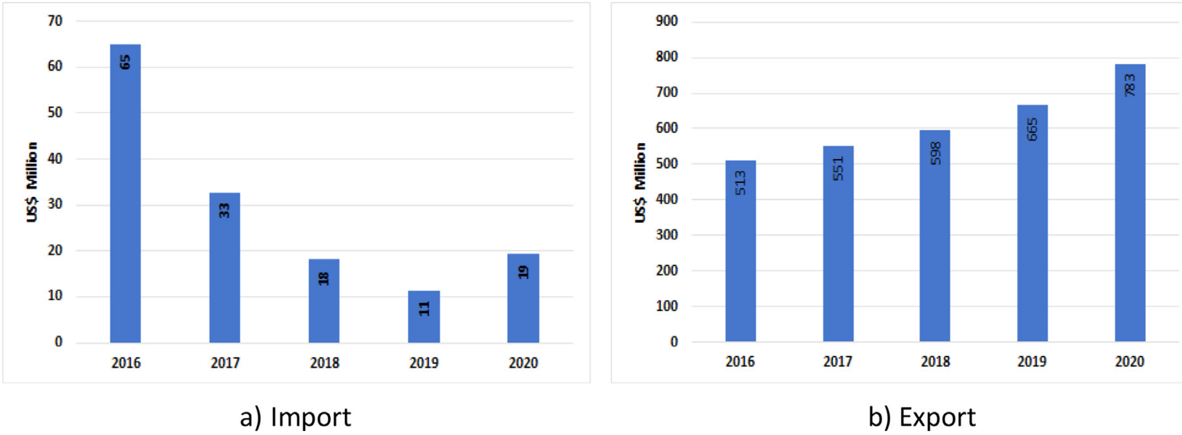


Fig. 1. Ceramic tile foreign trade between 2016 and 2020 (ITC, 2021) (custom tariffs of 6907 6908)

comotive product group of the sector is ceramic tile production (MST, 2020). Turkish ceramic tile industry has made investments since 1990. Turkey ranks 3rd in Europe and 6th in the world in terms of ceramic tile production with a production of 5.28 million tonnes of tiles. Turkey is the 3rd largest exporter of ceramic tile in Europe and the 6th in the world (MST, 2020; TURKSTAT, 2020). Although the domestic market for ceramic tiles has been limited over the years in parallel with the growth of the construction sector, the production of ceramic tiles has increased gradually and steadily over the years.

In terms of foreign trade, the export volume of Turkish ceramic tiles increased by 62.8% in 2020 compared to 2016. It has reached 131.6 million m^3, while import volumes have decreased by 26.0% compared to 2016. Import volumes amounted to 2.2 million m^3 in 2020. As seen in Fig. 1, the export of ceramic tiles has increased by 52.7% compared to 2016. It has reached US$782.7 million. In 2020, relative to 2016, ceramic tile imports have decreased by 70.3%. (ITC, 2021).

Turkish “Manufacture of ceramic tiles and flags” (Nace Rev.2 23.31) industry consists of 42 enterprises in 2018. In terms of production value, the ceramic sector is over US$2.90 billion in 2018, while the production value of “ceramic tiles and flags” was around US$1.6 billion in 2018 (MST, 2020).

In the production process of the ceramic industry, as can be seen in Fig. 2, energy, raw materials, auxiliary materials, and water are used. Depending on the specific production process, the main environmental sustainability problems of the ceramic industry are high energy consumption, greenhouse gas (GHG) emissions, wastewater, dust emissions, waste, and process losses (EC, 2007; Ibáñez-Forés et al., 2013).

The ceramic industry is one of the most energy-intensive industries due to the drying and firing processes at high temperatures and the heating of ceramics for calcination. Natural gas plays an important role as an energy source for burners (MOSA, 2016). Fuel oil, liquefied natural gas, biogas, electricity, and coal can also be used in the ceramic manufacturing process, but they are not economically interesting (EC, 2007). Most of the ceramics manufacturers in Turkey use natural gas (TURKSTAT, 2020). In 2019, the energy consumption of the Turkish manufacturing industry is around 29.8 Mtoe and 4% of this is in the ceramics industry (MENR, 2021). The specific energy consumption of the production of wall and floor ceramic tiles is 30-40 kWh/m^2 with an average weight of 22 $\pm$ 1 kg/m^2. The most significant energy demand is thermal energy in the production of ceramic tiles. The percentage of thermal energy consumed in spray drying the ceramic slurry, drying the formed ceramic tile, and firing of the ceramic tile is 36%, 9%, and 55%, respectively (Ros-dosda et al., 2018).

In conjunction with the high energy consumption, ceramic manufacturing produces various particulate matter, nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), carbon dioxide (CO_2), and volatile organic compounds (VOC). In addition, hazardous air pollutants such as hydrochloric acid (HCl) and hydrofluoric acid (HF) are formed (EC, 2007).

In general, the combustion of fuels in furnaces and dryers causes SO_x, NO_x, CO and results in CO_2 emissions. Kilns and dryers, used in the ceramic production process cause most of the fuel-related emissions. Therefore, the efficient operation of these types of equipment is very important in terms of emissions. Dust emissions can be generated during the delivery and preparation of raw materials due to transportation, raw material handling, storage, and grinding. There are also SO_x, hydrogen fluoride (HF), hydrogen chloride (HCl), and CO_2 emissions from the sulphur-containing, chlorinated, fluorinated, and carbonated compounds in the raw material. The polishing and surface coating stages where baked ceramics are processed also cause particulate matter and VOC emissions (EC, 2007; Ibáñez-Forés et al., 2013).

As presented in Table 1, the total GHG emissions in 2018 were calculated as 520.9 million tonnes (Mt) CO_2 eq., a decrease of 0.5% compared to 2017. The energy sector accounted for the largest share with 71.6%, followed by industrial processes and product use (IPPU) [1] with 12.5% (TURKSTAT, 2020).

In 2018, fuel-related emissions from the non-metallic minerals sector amounted to 30.18 Mt CO_2 eq. which is 5.8 % of Turkey's total emissions. Non-fuel related emissions of the ceramics sector are mainly generated as raw materials such as limestone and magnesite are calcined during production. Non-fuel related CO_2 emissions from ceramics processing show an overall increasing pattern between 1990-2018. CO_2 emissions from each raw material for the ceramics sector are shown in Table 2. In 2018, they amounted to 2.8 million tonnes of CO_2 eq., representing 0.5% of Turkey's total emissions and 6.5% of the non-metallic minerals sector (TURKSTAT, 2020). So, the reduction of GHG emissions from this sector is very important for the country to achieve emission targets. The environmental impacts of ceramic tile manufacturing are shown in Table 3.

A considerable amount of water is consumed in the factories, especially during masse preparation, glazing, spray dryer, and sizing-polishing stages (MOSA, 2016). Some of the process water evaporates during the spray dryer, drying, and firing steps (IFC, 2007; MEU, 2019).

[1] IPPU consists of the manufacturing industry as iron and steel, non-ferrous metal, chemicals, pulp, paper and print, food processing, beverages and tobacco, non-metallic minerals and other industries.

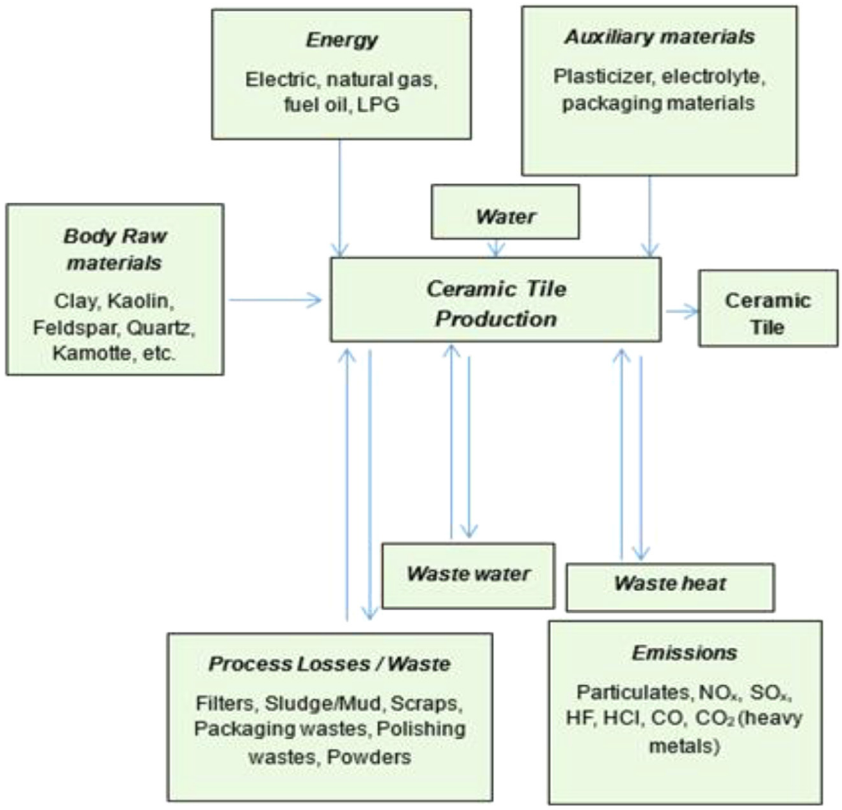


Fig. 2. Inputs and outputs of the ceramic tile production process (MEU, 2019)

Table 1
Turkish GHG emissions in Mt CO_2 eq., 1990-2018 (TURKSTAT, 2020).

