Master Thesis

Life Cycle Assessment of Ceramic Tiles: Improving Environmental Performance of a Factory located in Castellón de la Plana.

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Abstract: The ceramic tile sector is one of the key sectors of the Spanish economy and Industry due to its economic and social contribution**.** This is an energy-intensive sector, that had in 2021 a natural gas consumption of 50% of the total in the Valencian region and 7% of the total in Spain, which is why this sector has increased its focus on lowering greenhouse gas emissions. The Ceramics Cluster in the province of Castellón de la Plana is one of the most important not only in Europe, but in the world, having 93% of total Spanish exports**.** The aim of this study is to analyze and communicate the environmental impacts of the manufacturing process of a ceramic tile factory located in Castellón de la Plana. An LCA for the production process, which includes from the extraction of raw materials and transportation to the production of the packaged tile, was carried out to identify the main hotspots and propose improvements for two types of ceramic tiles produced in the factory. The results showed that the firing stage generates the most environmental impacts. Environmental impacts of two improvement proposals were evaluated, replacing natural gas for biomethane, and reducing the thickness of the ceramic tiles. The results revealed that

Keywords: Ceramic Tiles; Life Cycle Assessment; Sustainability; Environmental Impacts

1. Introduction

Ceramic tiles are decorative building materials which are shaped into plates or blocks and are utilized as covering for the walls and floors of buildings or structures. The great variety of ceramic products that currently exists on the market is conditioned by its application, since there are different uses for this material in interior decoration and architecture. Ceramic tiles have a high durability and performance, and this sector continues to develop new techniques in order to reduce environmental impacts and costs (1). The Spanish industry within the world ceramic sector is a leader in terms of technological development, quality of service, and design. Spain is a long way from the rest of the tile-producing countries within the European Union. Spanish ceramic products have a presence in nearly 190 countries. There is a high concentration of industries in the ceramic sector in the province of Castellón, where 80% of the companies from this sector are located, and approximately 94% of national production originates in this province (2)

In 2021, Spain had a production of 587 million m2 and a total turnover of 4,855 million euros, 26% higher than the previous year. Of the total sales, more than 75% are exports, reaching a record figure last year of 3.655 million euros. Meanwhile, the domestic market reached a figure of 1,189 million euros. Spain is the largest producer in the European Union and the fifth largest producer worldwide behind countries such as China, Brazil, Vietnam and India. Spain is also the second largest exporter in Europe and the second largest worldwide.

The ceramic sector is an energy-intensive sector, according to ASCER, the consumption of natural gas in the ceramics sector was 14.1 TWh, which is equivalent to 50% of the total gas consumption in the Valencian Region, and 7% of the industrial gas consumption in Spain. Ascer has also pointed out that the ceramic sector is at making strong efforts to reduce energy consumption, in 2021, energy consumption has been reduced by improving energy efficiency per m2 manufactured by around 6% in gas and 8% in electricity. (3)

The company analyzed is a small factory with an annual production of 20,000 m2 per month, it has a total of 95 employees, of which 65 are production employees.

This factory had a total production of 2,306,460 m2 in 2021, and is aiming to increase that total production to 2.7 million m2 in 2022. Increasing production under the current operation of the factory will require a greater consumption of raw materials, electricity, natural gas, and water, which will lead to greater environmental impact and costs. A Life cycle assessment was carried out to determine the main hotspots of the process and propose improvements that can help this factory lower their emissions. The factory produces two types of ceramic tiles, porcelain stoneware, which amounts 83% of the total production and white paste stoneware, amounts 17% of the total production, these two types of ceramic tiles will be analyzed and compared. The first and principal type of tile is made of porcelain stoneware. Porcelain have an exceptional strength and endurance. A mixture of sandy clay is fired in a tunnel kiln with high temperatures between 1200-1400 °C until a nonporous vitrified layer and impermeability are achieved. It is suitable for floor coverings due to its shape and physical properties. Low porosity gives the tiles better technical characteristics (4) The company also produces white paste stoneware ceramic tiles, this material is used for large formats due to its strength, which also allows it to be used for interior and exterior decoration. White body is mainly chosen for large-format products and the glaze applied to the tile adheres better to white body tile (4).

Ceramic glazes are mixtures of different minerals and compounds, which are applied on the surface of the tile and compounds, which are applied to the tile surface, and then melted to form a vitreous coating. The key component is silica, which is the most important substance for the hardening of the glass, to which are added elements such as alkaline, aluminum, lead or zinc, in order to maintain the firing temperature of the glaze at acceptable levels.

Frits are vitreous compounds prepared by melting, and then cooling in water different selected raw materials. The aim of this stage, is to obtain, ready-to-use glazes in the form of a fine-particle-aqueous suspension. Glazing consists of applying this glaze and decorations to the surface of formed and dried tiles (5). The tiles are fired in a tunnel kiln, which is considered as the most suitable kiln for mass production because it enables continues firing, and brings quality improvements in the product (6). The factory uses a waste heat recovery system, in which heat is recovered in the furnaces to preheat the air in the dryers. In the last exit section of the kiln, the air is cooled with outside air in countercurrent. This air leaves this section at approximately 400°C and is divided into two streams, one part as combustion air for the kiln burners, and another part that transfers heat to a thermal circuit. In the first section of the furnace, the combustion gases exit at about 1200°C and give heat back to the thermal oil circuit. The thermal oil then passes through another heat exchanger and gives up heat to the combustion air from the dryers. It then goes to a tank, variable flow pump and returns to the recovery exchangers. This system allows the factory to improve its energy efficiency and to reduce operating costs, energy consumption and emissions (8).