Emission sources	1990	1995	2000	2005	2010	2015	2016	2017	2018
Total emissions	**219.37**	**247.76**	**298.76**	**337.14**	**398.88**	**472.60**	**497.74**	**523.75**	**520.94**
Fuel Combustion	***135.09***	***162.30***	***209.91***	***238.21***	***278.82***	***335.41***	***351.07***	***373.20***	***365.44***
Manufacturing industries and construction	*37.16*	*39.99*	*57.94*	*63.00*	*52.33*	*59.58*	*60.07*	*60.18*	*59.58*
Non-metallic minerals	*8.26*	*8.79*	*9.25*	*14.88*	*21.36*	*29.95*	*31.63*	*32.58*	*30.18*
IPPU	**22.84**	25.25	**26.23**	**33.63**	**48.15**	**57.08**	**61.12**	**63.61**	**65.20**
Non-metallic minerals	13.42	17.55	18.42	23.25	33.39	38.48	42.00	44.27	43.82
Ceramics	0.43	0.70	1.09	1.57	1.66	2.56	2.64	3.22	2.84

Table 2
CO_2 emissions from raw material consumption in Turkey between 1990 and 2018 (kt) (TURKSTAT, 2020).

Year	Calcite	Limestone	Dolomite	Magnesite	Clay	Total
1990	3.3	122.2	3.6	125.1	179.5	433.7
2015	20.1	785.4	21.8	803.7	930.4	2,561.3
2016	20.8	815.3	22.6	834.3	951.7	2,644.7
2017	21.5	840.7	23.3	874.3	1458.6	3,218.5
2018	106.1	840.7	60.6	874.3	959.4	2,841.1

Examining the process-based average water consumption values of 20 ceramic tile plants in Spain, the highest water consumption is in the order of glazing, raw material preparation, other processes (maintenance, cleaning, operational services), and shaping (pressing) steps (Ibáñez-Forés et al. 2013) Mezquita et al. (2017) compared the water consumption of dry and wet grinding systems in tile production. It was found that water consumption was 0.12-0.16 m^3/tonne (dry weight) and 0.47-0.59 m^3/tonne (wet weight). This study shows that the water consumption in wet grinding is about four times higher compared to dry grinding. In the dry method, water consumption is reduced by 74%.

Process wastewater is generated mainly from units, and other process steps (e.g., glazing, decorating, polishing, and wet grinding). It contains suspended solids (e.g., clays and insoluble silicates), suspended and dissolved heavy metals (e.g., lead and zinc), sulfates, boron, and traces of organic matter. Wastewater formed in the process can be reused in sludge and glaze preparation processes after settling and purification processes (EC, 2007; IFC, 2007).

Process losses or wastes in the production of ceramics consist mainly of various types of sludges containing raw material components, deformed baked and uncooked ceramic semi-products, plaster moulds, sorption agents used, dust, ashes, sludge from wastewater treatment, and packaging waste (European Commission, 2007). It is possible to reuse the sludge and uncooked semi-products generated in the process. In addition, most of the wastes such as baked semi-finished products and used plaster moulds can be used as raw materials in the production processes of various industries (Koyuncu et al., 2015). Some tile manufacturers can obtain products with the same technical and aesthetic properties by using ceramic tile waste at high rates such as 80% (Dağlı et al. 2018).

Table 3
Direct environmental impacts of ceramic tile manufacturing industry and related processes (Modified from Dağlı et al. (2018)).

Process	Formation			
Raw Material Storage*	Dust	Gas emissions		
Masse and Glaze Preparation**	Wastewater	Dust Gas emissions Water vapor	Solid waste	
Forming and Drying	Dust	Gas emissions	Solid waste	Water vapor
Glazing and Decoration	Wastewater	Dust	Solid waste	
Firing	Gas emissions	Solid waste		
Polishing and Sizing	Wastewater	Solid waste	Noise	
Packaging and Storage	Solid waste	Gas emissions	Packaging wastes	

*Gasoline and diesel
** Grinding, spray dryer

2. Literature review

Life Cycle Assessment (LCA) is a quantitative tool, generally used to evaluate and improve the environmental sustainability of the product (Matthews et al., 2015). When searching for published articles related to LCA of ceramic tiles (see Table 4), it was found that most studies aimed to assess the environmental impact of ceramic tiles. Only a few studies discussed the economic and technical feasibility of improvement scenarios regarding hotspots identified in ceramic tile production (Ibáñez-Forés et al., 2013; Wang et al., 2020).

Wang et al. (2020) assessed the environmental impacts of ceramic tiles produced by various scenarios by using LCA methodology. The authors compared the environmental impact of products manufactured using producer gas from coal and natural gas. The results showed that the use of natural gas instead of producer gas reduced the indicators of particulate matter formation potential (PMFP), photochemical oxidant formation potential: ecosystem quality (EOFP), and terrestrial acidification potential (TAP) by 38.7%, 19.4%, and 20.4%, respectively. It was also highlighted that the global warming potential (GWP), PMFP, TAP, and fossil resource scarcity potential (FFP) indicators of the dry milling process were lower than those of the wet milling process by 22.9%, 22.8%, 23.4%, and 25.1%, respectively. In another study, the environmental hotspots were identified to select the Best Available Technique (BAT) options to improve the hotspots (Ibáñez-Forés et al. 2013). The most economically and environmentally sustainable options included heat recovery from the flue gas and its clean-up. These improvements reduced the environmental impact by over 95% and cost savings were up to 30%. With the wet flue gas cleaning scenario, the impacts of acidification potential (AP), photochemical oxidant creation potential (POCP), abiotic depletion potential elements (ADP), and GWP were reduced by 70.3%, 47.3%, 14.3%, and 14.1%, respectively. Ros-Dosdá et al. (2018) evaluated the different types of porcelain stoneware tile (PST) in terms of life cycle environmental sustainability. Due to increased energy and materials input, the variation in thickness of PST had a negative effect on all the impact categories except ADP.

In the study conducted by Bovea et al. (2010), the firing process was considered the most critical process in terms of environmental impacts. The first improvement option was to recover the heat of the combustion gas from the kilns and then reuse it in pre-dryers. This improvement option reduced the impact categories ADP, GWP, ozone depletion potential (ODP), POCP, AP, eutrophication potential (EP) by 8.1%, 4.2%, 4.3%, 7.6%, 11.8%, and 2.1%, respectively. The presses were enclosed with sound-absorbing material to reduce the noise level. Thus, an improvement of 3.7% was achieved. Another study by Almeida et al. (2016) analysed the measures taken to reduce the environmental impacts of tile production. The improvement option associated with transport substitution resulted in a reduction of the impact categories GWP, abiotic depletion potential fossil (ADP fossil), AP, EP, and human toxicity potential: non-cancer (HTnc) by 5.4%, 4.9%, 4.7%, 6.7%, and 4.5%, respectively. While the implementation of EU ecolabel was the most effective for the indicators GWP (4.8%), ODP (6.6%), particulate matter (PM) (4.7%), and ADP fossil (5.0%).

This paper aims not only to assess the life cycle environmental impact of glazed ceramic tile, but also to identify hotspots, and to compare different improvement scenarios for the conventional ceramic manufacturing system. In Turkey, there is a lack of reviewing improvement options to reduce the environmental impacts arising from the ceramic tile manufacturing industry. In this work, we attempt to fill this research gap. Since this research focuses on improving hotspots in ceramic tile production the authors believe that it will serve as a guideline for the reduction of environmental impact. The following section explains the methods and inventory data used for this analysis, including a summary of the scenarios. The results of the modelling of the base case and the scenarios are presented and discussed in the Results and Discussion section and conclusions are drawn in the Conclusions section.

3. Methods

This study applies LCA methodology, following the ISO 14040/14044 standards (ISO, 2006a; ISO, 2006b). The LCA was developed with GaBi software v9.5 (Sphera, 2020), employing the Ecoinvent v3.5 database (Ecoinvent, 2019) and the environmental impact assessment method selected was the CML 2001 method, January 2016 update (Guinee, 2002).

The next parts of the paper detail the goal and scope, assumptions, inventory data used in this study, and the scenarios together with the findings of the environmental impact assessment.

3.1. Goal and scope definition

This paper aims to evaluate and compare the environmental sustainability of ceramic tiles by using the LCA method on various improvement scenarios for reducing environmental impacts. The scope of the study is from 'cradle to gate'. It includes all activities from the raw material extraction and processing through

Table 4
Recent studies related to life cycle assessment of ceramic tile manufacturing in different countries

Authors	Country	Product	Aim	Functional unit	Scope	Impact Method	Environmental Impacts	Improvement Scenarios
Wang et al. (2020)	China	Ceramic tile	to quantify the environmental improvements	1 m^2 of ceramic tile	Energy generation, raw material extraction, transportation, production	ReCiPe 2016	GWP; PMFP; HTPnc; EOFP; TAP; LOP; SOP; FFP; HH; ED; RA	• Natural gas usage instead of producer gas as fuel • Dry-milling process instead of the wet-milling
Ros-Dosdá et al. (2018)	Spain	Porcelain stoneware tile (PST)	to assess the life cycle environmental impacts of PST	1 m^2 of floor surface cover	Raw material extraction, transportation, production, construction, use, end of life	CML 2001	ADP; ADP fossil; AP; EP; GWP; ODP; POCP	• Thickness reduction • Amount of glaze • Mechanical treatment
Ye et al. (2018)	China	Combination of a 0.4 m^2 wall tile and 0.6 m^2 polished tile	to quantify the environmental and economic impacts	1m^2 of ceramic tile	Raw material preparation, pressing, glazing, firing, waxing, polishing	ReCiPe 2016	TAP; ME; FEP; MEP; PMFP; FE; HT; CC; MD; FD; WD; POCP; TE; ODP; IR; LOP	Not available (NA)
Sangwan et al. (2018)	India	Vitrified ceramic tile	to assess the environmental impact of vitrified floor tile	1 m^2 of vitrified ceramic tile	Raw material extraction, production, distribution, installation, disposal	ReCiPe 2016	CC; FD; FE; HT; MD; ODP; PMFP; TAP; WD	NA
Maia de Souza et al. (2016)	Brazil	Ceramic and concrete brick	to compare life cycle environmental impacts of ceramic and concrete brick	1 m^2 of roof cover	Raw material extraction, transportation, production, use, end of life	Impact 2002 v.Q2.2	CC, HH, Ecosystem quality, ADP	NA
Almeida et al. (2016)	Portugal	Ceramic tile	to assess the life cycle environmental impacts of ceramic tiles	1 m^2 of ceramic tile	Raw material extraction, transportation, production, use, disposal	CML 2001 ILCD	GWP; AP; EP; EOFP; ADP; ADP fossil; ODP; HTnc; HTc; ecotoxicity; PMFP; LOP; WD; PM	• Heat recover from the burners of the kiln • Heat recovery from the dryer • Lighting system • Substitution of foreign materials with local materials
Tikul (2014)	Thailand	Glazed ceramic floor tiles	to quantify the environmental impact of production	glazed ceramic floor tiles cover 1 m^2	Manufacturing	EcoIndicator 95	GWP; AP; EP; ODP	NA
Pini et al. (2014)	Italy	Ceramic tile reinforced with a fiberglass backing	to assess the environmental impacts of ceramic tile	1 m^2 of black, large, thin ceramic tile	Raw materials supply, transportation, production, distribution, end of life	IMPACT 2002+	Human health; ecosystem quality; GWP; resources; single score	NA
Ibáñez-Forés et al. (2013)	Spain	Glazed stoneware tile	to guide for improving the environmental sustainability of tiles	1 m^2 of glazed stoneware tile	Mining and atomizing production, distribution, installation, use, end of life	CML 2001	ADP; GWP; ODP; AP; EP; POCP; HT; pay-back, costs, annual savings, noise; maintenance requirements; the level of knowledge; accessibility	• Heat recovery • Traditional bag filters • High-temperature synthetic filter • Electrostatic precipitator • Full enclosure of bulk storage areas • Dust valves with suction • Water spraying • Cascade-type packed-bed absorber • Module adsorber • Dry flue gas cleaning • Wet flue gas cleaning • Sound insulation

(continued on next page)

Table 4 (*continued*)

Authors	Country	Product	Aim	Functional unit	Scope	Impact Method	Environmental Impacts	Improvement Scenarios
Ibáñez-Forés et al. (2011)	Spain	Glazed stoneware tile	to assess the environmental impacts of ceramic tile	1 m^2 of ceramic tile	Mining and atomizing production, distribution, installation, use, end of life	CML 2001	ADP; GWP; ODP; AP; EP; POCP; HT	NA
Cellura et al. (2011)	Italy	Ceramic roof tile (Sicilian tile)	to identify the most relevant sources of uncertainty in the LCA study	1000 kg of tiles	raw materials and fuels supply and transportation; production; distribution	EPD 2008	ODP; AP; EP; POCP; GWP	NA
Bovea et al. (2010)	Spain	Wall and floor tiles	to assess the environmental impacts of floor and wall tiles	1 m^2 of ceramic tile	Extraction of raw materials, transport, production and delivery to the customer	CML 2001	ADP; GWP; ODP; AP; EP; POCP; noise	• Use of the exhaust gases from the kilns to pre-dry, • Bag filter with absorber • Use modular soundproofing panels
Benveniste et al. (2010)	Spain	Red - white wall tiles Glazed white - red stoneware tiles Porcelain tiles	to establish the magnitude and nature of the environmental impacts of ceramic tiles	1m^2 ceramic tile	extraction of raw materials, transportation, production, distribution, use, end of life	CML 2001	GWP; ADP; POCP; AP; EP; ODP; consumption of primary energy and water	NA

GWP: Global warming potential, PMFP: particulate matter formation potential, HTPnc: human toxicity potential: non-cancer, HTPc: human toxicity potential: cancer, EOFP: photochemical oxidant formation potential: ecosystem quality, TAP: terrestrial acidification potential, LOP: land use potential, SOP: mineral resource scarcity potential, FFP: fossil resource scarcity potential, HH: human health, ED: ecosystem, RA: resource, ADP: abiotic depletion potential, AP: acidification potential, EP: eutrophication potential, ODP: ozone depletion potential, POCP: photochemical oxidant creation potential p, HT: Human toxicity potential, CC: Climate change, FD: Fossil depletion, MD: metal depletion, WD: water depletion, FE: freshwater ecotoxicity, ME: marine ecotoxicity, FEP: Freshwater eutrophication potential, MEP: marine eutrophication potential, TE: terrestrial ecotoxicity, IR: ionizing radiation, PM: particulate matter

the manufacture of ceramic tile. The model also takes into consideration waste management in the facility. In this study, the inventory data for the production stage was broken down as far as possible into processes to determine the processes that have the biggest environmental impact. The system boundaries are outlined in Fig. 3. Facility construction, machinery and equipment, and decommissioning of the facility were excluded due to lack of data. This is not considered as a significant limitation of the study as previous studies indicated that their contribution to the impacts is negligible (Institut Bauen und Umwelt e.V., 2016; Metsims, 2015; EPD Turkey, 2015).

The functional unit of this research is defined as the "1 m^2 ceramic tile". As presented in Table 3, this functional unit is commonly used in LCA studies of ceramic tile production (Ferrari et al., 2019; Kamalakkannan et al., 2019; Settembre Blundo et al., 2018).