Biofuels in the Ceramics Industry

The European Ceramic Industry indicates that substituting natural gas with syngas or biogas from waste, is the most effective way to mitigate fuel emissions for high-temperature processes. Biogas is a more suitable option than other options such as electrification because of the high temperatures required for the firing process (9). Bioenergy is considered as the only renewable energy that is capable of acting on the carbon cycle, because it is capable of capturing the methane generated by livestock and wastes, the economy of digestate and organic fertilizers is able to increase the amount of carbon sequestered in soils, the production of such renewable carbon will not aggravate CO2 emissions from the primary sector, costs will be as low as possible and it also has a lot of positive externalities. Bioenergy has the potential to cover the thermal demand that cannot be covered by electrification (10). The most suitable biofuel for the ceramic industry is biomethane because it does not involve any adjustment for the ceramic process. Biomethane is a renewable gas that can be obtained from biogas. It has a similar composition to natural gas, but with a better quality. Biomethane can be used as natural gas or liquefied natural gas as a fuel. The objective of upgrading biogas into biomethane is to separate CH4 from CO2 and other different compounds to enhance the calorific value of the gas, this makes the gas suitable for it to be injected into the gas grid, and also it reduces the NOx emissions. For biogas to be transformed into biomethane, it must undergo a process called upgrading, which is the purification and enrichment process, where different impurities such as CO2 are eliminated. Biogas reaches an average methane purity of close to 95%. During the process, CO2 is separated from H2O, H2, N2, O2 and H2S increasing the proportion of methane (11)

Hydrogen and the Ceramics Industry

Hydrogen is an alternative for the decarbonization of hard-to-abate industries like the Ceramics Industry and can be used in different formats or transported via an H2 carrier. It can be used in many ways such as:

- Gas: H2 can be burned for power generation as a substitute for natural gas or for use in fuel cells.
- Liquid: H2 is mainly used for H2 transport
- E-fuels: H2 is used for light and heavy-duty road vehicles, marine and aviation fuels.
- Ammonia: Possible use as a marine fuel or as a heat source replacing natural gas
- Methanol: Potential use in transport or multiple chemical applications

As mentioned above, Hydrogen can be used in different formats, but it has significant barriers as it is a technology that is still under development. Hydrogen is a highly volatile gas, which makes storage and transportation a costly and challenging task, and because of its low density, it has to be liquefied or pressurized. It also has a high current cost due to limited efficiency, dependence on renewable energy generation and high CAPEX (12).

The deployment of Renewable Hydrogen as a decarbonization lever for multiple applications requires additional investments such as:

- Modification of industrial boilers to adapt to the thermal properties of hydrogen, which are different from natural gas.
- Investment in infrastructure to adapt the natural gas transmission and distribution network to make it compatible with hydrogen.
- Adaptation of internal combustion engines for use with hydrogen or its derivatives.

Main Environmental Aspects of Ceramic Tile and Glaze Manufacturing

Raw Material Consumption

They are usually used as they are extracted or after being subjected to a simple physical treatment. The mixing of raw materials necessary for the manufacture of ceramic tiles is very important in order to be able to mold them correctly, and also give the piece the enough raw strength to be processed (13)

Energy Consumption

Mostly due to the preparation of raw materials for the support, drying and firing. Also due to the drying process and in the glaze manufacture. A large amount of thermal energy is required for the manufacture of ceramic tiles. The most commonly used fuel today for the production process is natural gas. Electricity is used in most of the manufacturing process. Its consumption is much lower than the thermal energy consumption. The ceramic sector is considered energy-intensive because the energy consumed in produced ceramic tiles is approximately 30% of the total production cost (9)

Water Consumption

Water is one of the main raw materials for the ceramic industry, it is very important for different parts of the manufacturing process. Water is used in the preparation of raw materials, preparation of glazes and in the cleaning of the equipment and installations in general.

Emissions of particle and gaseous compounds

The emission of particles is considered one of the most significant environmental aspects of the process, since it is an activity that uses many materials that generate a lot of dust. Gaseous emissions are generated in the parts of the process where there are high temperatures, or where combustion processes are used. Emissions from the ceramics industry depend on two factors, combustion processes and chemical transformation of raw materials.

Wastewater

This water is mainly generated in the cleaning of facilities, equipment and machining processes. The content of these waters is mainly minerals, and inorganic materials, but also include small amounts of organic materials and heavy metals.

Waste generated during process

Broken pieces generated before and after firing, adsorption agents used, material collected by the purification systems, and different types of sludge.

Non-Ceramic Waste

Most of this waste is generated in the maintenance of the machinery used, such as oil, paper, metal or plastic containers, cardboard, wood, scrap metal, etc.

Key Parameters for Environmental Impacts

- **Thickness**

This parameter affects the quantity of raw materials processed, inputs and outputs of raw material preparation, thermal energy, particles, gaseous emissions, ceramic waste, load transported.

- **Glaze**

This parameter affects the fabrication and transport, water consumption, wastewater generated, particles emissions.

- **Mechanical Treatments**

This parameter affects the electricity consumption, water consumption, waste generated and wastewater generated.

Different LCA studies of ceramic tiles have been published, for this study those LCAs have been consulted and compared in order to carry out this study in the best possible way by comparing the processes of a factory in the same area, as well as others in different countries. (Atilgan Turkmen et al., 2021) developed a Life Cycle Assessment on ceramic tiles with four improvement scenarios, combining heat recovery from the furnace, energy saving combustion and tile thickness reduction, and a combination of the three scenarios previously mentioned, which showed significant improvements in the environmental performance of the process analyzed. (Bovea et al., 2010) performed an LCA with an improvement proposal introducing a gas-air heat exchanger in which exhaust gases from the kilns to pre-dry the ceramic tiles were used, a bag filter with an absorber that reduced hydrogen fluoride emissions. Wang et al, (2020), made a comparison between different fuel scenarios and milling processes. In all previously mentioned studies, it has been concluded that energy consumption and emissions from fuel combustion are the most critical point in the ceramic tile production process.

2. Objectives

The aim of this study, is to find the main hotspots of a cradle-to-gate Life Cycle Analysis of a ceramic tile factory in Castellón de la Plana, in order to develop proposals for possible improvements, considering the SDGs and current drivers and trends in the ceramic sector. In order to be able to achieve this goal, the following actions were carried out during a period of 7 months:

- Research and investigation about the ceramic tile production process.
- A visit to the factory was made in December to learn about the company and their manufacturing process.
- Obtained first-hand data weekly from the factory.
- A Life Cycle Assessment was conducted using SimaPro with data obtained from the factory.
- Improvement proposals were developed considering current trends and drivers from the ceramic sector

4. Methodology

The manufacture of ceramic tiles generates different environmental impacts throughout their entire life cycle. Life Cycle Assessment is the most accepted methodology to identify, quantify and characterize the different potential environmental impacts associated with each of the stages of the life cycle of a product or service. By defining the life cycle processes and identifying the most significant input and output flows, it is possible to analyze the environmental impacts and propose improvements to optimize the entire product or process. This study applies the LCA methodology following the ISO 14040/14044 standards. The tool used to conduct the Life Cycle Assessment was SimaPro 9.3.0.3. which is a science-based tool designed to perform LCAs. SimaPro is an analytical software used to measure the environmental footprint of different products and services with a high level of transparency. It is used by hundreds of organizations worldwide. SimaPro has been built and improved for a long time by LCA leaders who have been working in major public policy developments (14) Ecoinvent data base was used and the environmental impact assessment method selected was the CML-IA Baseline method. The Ecoinvent Database is a Life Cycle Inventory database that supports various types of sustainability assessments. This Database allows users to gain a deeper understanding of the environmental impacts of their products and services (15).