3.2. Description of the process of manufacturing ceramic tiles

Fig. 3 presents the process for glazed ceramic tile production. The main raw materials used to produce the ceramic tile body are clay, kaolin, magnetite, bentonite, sand, feldspar, and recycled ceramic tile. The first stage of the preparation of the ceramic tile body process consists of combining the components, obtaining a chemically and physically homogeneous mixture. Then this mixture is pumped into a spray dryer to meet the ideal moisture content (around 5%) for the pressing and forming step. The pressing and forming stages aim to transform the spray-dried powder into a compact piece of unfired tile. The formed ceramic tiles must be dried. This is essential for increasing the strength of the ceramic tiles. The pressing and forming stages follow glaze preparation. The glaze is made of frit and the other raw materials presented in Fig. 3. The next stage in ceramic tile production is firing. Glazed ceramic tile products are fired at a temperature above 1100°C. Firing is a crucial phase in ceramic tile production for the manufacture of strong and durable products. The tiles are then sized. After sizing, ceramic tiles are packaged using cardboard boxes, plastics, and wooden pallets. The waste management stage includes wastewater treatment and solid waste disposal in process. The main waste types generated from the production stage are different types of sludge, broken products, used agents, solid residues such as dust, ash, and packaging wastes. In the facility, all the solid waste is sent to the landfill without any further treatment (EC, 2007; Salminen et al., 2019).

3.3. Inventory analysis

Ceramic tiles are thin slabs made of clay and/or other inorganic ingredients, commonly used for the floor and wall coverings (Bovea et al., 2010). 'Glazed ceramic tile' was selected for LCA. The amount and origin of data for the whole ceramic tile manufacturing system have been obtained directly from Yurtbay Seramik Eskişehir Plant for the year 2018 through questionnaires or measurements. The collected data have been assigned to the life cycle stages presented in Fig. 3.

The life cycle inventory data for the glazed ceramic tiles are shown in Table 5. The ceramic industry employs a large variety of materials. The quantities of colorants and some additives such as boric acid, magnetite, and salt are too small, so they have not been taken into account in the model. These raw materials are transported and stored at the ceramic tile production facility. Transportation of the raw materials to the facility is mainly undertaken by lorry but also by ship. Transportation in the facility is carried out by the conveyor belt system. Electricity and natural gas are consumed during the manufacturing of glazed ceramic tiles.

Table 5
Inventory data for the ceramic tiles.

Data Raw material	1 kg glazed ceramic tile		Data source
Ceramic Body			
Clay (kg)	3.86E-01		Manufacturer
Kaolin (kg)	1.45E-01		II
Feldspar (kg)	5.56E-01		II
Silica sand (kg)	2.00E-04		II
Sodium silicate (kg)	1.20E-02		II
Magnetite (kg)	8.00E-03		II
Bentonite (kg)	5.00E-03		II
Water (kg)	6.00E-01		II
Raw waste (kg)	2.10E-02		II
Glaze			
Aluminium oxide (kg)	1.22E-03		Manufacturer
Limestone (kg)	3.00E-05		II
Feldspar (kg)	5.33E-03		II
Dolomite (kg)	1.16E-03		II
Magnetite (kg)	1.00E-05		II
Zircon (kg)	2.28E-03		II
Zinc (kg)	1.00E-05		II
Sodium silicate (kg)	6.30E-04		II
Frit (kg)	2.77E-02		II
Kaolin (kg)	4.41E-03		II
Calcium silicate (kg)	5.40E-04		II
Silica sand (kg)	3.08E-03		II
Clay (kg)	4.29E-03		II
Sodium chloride (kg)	1.00E-05		II
Water (kg)	1.72E-02		II
Frit			
Aluminium oxide (kg)	4.50E-04		Manufacturer
Limestone (kg)	2.28E-03		II
Feldspar (kg)	2.23E-03		II
Dolomite (kg)	6.50E-04		II
Zircon (kg)	4.80E-04		II
Zinc (kg)	1.12E-03		II
Boric acid (kg)	5.80E-04		II
Silica sand (kg)	5.79E-03		II
Soda (kg)	3.40E-04		II
Magnetite (kg)	9.00E-05		II
Water (kg)	7.90E-04		II
Packaging			
Cartoon (kg)	8.00E-03		Manufacturer/Ecoinvent*
Plastic film (kg)	1.00E-03		II
Styrofoam (kg)	2.30E-02		II
Raw material transportation			
	Lorry (km)	**Ship (km)**	
Clay	2.49E+02	-	Manufacturer
Kaolin	1.05E+02	-	II
Feldspar	2.51E+02	-	II
Additives	1.85E+02	3.34E+03	II
Aluminium oxide	3.52E+02	2.42E+03	II
Calcite	1.00E+01	-	II
Bentonite	8.00E+02	-	II
Dolomite	4.40E+01	-	II
Zircon	1.70E+02	2.26E+03	II
Zinc	2.00E+02	-	II
Silica sand	256		
Magnetite	50		
Sodium silicate	400		
Sodium chloride	45		
Boric acid	150		
Packaging: Cardboard	1.00E+02	-	II
Packaging: Others	0.85E+02	-	II
Packaging: Plastics	2.40E+02	-	II
Conveyor belt (m)	8.90E-06		Manufacturer
Production			
Energy consumption			
	Electricity (MJ/kg product)	**Natural gas (MJ/kg product)**	
Raw material mixing	1.68E-01	-	Manufacturer
Glaze preparation	4.90E-02	-	II
Frit preparation	0.90E-03	2.40E-02	II
Spray dryer	1.13E-01	1.20E+00	II
Pressing and forming	1.63E-01	4.50E-01	II
Glazing	3.40E-02	-	II
Firing	2.21E-01	2.36E+0	II
Sizing	0.98E-01	-	II
Packaging	1.16E-01	-	II
Waste management	2.20E-02	-	II
Waste management			
Hazardous waste (kg)	9.00E+00		Manufacturer/Ecoinvent*
Wastewater (m^3)	1.90E-01		II

* Ecoinvent v3.5 database

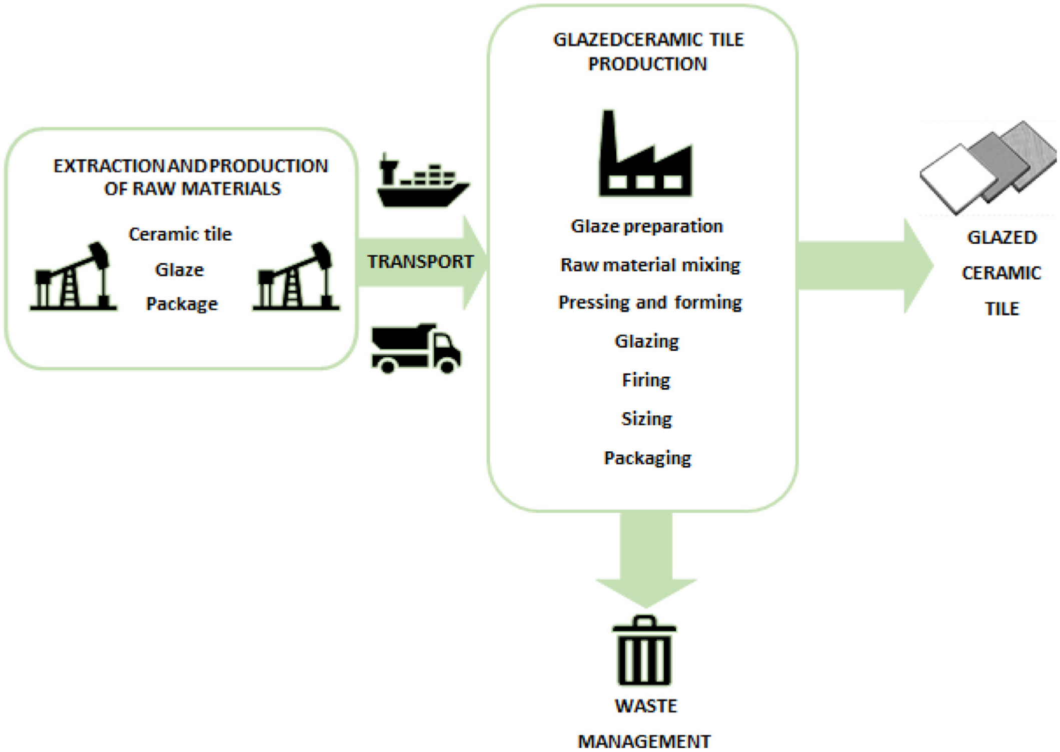


Fig. 3. Life cycle diagram for the ceramic tiles

3.4. Scenarios

Four scenarios are considered for the improvement of the life cycle environmental sustainability of glazed ceramic: Scenario A, Scenario B, Scenario C, and Scenario D. These scenarios have been prepared according to the manufacturer's strategies for the future to reduce the environmental impacts and mitigate GHG emissions. In the scope of this study, site visits and interviews facilitated the development of scenarios and the collection of data. For comparison, the sustainability of the current ceramic tile manufacturing process of the facility is considered as the base case.