4.1. Goal and Scope definition

This study aims to identify the main hot-spots across the manufacturing process of glazed ceramic tiles by quantifying the life cycle environmental impacts across the process to identify opportunities for improvement. The functional unit considered is the production of 1 m^2 of glazed ceramic tile for wall and floor coverings made of porcelain stoneware and white paste stoneware. Porcelain stoneware ceramic tiles have a thickness of 10.5 mm and a density of 22.5 kg/m^2, and white paste stoneware ceramic tiles have a thickness of 10 mm and a density of 18.7 kg/m^2. The scope of the study is from cradle to gate. As shown in Figure 1, the system boundaries include the following life cycle stages: the extraction of raw materials, transportation, and the manufacturing process of glazed ceramic tiles. The production stages that were considered in this study are the following: atomized, pressing, drying, glazed preparation, glazing, firing, cutting and classification and packaging, the electricity and water consumption of the office was also considered in this study, while the impacts of the factory construction, production of industrial equipment and machinery, the diffuse emissions of particles into the atmosphere generated during the transformation and storage of raw materials and the process of recycling and reusing the waste generated throughout the life cycle of ceramic tiles are not included in the system boundary due to lack of data.

4.1.1. Description of the process of manufacturing ceramic tiles.

The first stage is the atomization of the clays, the objective of this stage is to obtain a powder with the particle size and humidity required for the production of ceramic tiles, the next step is the receipt of the atomized clay, this clay is loaded into silos the then go to the pressing process, where the material is shaped by hydraulic presses that compress the atomized material in shaped molds. Once is already shaped, it goes to the drying process to reduce the moisture content low enough for the glazing and firing phases. In the glazing process, glaze is prepared and then applied to the dry product to decorate the pieces before they are fired. This will make the purpose surface of the clay waterproof and will give it better chemical and mechanical properties. The firing process is responsible for giving the pieces their main mechanical properties increasing its hardness and resistance by eliminating the moisture taken up during the glazing process. This process consists of an increase in the temperature of the pieces, through a large line oven, bringing the material to high temperatures to subsequently cool it down gradually. Then, the cutting and machining process constitutes a post-treatment stage of the pieces, where at the end of the main process, a cutting and machining of the edges and surfaces will be carried out, suitable for the needs of each of the formats. The last process considered is packaging, in this process the tiles are sorted and divided into categories to be ready for packaging and storage, which is a process made by robots that place the tiles on pallets for them to be deposited later until they are delivered to customers (16).

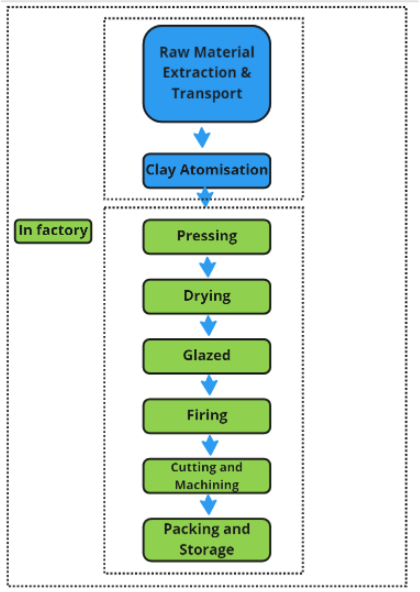


Figure 1. Cradle-to-Gate Flow Chart of Ceramic Tiles. (17)

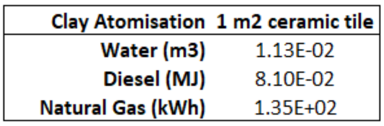
4.2. Life Cycle Inventory

The primary data related to the production of glazed ceramic tile, including the water consumption, energy consumption, raw materials were directly obtained from the factory. Water consumption was taken into account in the complete process, not in different stages. Table 1 includes real data obtained directly from the factory, for every stage included in the study.

Inputs	Raw Material Extraction and Transport	Pressing	Drying	Glazed	Firing	Cutting and Machining	Packing and Storage	Compressor /Vacuum Cleaner	Total
Clay (kg)	11.25								11.25
Carbonato Cálcico (kg)	1.35								1.35
Bentonite (kg)	0.45								0.45
Sodium Silicate (kg)	0.45								0.45
Feldspar (kg)	9.45								9.45
Glaze (kg)				1					1
Packing (kg)							1.24		1.24
Electricity (kWh)		0.93	0.21	0.42	0.42	1.26	0.42	0.50	4.16
Natural Gas (kWh)			3.32		18.78				22.10
Water (m3)									0.009

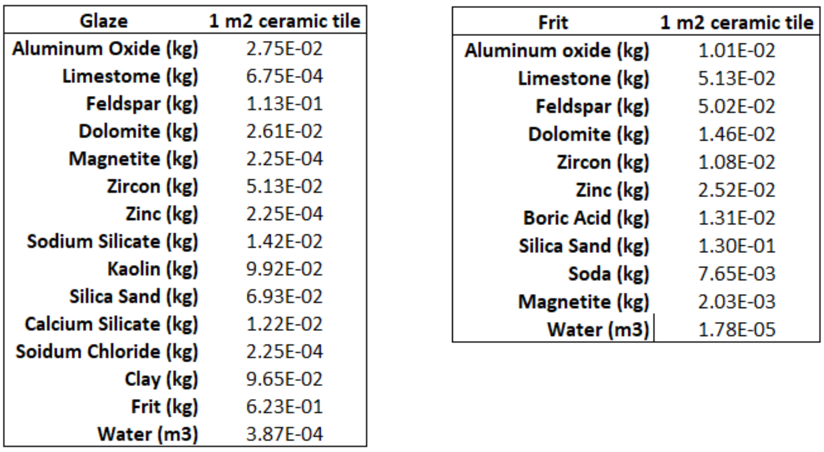
Table 1. LCI data for Ceramic Tile Production (F.U. 1m^2)

The extraction of raw materials, transport, clay atomization, and raw materials used for glaze were obtained from different sources from the same area due to lack of data. The clay is brought in to the factory from different countries such as Ukraine, Turkey, France and England, but the transport distances from raw materials were included in the Ecoinvent processes used. Materials who were used in very small amounts and were not significant for the results in the study were excluded from the life cycle inventory. Data obtained from different sources had to be referred to the functional unit considered in this study, i.e., the functional unit for the glaze LCI was 1 m^2 but from a ceramic tile that has a lower density than the density used for the software modelling. The LCI data had to be adapted to a density of 22.5 kg/m^2 and 18.7 kg/m^2 by applying a rule of three with the density of the ceramic tile from the data obtained from different sources, such as "Improving the sustainability of ceramic tile production in Turkey. Sustainable Production and Consumption" by (Atılgan Türkmen et al., 2021) for the glaze and frit raw materials, and "Environmental performance of ceramic tiles: Improvement proposals" by (Bovea et al., 2010), in order to make the calculations more accurate.



Clay Atomisation	1 m2 ceramic tile
Water (m3)	1.13E-02
Diesel (MJ)	8.10E-02
Natural Gas (kWh)	1.35E+02

Table 2. LCI data for Clay Atomisation (F.U. 1 m2) **(16)**



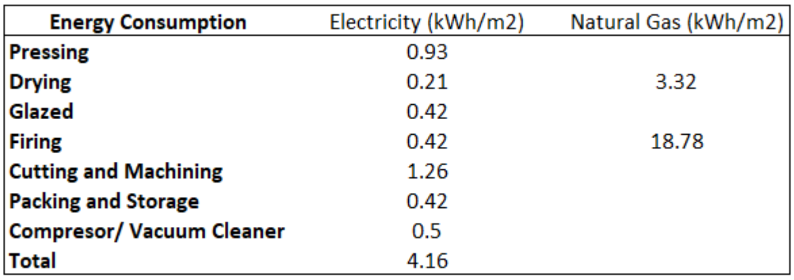
Glaze	1 m2 ceramic tile
Aluminum Oxide (kg)	2.75E-02
Limestone (kg)	6.75E-04
Feldspar (kg)	1.13E-01
Dolomite (kg)	2.61E-02
Magnetite (kg)	2.25E-04
Zircon (kg)	5.13E-02
Zinc (kg)	2.25E-04
Sodium Silicate (kg)	1.42E-02
Kaolin (kg)	9.92E-02
Silica Sand (kg)	6.93E-02
Calcium Silicate (kg)	1.22E-02
Soidum Chloride (kg)	2.25E-04
Clay (kg)	9.65E-02
Frit (kg)	6.23E-01
Water (m3)	3.87E-04

Frit	1 m2 ceramic tile
Aluminum oxide (kg)	1.01E-02
Limestone (kg)	5.13E-02
Feldspar (kg)	5.02E-02
Dolomite (kg)	1.46E-02
Zircon (kg)	1.08E-02
Zinc (kg)	2.52E-02
Boric Acid (kg)	1.31E-02
Silica Sand (kg)	1.30E-01
Soda (kg)	7.65E-03
Magnetite (kg)	2.03E-03
Water (m3)	1.78E-05

Table 3. LCI data for Glaze Production for Ceramic Tiles (F.U. 1 m2) (18)

Energy Consumption in the Factory

In table 4, the energy consumption for every stage of the process is shown, the Cutting and Machining process requires the most electricity, while the firing requires the most natural gas consumption. Natural gas is only used as a fuel in two of the stages, which are drying and firing.



Energy Consumption	Electricity (kWh/m2)	Natural Gas (kWh/m2)
Pressing	0.93	
Drying	0.21	3.32
Glazed	0.42	
Firing	0.42	18.78
Cutting and Machining	1.26	
Packing and Storage	0.42	
Compresor/ Vacuum Cleaner	0.5	
Total	4.16	

Table 4. Energy Consumption in the factory.