Glazed ceramic tiles are manufactured from raw materials requiring high firing temperatures and intensive processing procedures. Scenarios A and B refer to the energy savings from the manufacturing process of ceramic tiles. The production system consumes a significant amount of energy, primarily thermal energy, which is derived from the combustion of natural gas. The impact of the production, mainly deriving from the pressing and forming, spray drying (masse) and firing step could be reduced by decreasing fuel consumption, thereby reducing the emissions. Ceramic manufacturing needs large quantities of raw materials. Concerning raw material extraction and processing as a hotspot, Scenario C relates to the reduction of the thickness of ceramic tiles to minimize energy consumption and to save raw materials. Scenario D is a combination of Scenario A, Scenario B, and Scenario C. This scenario consists of the best possible improvements for glazed ceramic tile production.

The technical or economic viability of the scenarios presented in this paper have been discussed with the company. The scenarios and the suggested improvement actions are detailed in the following parts.

3.4.1. Scenario A: Energy recovery

Ceramic factories consume large amounts of fossil fuel-based heat for the drying process, which is used to remove water from the ceramic body. Scenario A consists of hot air recovery to supply heat for the drying in order to reduce the fuel consumption and the associated emissions from the spray dryer. Dryers are generally heated by natural gas. In this scenario, 65% of the natural gas used for the drying stage is reduced according to the data obtained from the manufacturer.

3.4.2. Scenario B: Energy-saving combustion

Scenario B is related to the firing stage. Firing is one of the most important steps in the production of ceramic tiles because it controls the technological properties of ceramic tiles. The thermal energy used in the firing stage is primarily obtained by natural gas. Reducing the natural gas consumption of the firing stage decreases the emissions and the costs. The average natural gas consumption in this stage is estimated at 0.22 MJ/kg glazed ceramic tile. Nearly 50% of the energy is lost through the combustion of furnace flue gas and cooling gas stacks in the conventional ceramic tile firing process. The new energy-saving combustion technology has been adopted in the manufacturing process. This system allows for 15% lower natural gas consumption compared to the conventional firing system. Automatic air-gas control mounted on each burner ensures a stable combustion process and saves fuel.

3.4.3. Scenario C: Reduction of the thickness

Concerning the amount of raw material consumption as a hotspot for environmental impacts, the first choice should be the reduction of the tile thickness to decrease the raw material consumption. Ceramic tiles with reduced thickness have a lower mass to be fired, reducing energy consumption during drying and firing, and saving raw materials. The manufacture of reduced thickness ceramic tiles is an important technical advancement aimed at reducing both the cost of production per unit and the cost of packaging, transportation, and final disposal. Therefore, reduction of the thickness is important for the sector. (V. Ibáñez-Forés et al., 2013). Scenario C aims at minimizing the impacts by reducing energy consumption and saving on raw materials by thickness reduction of the ceramic tile. This scenario has been carried out for a thickness reduction of 0.5–0.6 mm without compromising quality parameters such as strength and deformation. The total weight of the selected types of 1 m^2 ceramic tile is 20.7 kg. In this scenario, the raw materials of the ceramic tiles were reduced by 7% according to the data obtained directly from the manufacturer. Energy consumption of the spray dryer and firing is reduced by 4% and 9%, respectively. These energy reduction rates have been calculated based on the production data of the manufacturer for different years.

3.4.4. Scenario D: Combination

Scenario D is a combination of Scenarios A, B, and C. These three systems can be integrated into one mechanism. This scenario involves the best possible improvements to the production of glazed ceramic tile.

4. Results and discussion

This section presents the results of the life cycle environmental assessment comparing the base case and four alternatives considering the raw materials and energy consumption reduction. The following eleven environmental impact categories are considered: global warming, resource depletion, resource depletion fossil, acidification, eutrophication, human toxicity, ozone layer depletion, and freshwater, marine, and terrestrial ecotoxicity.

The life cycle environmental impacts for the base case and the different scenarios are presented in Fig. 4 and Fig. 5. Fig. 4 compares the performance of the conventional production of glazed ceramic tile for all the suggested improvement scenarios considering each life cycle stage. Fig. 5 presents the details of the production stage's contribution to the total environmental impact of the production stage. Each impact category is discussed in turn below. Details on the results of each impact can be found in Appendix 1.

4.1. Abiotic depletion potential (ADP)

As presented in Fig. 4a, within this impact category, the largest contribution comes from the raw material supply stage for the base case and all the scenarios. The raw material supply stage includes the extraction and processing of ceramic tile raw materials such as clay, feldspar, and kaolin.

Fig. 4a shows that the depletion of elements in Scenario A and Scenario B is nearly the same as the base case, about 55.0 mg Sb eq. per 1 m^2 of glazed ceramic tile production. This is due to the only changes in energy consumption in these scenarios. However, the decrease in the raw materials used (Scenario C and Scenario D) means a decrease in ADP. The lowest ADP value is observed for Scenario D and a 9% reduction is obtained compared to the base case.

4.2. Abiotic depletion potential (ADP fossil)

For all cases, the main contribution to this category of the effect comes from the stage of production (64% for Scenario C - 75% for the base case) mainly due to the firing process (see Fig. 5b). Burdens from the raw material supply stage (up to 24% for Scenario C) are the second largest contributor to this impact.

As shown in Fig. 4b, all the scenarios have a lower ADP fossil than the base case. This is primarily due to a reduction in thermal energy demand or an improvement in the energy efficiency of the scenarios. The lowest ADP fossil value is observed for Scenario D and a 21% reduction is obtained with this scenario compared to the base case. Ceramic tiles with reduced thickness allow the reduction of natural gas consumption in the drying and firing stages. The total ADP fossil of the ceramic tile with reduced thickness (Scenario C) is 201 MJ/m^2.

4.3. Acidification potential (AP)

This impact is due to the emissions of sulphur dioxide and nitrogen oxides to air from the production stage which contributes between 57% for Scenario C and 59% for the base case to the total, see Fig. 4c. Raw material supply and raw material transportation stages are also high impacts on the total AP.

This impact is 47.4 g SO_2 eq. per m^2 of glazed ceramic tile production for the base case. Fig. 4c presents that replacing the current production with any of those considered in the scenarios would lead to a reduction in the AP per m^2 ceramic tile produced. The estimates for the AP from Scenario A and Scenario B are 46.4 and 46.9 g SO_2 eq. per m^2 ceramic tile, respectively. For the best case, Scenario D, this impact is nearly 12% lower than the base case.

4.4. Eutrophication potential (EP)

Fig. 4d reveals that the main source of this category is the ceramic tiles production stage contributing up to 63% to the total EP due to high energy consumption, mainly natural gas. The next major contributors to this EP are raw material supply and transport of raw materials.

As shown in Fig. 4d, this impact of the base case is estimated at around 20.5 g phosphate eq./m^2 glazed ceramic tile. The total EP of Scenario A and Scenario B is almost the same. Scenario D is the best scenario, mainly due to the best possible improvements in the production of ceramic tiles. The combination of reduction of raw materials, use of heat recovery system, and energy efficiency for the firing stage offer the potential to save up to 10% of the total EP.

4.5. Freshwater aquatic ecotoxicity potential (FAETP)

The largest contributor is again the ceramic tile manufacturing step which contributes up to 59% to the total of this impact mainly from firing, mixing, and pressing stages for the base case and all the scenarios (Fig. 4e and Fig. 5e).

The total FAETP of the base case is 3.8 kg DCB eq./m^2 ceramic tile. As indicated in Fig. 4e, Scenarios A and Scenario B, energy-saving scenarios, are nearly the same as the base scenario. A decrease in phosphate eq. emissions can be observed for Scenario C and Scenario D mainly due to lower raw materials and energy consumption. For Scenario D, this impact is nearly 9% lower than the base case.

4.6. Global warming potential (GWP)

For all cases, this impact is largely due to the impacts of the glazed ceramic tile production stage (63-74%), see Fig. 4f. This stage is a significant emitter of greenhouse gases, especially CO_2. The CO_2 emissions account for more than 90% of the total of this impact.

The total GWP of the base case is estimated at 14.4 kg CO_2 eq. per m^2 glazed tile. All the scenarios perform well for GWP when compared to the base case. This is associated with a decrease in the energy consumption of scenarios due to the improvements of the ceramic tile production process related to the heat recovery unit usage, efficient firing, and thickness reduction. Scenario B has the highest GWP among the scenarios considered (see Fig. 4f). However, this is still nearly 3% lower per m^2 produced ceramic tile than from the base case. The best option is Scenario D with a 21% lower impact than at present.

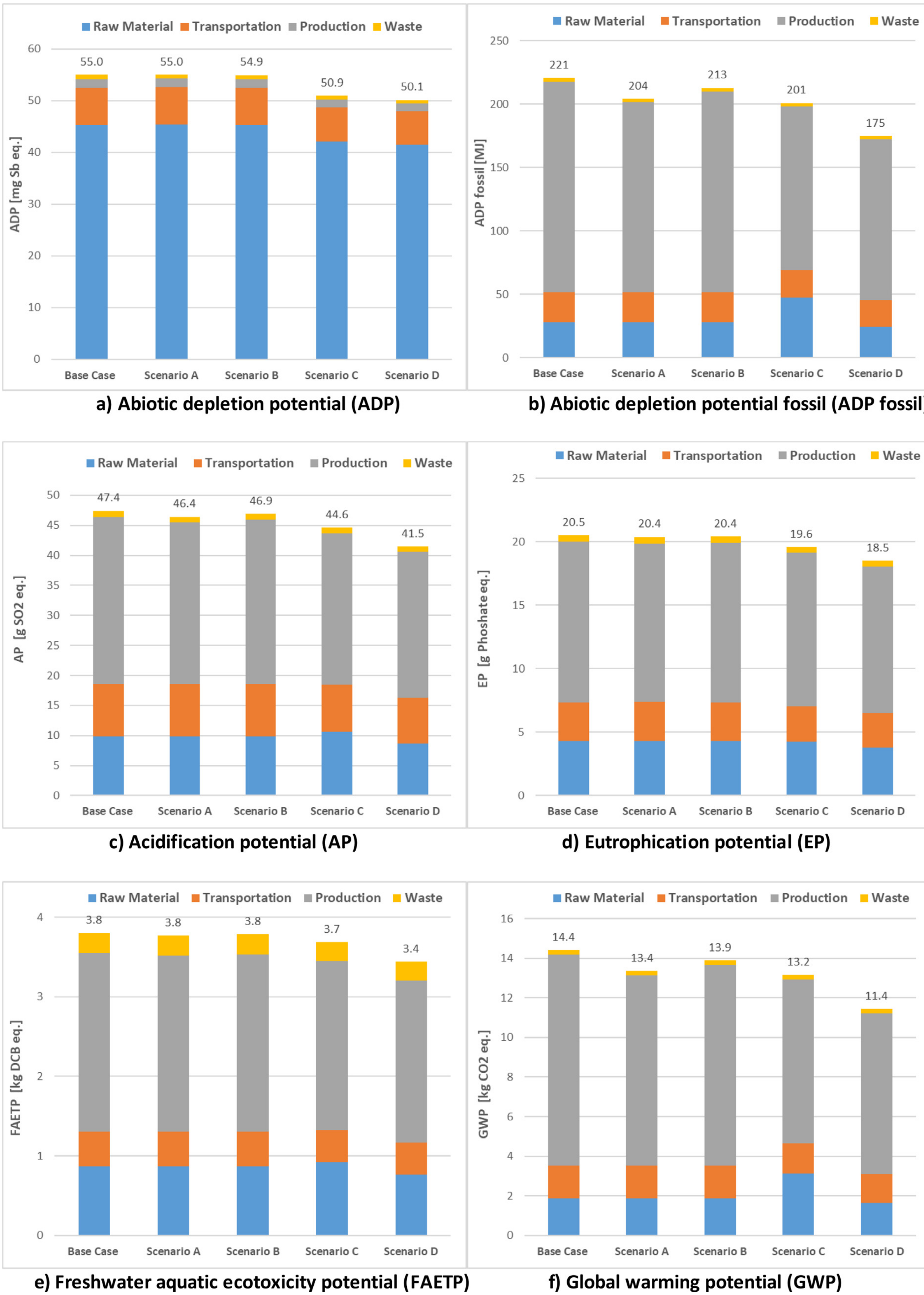
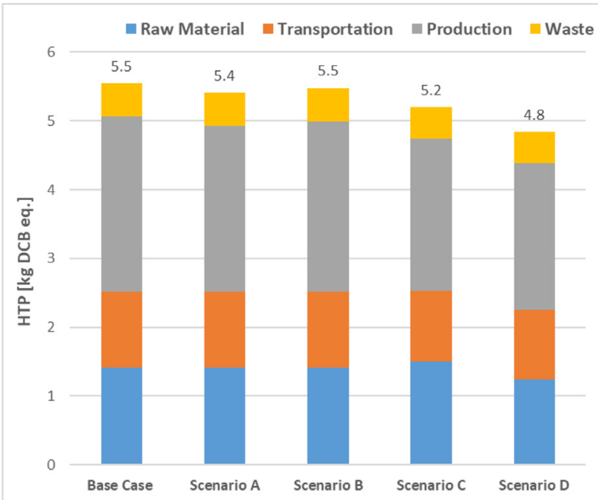
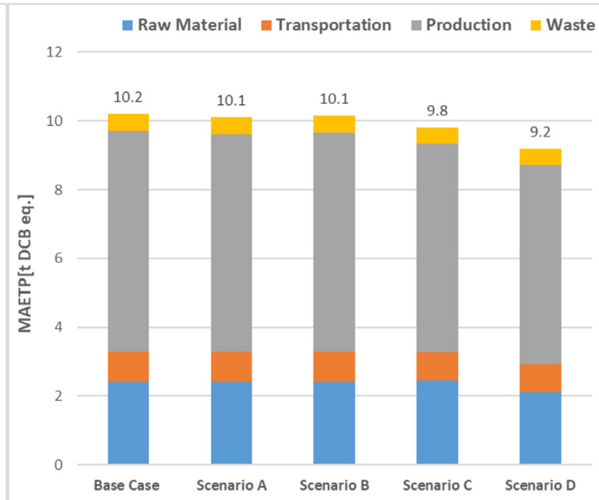


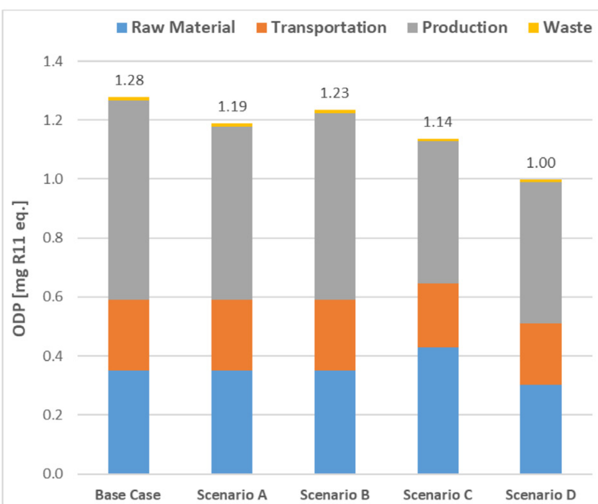
Fig. 4. Contribution of life cycle stages to the total environmental impacts of each scenario
[1 m^2 of ceramic tiles. Scenario A: Energy recovery, Scenario B: Energy-saving combustion, Scenario C: Reduction of the thickness, Scenario D: Combination]



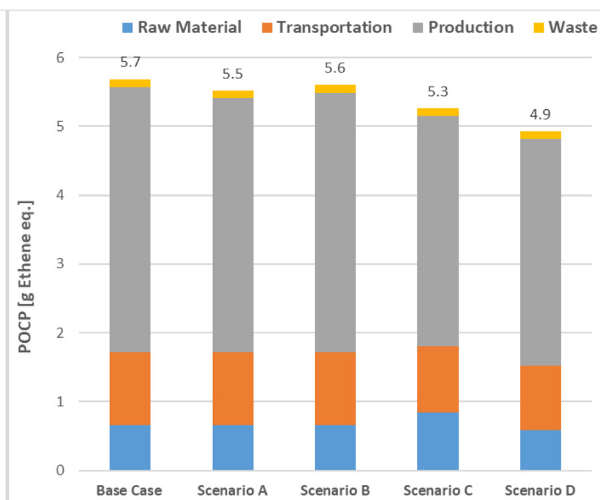
g) Human toxicity potential (HTP)