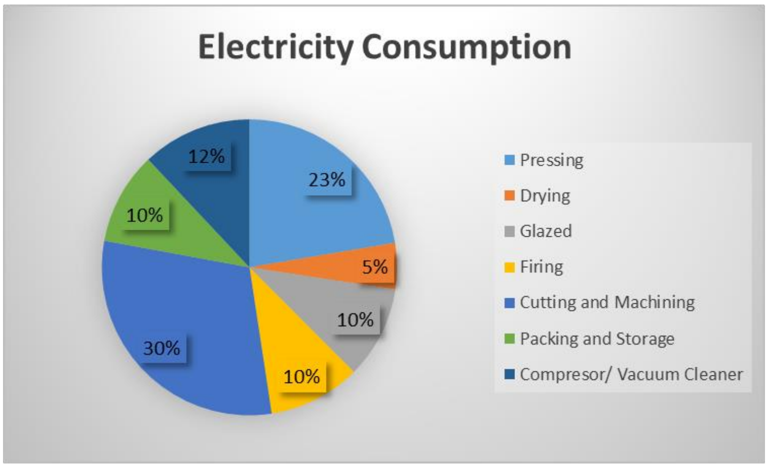


Figure 2. Electricity Consumption in the factory by stage

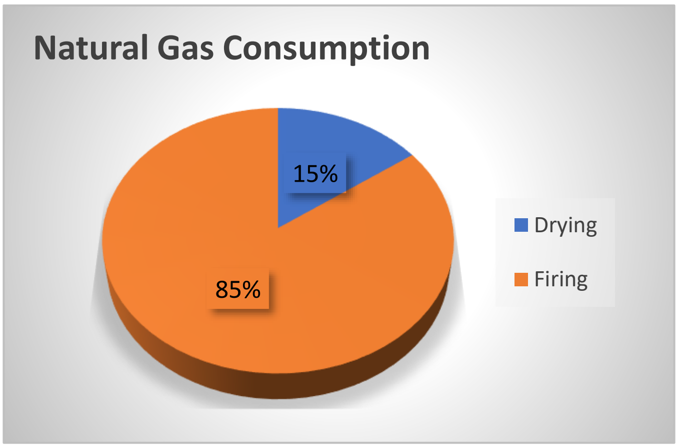


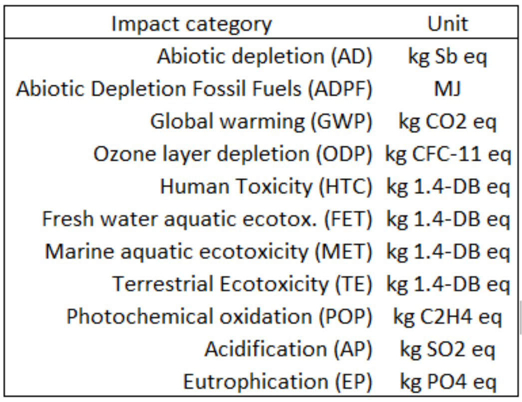
Figure 3. Natural Gas Consumption in the factory by stage

Ceramic Waste

There are two types of ceramic waste, non-hazardous and hazardous waste. Most of the waste is reincorporated in the process, but according to (Furszyfer Del Rio, Dylan D. et al., 2022), around 30% of the materials used in the ceramic industry go to landfills because they require special landfill treatment. Ceramic waste contains rich mineralogical variability and it has a great potential to be used as a by-product for other industries (9)

4.3. Impact Assessment

The impact assessment method used was CML-IA Baseline. there are eleven impact categories, which are the following:



Impact category	Unit
Abiotic depletion (AD)	kg Sb eq
Abiotic Depletion Fossil Fuels (ADPF)	MJ
Global warming (GWP)	kg CO2 eq
Ozone layer depletion (ODP)	kg CFC-11 eq
Human Toxicity (HTC)	kg 1.4-DB eq
Fresh water aquatic ecotox. (FET)	kg 1.4-DB eq
Marine aquatic ecotoxicity (MET)	kg 1.4-DB eq
Terrestrial Ecotoxicity (TE)	kg 1.4-DB eq
Photochemical oxidation (POP)	kg C2H4 eq
Acidification (AP)	kg SO2 eq
Eutrophication (EP)	kg PO4 eq

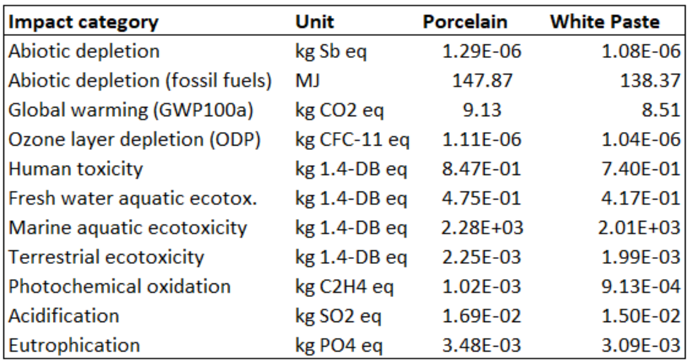
Table 5. Impact Categories considered for the LCA.

5. Results and Interpretation

5.1. Craddle-To-Gate Perspective

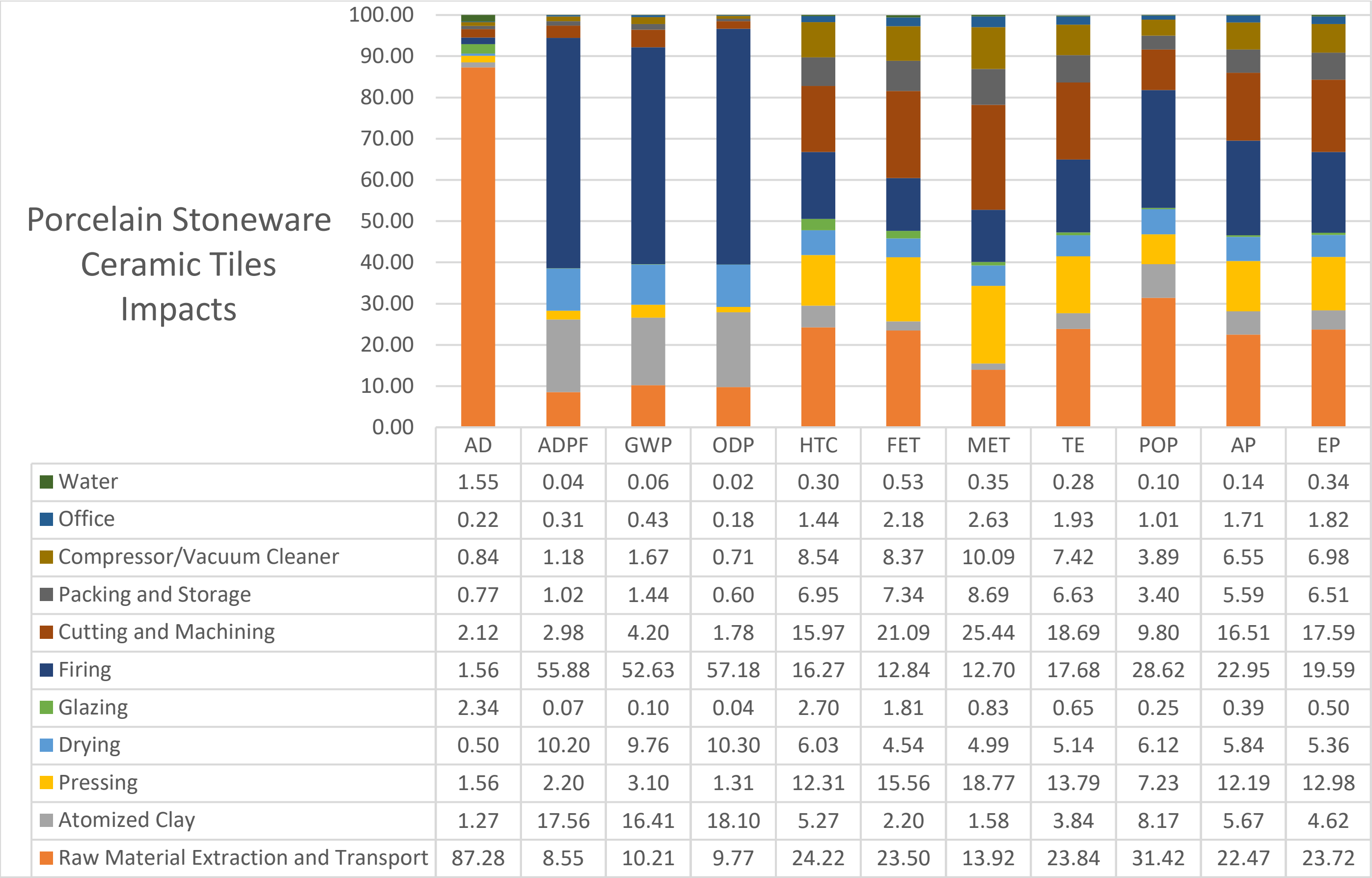
This section of the study shows the results of the life cycle environmental assessment of porcelain and white paste stoneware ceramic tiles, and the comparison between their environmental impacts. This section also includes the results compared to the original process from three different scenarios considering 2 of the key parameters for the environmental impacts of the process, which are: raw material and energy consumption.