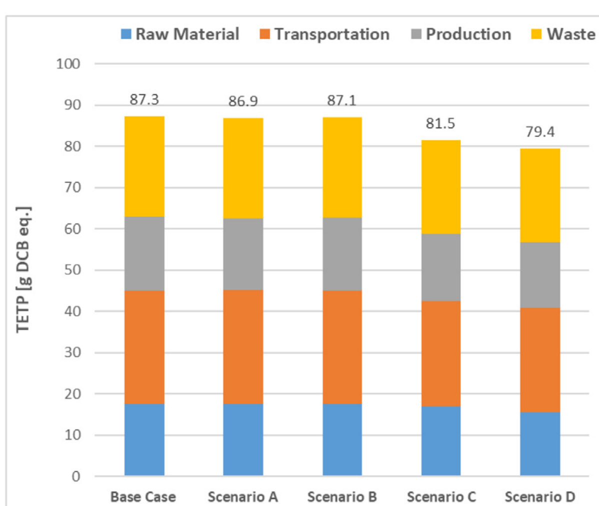
h) *Marine aquatic ecotoxicity potential (MAETP)*



i) Ozone layer depletion potential (ODP)



j) Photochemical oxidant creation potential (POCP)



k) Terrestrial ecotoxicity potential (TETP)

Fig. 4. Continued

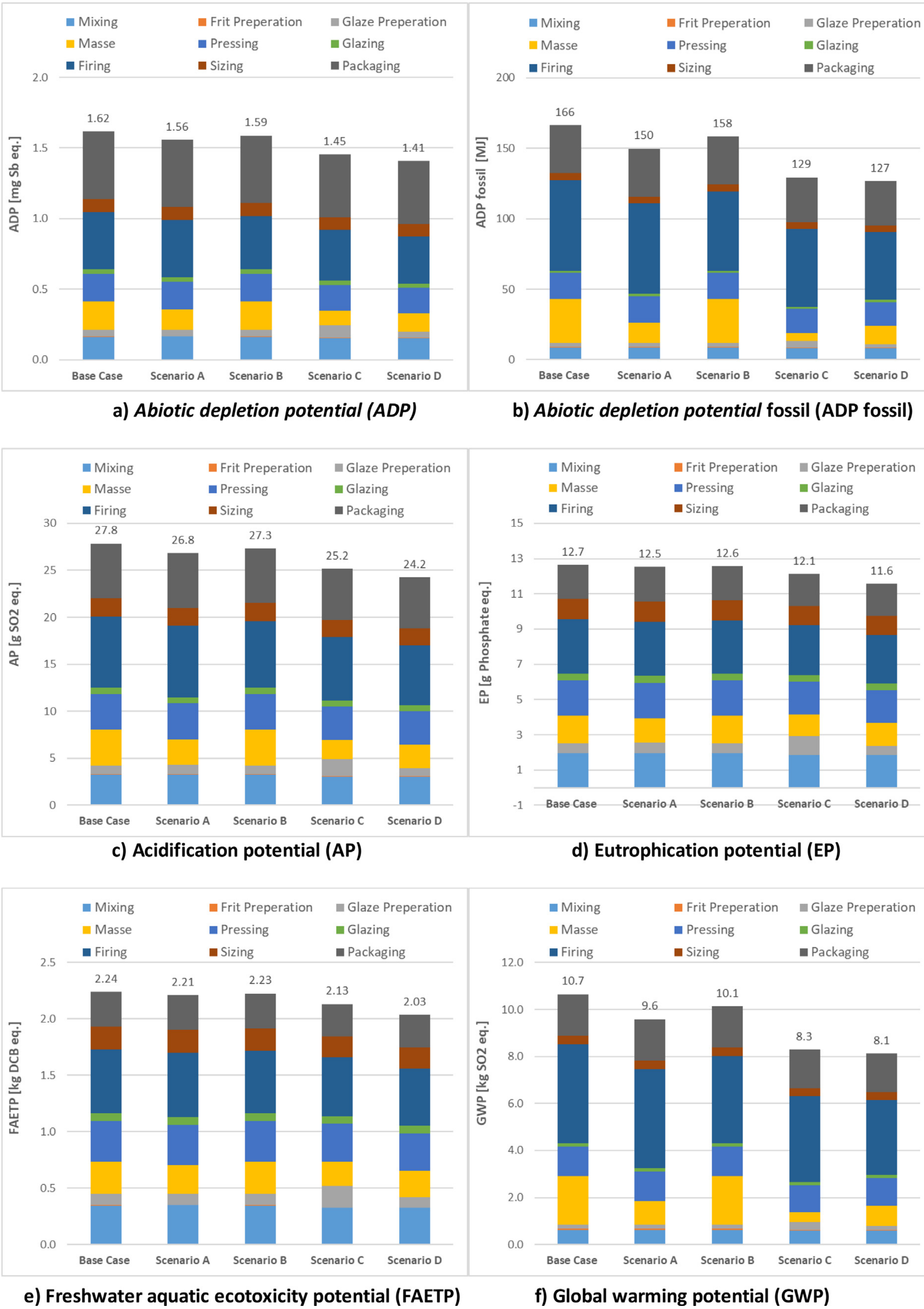
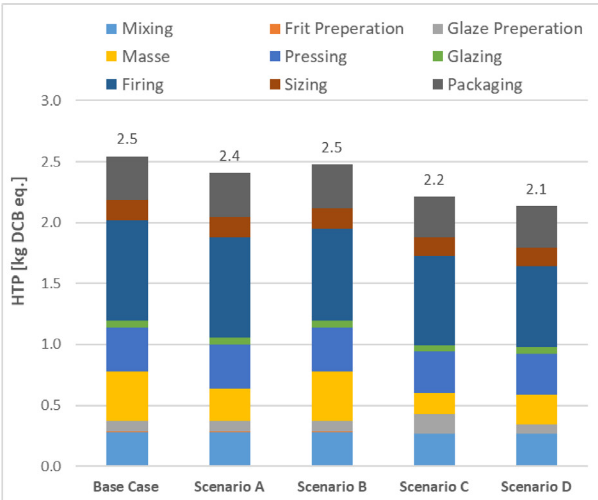
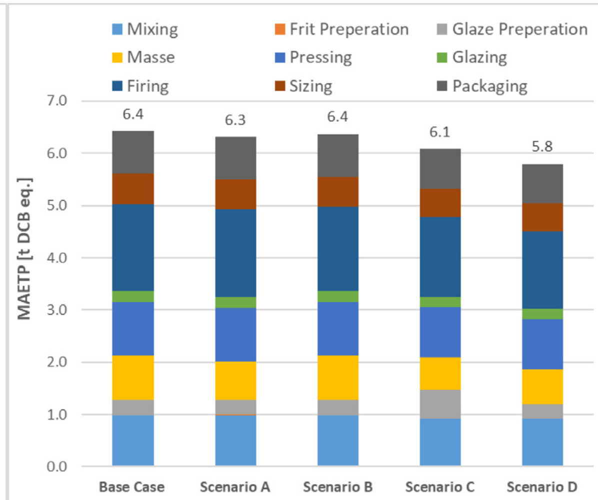


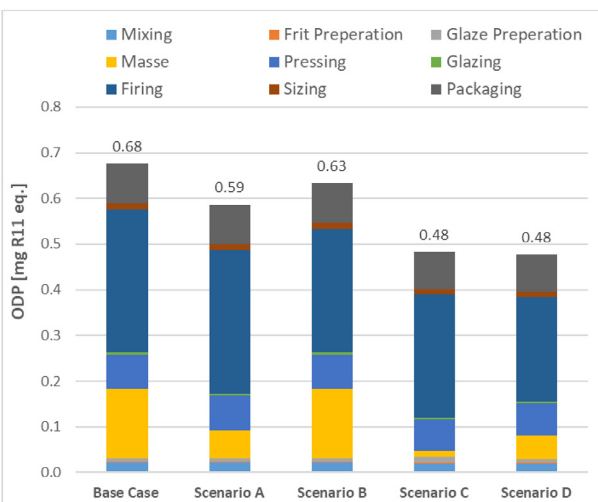
Fig. 5. Contribution of production stages to the environmental impacts from the production [1 m^2 of ceramic tiles. Scenario A: Energy recovery, Scenario B: Energy-saving combustion, Scenario C: Reduction of the thickness, Scenario D: Combination].