The environmental impacts per m^2 of the production of porcelain and white paste stoneware glazed ceramic tiles from a cradle-to-gate perspective are presented in Table 6. In fig. 4 and 5 the contribution (%) of every stage in the process for every environmental impact category can be seen. Results revealed that white paste stoneware ceramic tiles have less environmental impacts than porcelain stoneware ceramic tiles due to the fact that they have less density, natural gas consumption is 20% lower, the process does not require polishing and cutting is easier, it also requires less pressure during the pressing stage, therefore, less electricity consumption.



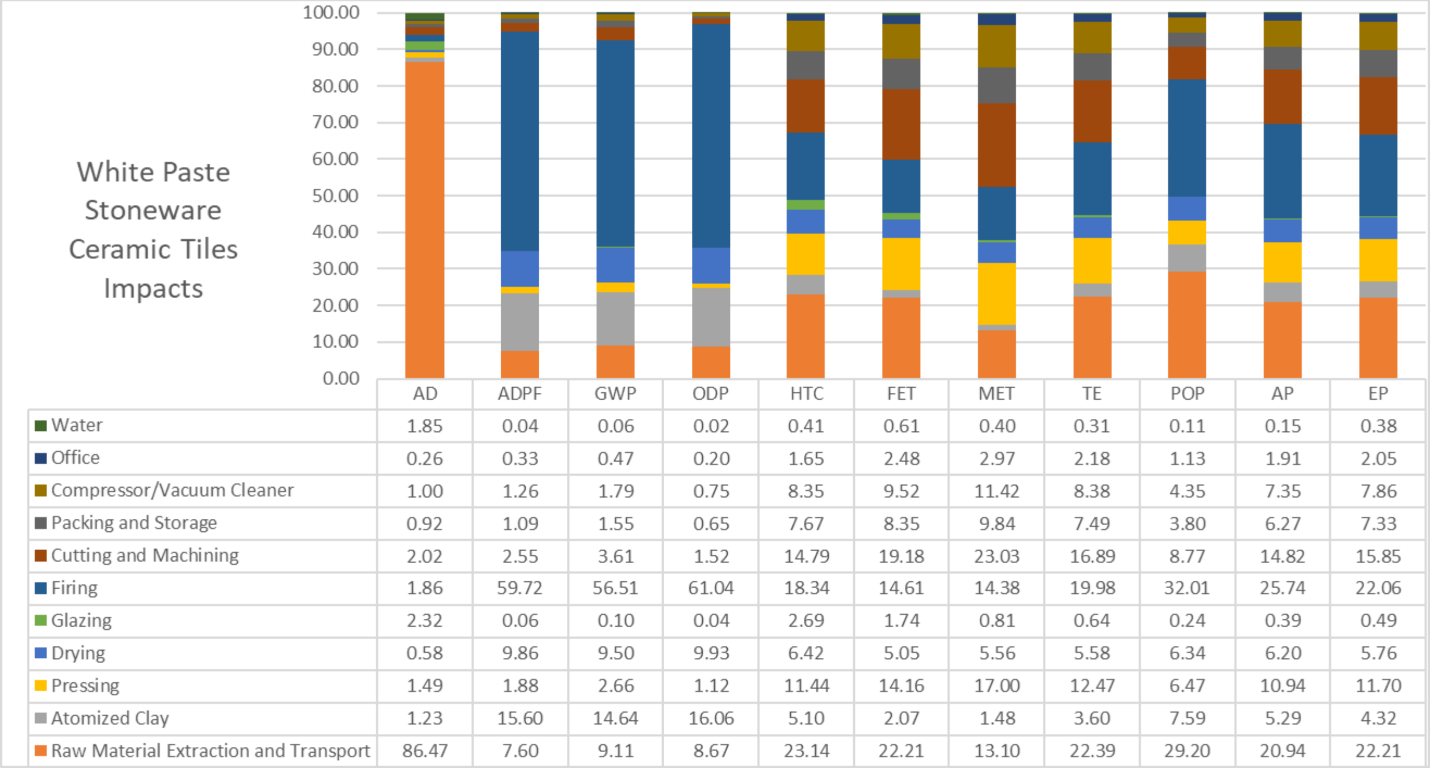
Impact category	Unit	Porcelain	White Paste
Abiotic depletion	kg Sb eq	1.29E-06	1.08E-06
Abiotic depletion (fossil fuels)	MJ	147.87	138.37
Global warming (GWP100a)	kg CO2 eq	9.13	8.51
Ozone layer depletion (ODP)	kg CFC-11 eq	1.11E-06	1.04E-06
Human toxicity	kg 1.4-DB eq	8.47E-01	7.40E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	4.75E-01	4.17E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.28E+03	2.01E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	2.25E-03	1.99E-03
Photochemical oxidation	kg C2H4 eq	1.02E-03	9.13E-04
Acidification	kg SO2 eq	1.69E-02	1.50E-02
Eutrophication	kg PO4 eq	3.48E-03	3.09E-03

Table 6. Environmental Impacts of porcelain and white paste stoneware ceramic tiles



	AD	ADPF	GWP	ODP	HTC	FET	MET	TE	POP	AP	EP
Water	1.55	0.04	0.06	0.02	0.30	0.53	0.35	0.28	0.10	0.14	0.34
Office	0.22	0.31	0.43	0.18	1.44	2.18	2.63	1.93	1.01	1.71	1.82
Compressor/Vacuum Cleaner	0.84	1.18	1.67	0.71	8.54	8.37	10.09	7.42	3.89	6.55	6.98
Packing and Storage	0.77	1.02	1.44	0.60	6.95	7.34	8.69	6.63	3.40	5.59	6.51
Cutting and Machining	2.12	2.98	4.20	1.78	15.97	21.09	25.44	18.69	9.80	16.51	17.59
Firing	1.56	55.88	52.63	57.18	16.27	12.84	12.70	17.68	28.62	22.95	19.59
Glazing	2.34	0.07	0.10	0.04	2.70	1.81	0.83	0.65	0.25	0.39	0.50
Drying	0.50	10.20	9.76	10.30	6.03	4.54	4.99	5.14	6.12	5.84	5.36
Pressing	1.56	2.20	3.10	1.31	12.31	15.56	18.77	13.79	7.23	12.19	12.98
Atomized Clay	1.27	17.56	16.41	18.10	5.27	2.20	1.58	3.84	8.17	5.67	4.62
Raw Material Extraction and Transport	87.28	8.55	10.21	9.77	24.22	23.50	13.92	23.84	31.42	22.47	23.72

Figure 4. Contribution made by every stage of the process to each impact category (%) (Porcelain Stoneware)



	AD	ADPF	GWP	ODP	HTC	FET	MET	TE	POP	AP	EP
Water	1.85	0.04	0.06	0.02	0.41	0.61	0.40	0.31	0.11	0.15	0.38
Office	0.26	0.33	0.47	0.20	1.65	2.48	2.97	2.18	1.13	1.91	2.05
Compressor/Vacuum Cleaner	1.00	1.26	1.79	0.75	8.35	9.52	11.42	8.38	4.35	7.35	7.86
Packing and Storage	0.92	1.09	1.55	0.65	7.67	8.35	9.84	7.49	3.80	6.27	7.33
Cutting and Machining	2.02	2.55	3.61	1.52	14.79	19.18	23.03	16.89	8.77	14.82	15.85
Firing	1.86	59.72	56.51	61.04	18.34	14.61	14.38	19.98	32.01	25.74	22.06
Glazing	2.32	0.06	0.10	0.04	2.69	1.74	0.81	0.64	0.24	0.39	0.49
Drying	0.58	9.86	9.50	9.93	6.42	5.05	5.56	5.58	6.34	6.20	5.76
Pressing	1.49	1.88	2.66	1.12	11.44	14.16	17.00	12.47	6.47	10.94	11.70
Atomized Clay	1.23	15.60	14.64	16.06	5.10	2.07	1.48	3.60	7.59	5.29	4.32
Raw Material Extraction and Transport	86.47	7.60	9.11	8.67	23.14	22.21	13.10	22.39	29.20	20.94	22.21

Figure 5. Contribution made by every stage of the process to each impact category (%) (White Paste Stoneware)

Abiotic Depletion

This category is strongly related to the extraction of raw materials stage, figure 12 shows that the largest contribution from the cradle-to-gate scope, comes from the extraction and processing of raw materials needed for the production of ceramic tiles. As presented in figure 11, this impact is estimated at 1.29e-6 kg Sb eq. per m^2 of porcelain stoneware ceramic tile produced, which accounts for 87% of the impact and 1.08e-6 kg Sb eq. per m^2 of white paste ceramic tile produced, which represents 86% of the total impact.

Abiotic Depletion (fossil fuels)

The largest contribution from the cradle-to-gate scope to this category is the manufacturing process, the firing process represents 56% of the total impact in porcelain ceramic tiles and 60% in white paste ceramic tiles, this is mainly to the use of natural gas and electricity in the atomizing, firing and drying processes. As presented in figure 11, this impact is estimated at 148 MJ per m^2 of porcelain stoneware ceramic tile produced and 138 MJ per m^2 of white paste ceramic tile produced.

Global Warming Potential

The main contribution from the cradle-to-gate scope to this category is the impacts of the production stage, which is mainly due to the CH_4 emitted during the combustion of natural gas, CO_2, N_2O, and NO_2 also make a strong contribution to this impact category. The firing stage is responsible for 53% of the total impact in porcelain ceramic tile production and 57% in white paste ceramic tile production. As presented in figure 11, the total Global Warming Potential is estimated at 9.13 kg CO2 eq. per m^2 of porcelain stoneware ceramic tile produced and 8.51 kg CO2 eq. per m^2 of white paste ceramic tile produced.

Ozone Layer Depletion

Most of the impacts from the cradle-to-gate scope come from the manufacturing process mainly due to the thermal energy generation from natural gas combustion, raw material supply and transport are also key contributors. The firing stage accounts for 57% of the total impact in porcelain ceramic tile production and 61% in white paste ceramic tile production. Figure 11 shows that porcelain stoneware ceramic tile production has an Ozone Layer Depletion of 1.11e-6 kg CFC-11 eq. per m^2 of porcelain stoneware ceramic tile produced and 1.04e-6 kg CFC-11 eq. per m^2 of white paste ceramic tile produced.

Human Toxicity

The main contribution from the cradle-to-gate scope to his impact category is the Raw Material Extraction and Transport stage, which is responsible for 24% of the total with an estimated impact of 8.47e-1 kg 1.4 DB eq. in porcelain ceramic tile production and 23% in white paste ceramic tile production, with an estimated impact of 7.40e-1 kg 1.4 DB eq

Freshwater Aquatic Ecotoxicity

The largest contribution from the cradle-to-gate scope to this category is the is the Raw Material Extraction and Transport stage, which is responsible for 23% of the total with an estimated impact of 4.75e-1 kg 1.4 DB eq. in porcelain ceramic tile production and 22% in white paste ceramic tile production, with an estimated impact of 4.17e-1 kg 1.4 DB eq.

Marine Aquatic Ecotoxicity

Most of the impacts from the cradle-to-gate scope come from the Cutting and Machining stage, which is responsible for 25% of the total with an estimated impact of 2.28e3 kg 1.4 DB eq. in porcelain ceramic tile production and 23% in white paste ceramic tile production, with an estimated impact of 2.01e3 kg 1.4 DB eq.