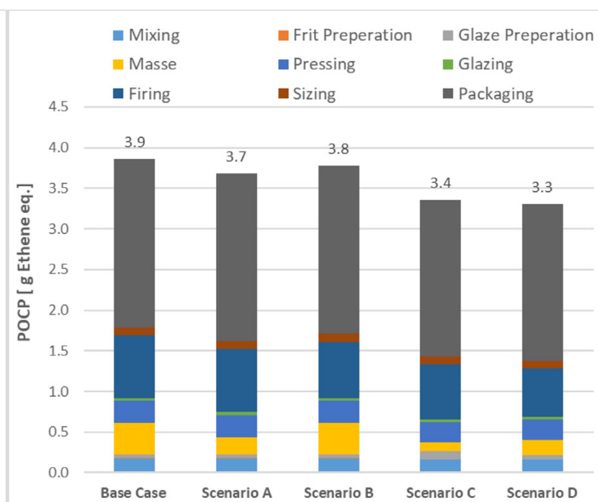
g) Human toxicity potential (HTP)



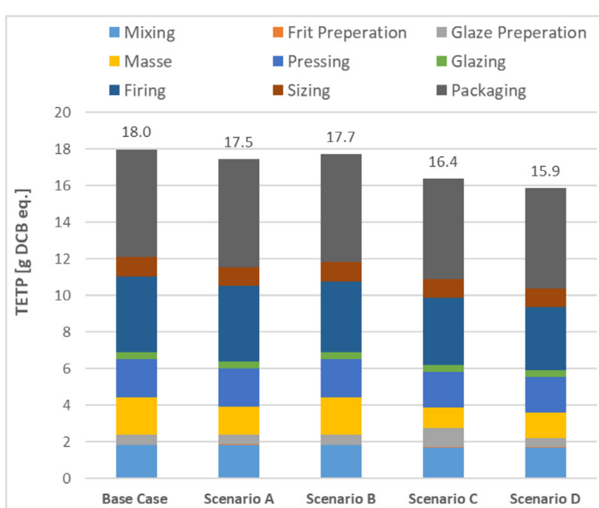
h) Marine aquatic ecotoxicity potential (MAETP)



i) Ozone layer depletion potential (ODP)



j) Photochemical oxidant creation potential (POCP)



k) Terrestrial ecotoxicity potential (TETP)

Fig. 5. Continued

4.7. Human toxicity potential (HTP)

Over 43% of this impact comes from the manufacturing process of ceramic tiles for all the cases. As presented in Fig. 4g, the other key contributors to this impact are raw material supply and transport of raw materials.

As shown in Fig. 4g, this impact of the base case is measured at 5.5 kg DCB eq. per m^2 glazed ceramic tile. The total HTP of the scenario includes a heat recovery unit (Scenario A) and the scenario related to the efficient firing (Scenario B) is almost the same. Scenario D is the best scenario, mainly due to the combination of all possible improvements in the production of ceramic tiles. The total EP from this scenario is 13% lower than at present.

4.8. Marine aquatic ecotoxicity potential (MAETP)

For all cases, the main contribution to the total MAETP comes from the ceramic tile production stage (around 63%) mainly due to the firing, pressing, and raw material mixture stages, see Fig. 4h and Fig. 5h. Burdens from the raw material supply stage (up to 25%) due to the emissions from raw material extraction and processing are the other biggest contributors to this impact.

As with the other toxicity categories, this impact of Scenarios A and B are almost the same as the base case. As shown in Fig. 4h, the total MAETP of the base case is equal to 10.2 t DCB eq./m^2 ceramic tile. On the other hand, this impact from Scenario C and Scenario D is nearly 4% and 10% lower than the base case, respectively. This is mainly due to the decrease in the energy and raw materials needed to manufacture per m^2 ceramic tile.

4.9. Ozone layer depletion potential (ODP)

The key contributors to the total ODP are the release of non-methane volatile organic compounds (NMVOC) to air primarily from the ceramic tile production stage (up to 53%) for all the cases (Fig. 4i) due to the natural gas consumption for thermal energy generation.

Ceramic tile production has an ODP of 1.3 mg CFC-11 eq. per m^2 ceramic tile. All scenarios have a lower ODP per m^2 ceramic tile than the base case, with the reductions ranging between 4% (Scenario B) and 22% (Scenario D).

4.10. Photochemical oxidant creation potential (POCP)

Fig. 4j shows the majority of this impact is from the production stage (64% for Scenario C-68% for the base case) due to the emissions of sulphur dioxide, nitrogen oxides, carbon monoxide, and methane which are produced during the firing, and spray drying (masse), and pressing steps.

In the base case, the total POCP amounts to 5.7 g ethane eq./m^2 ceramic tile. The lowest POCP value is observed for Scenario D and a 13% reduction is obtained compared to the base case. The reduction is mostly due to the reduction of the energy and raw materials required to produce 1 m^2 ceramic tiles.

4.11. Terrestrial ecotoxicity potential (TETP)

Different from the other environmental impacts, the major contribution to the total TETP comes from the raw material transportation step (around 31%) for the base case and all the scenarios (see Fig. 4j). The waste treatment (up to 28%) stage is the second major contributor to this impact.

The lowest TETP value observed is 79.4 g DCB per m^2 ceramic tile for Scenario D and a 9% reduction is obtained compared to the base case. This reduction is mainly due to lower raw materials and energy consumption.

4.12. Comparison with previous studies

It is difficult to compare the results of this study with previous studies because of some limitations. One of these limitations is that some studies explain the results as a relative percentage. The other is the use of different impact assessment methods in the studies. However, the results of the studies that used CML 2001 (Guinee, 2002) as an impact assessment method were examined and compared with the findings of this study. Also, a comparison has been made by taking into account the studies examining similar scenarios.

The results estimated in this study are compared to similar studies in the literature. Based on the obtained results for the ceramic tile production step, for the environmental impact categories of EP, AP, GWP, ODP, and HTP, drying and firing stages are the major hotspots. It should also be noted that Ros-Dosdá et al. (2018), Ibáñez-Forés et al. (2013), and Bovea et al. (2010) also found that these stages are the most significant for these environmental impact categories. The results from the scenarios show that improvement actions can be suggested to reduce the environmental effect of the hotspots found. Such as reducing fuel consumption in the firing process by recovering the waste heat from the firing stage and reusing it in pre-dryers could reduce AP, EP, GWP, and ODP by 11.8%, 2.1%, 4.2%, and 4.3%, respectively as indicated in the study by Bovea et al. (2010).

5. Conclusions

In this study, the environmental impacts of ceramic tile production were evaluated with a life cycle approach comparatively with four scenarios. All the scenarios considered in this paper were driven by the manufacturer's strategies for the future to improve environmental sustainability.

The results revealed that the scenario which combines heat recovery from the furnace, energy-saving combustion, and tile thickness reduction, is the most environmentally friendly option among the four scenarios considered. Application of this scenario leads to 22.0% and 21.0% savings in ODP and both GWP and ADP fossil, respectively, while savings in FAETP, EP, TETP, and ADP are less than 10.0%. These results confirm the importance of the reduction in energy consumption on the environmental effects of ceramic tile production. While total GHG emissions of Turkey are expected to grow steadily to about 1.2 billion tonnes of CO_2 eq. by 2030, the Mitigation Scenario is expected to result in an 18.4% (216 Mt) reduction. This study will assist in achieving this goal. Moreover, it will also serve as a guide in reducing environmental impacts from the industry, especially greenhouse gases.

For all cases, the ceramic tiles production stage is the main hotspot for nine out of eleven environmental impact categories. The results reveal that in terms of production stages, firing, pressing and forming, and spray-drying processes are the major environmental impact sources. Considering impact categories in the production stage, the highest impacts were determined for ADP fossil, AP, EP, MAETP, HTP, GWP, FAETP, ODP, and HTP due to the production and consumption of natural gas. For ADP, raw material supply is the biggest contributor (up to 82.9%) while for TETP, most of the impact is from raw material transportation (up to 31.9%). This research will be used to assess the environmental impacts of ceramic tiles in Turkey's ceramic tile manufacturing industry. Ceramic tile manufacturers can use hotspots and related improvement suggestions to make strategic decisions.

Overall, cleaner production technologies are critical for the ceramic industry's sustainability. Although the scenarios studied in this study have the potential to improve the environmental performance of ceramic tiles production, there are many other cleaner ceramic production options available including new ceramic body and glaze compositions, different production techniques such as dry production, and the low-temperature fast-firing system that aren't considered in this study. In order to achieve the best energy savings and emission reduction, cleaner production technology should be assessed and chosen based on the facility's requirements.

Finally, future research should extend the system boundaries of the LCA study including distribution, usage, and end of life stages. Researchers might focus on the comparison of the environmental impacts arising from different sized plants. Furthermore, the environmental sustainability of ceramic manufacturing should be integrated with economic costs and social impacts for the more sustainable construction sector.

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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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.spc.2021.05.007.

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