Terrestrial Ecotoxicity

The key contribution from the cradle-to-gate scope to this category is the Raw Material Extraction and Transport stage, which is responsible for 24% of the total of an estimated impact of 2.25e-3 kg 1.4 DB eq. in porcelain ceramic tile production and 22% in white paste ceramic tile production, of an estimated impact of 1.99e-3 kg 1.4 DB eq.

Photochemical Oxidation

The production stage represents 69% of the total impact from the cradle-to-gate scope in porcelain ceramic tile production and 71% in white paste ceramic tile production, emissions of SO_2, NOx, CO, and CH_4 mainly from the firing process are the main contributors to this impact category. Figure 11 shows that this impact is 1.02e-3 kg C2H4 eq. per m^2 of porcelain stoneware ceramic tile produced and 9.13e-4 kg C2H4 eq. per m^2 of white paste ceramic tile produced.

Acidification

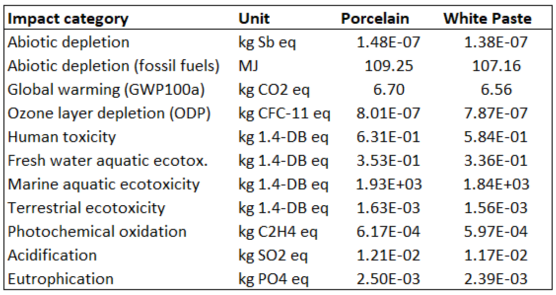
Emissions of SO2, NOx to air from the manufacturing process which contributes for 70% of the total impact from the cradle-to-gate scope for porcelain ceramic tile production and 74% for white paste ceramic tile production. As presented in figure 11, this impact is estimated at 1.69e-2 kg SO2 eq. per m^2 of porcelain stoneware ceramic tile produced and 1.50e-2 kg SO2 eq. per m^2 of white paste ceramic tile produced

Eutrophication.

As a consequence of high energy consumption, the highest contributor from the cradle-to-gate scope to this impact category is the manufacturing process of ceramic tiles which accounts for 57% of the total impact for porcelain ceramic and 62% for white paste ceramic tile production. Figure 11 shows that this impact is 3.48e-2 kg PO4 eq. per m^2 of porcelain stoneware ceramic tile produced and 3.09e-2 kg PO4 eq. per m^2 of white paste ceramic tile produced.

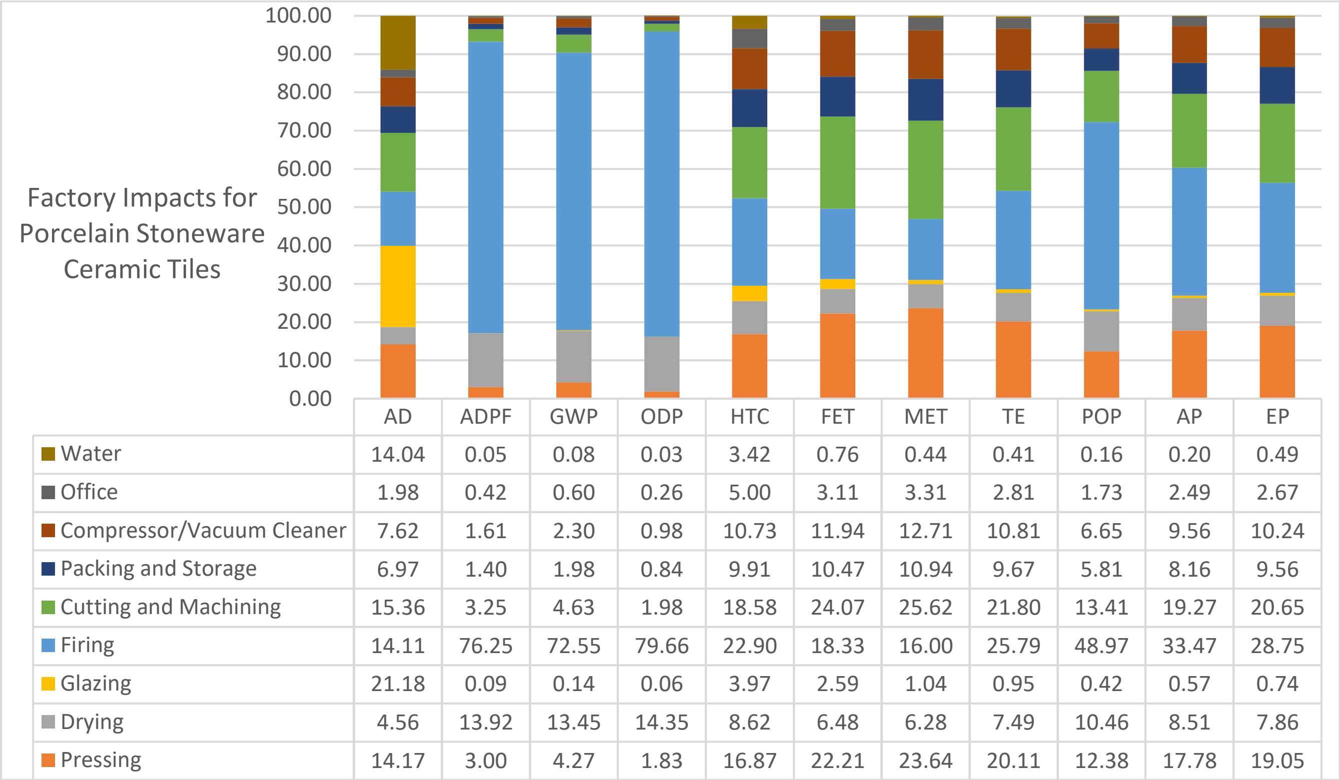
5.2. In-Factory Perspective

Table 6 shows, the environmental impacts of the production of ceramic tiles from a craddle-to-gate perspective, the following table, shows the environmental impacts for the processes that occur in the factory. The environmental impacts shown in table 7, are not considering the raw material extraction and processing, transport, and clay atomization stages because those processes do not occur on the factory, as the objective of this study is to analyze and communicate the environmental impacts caused by the factory itself.



Impact category	Unit	Porcelain	White Paste
Abiotic depletion	kg Sb eq	1.48E-07	1.38E-07
Abiotic depletion (fossil fuels)	MJ	109.25	107.16
Global warming (GWP100a)	kg CO2 eq	6.70	6.56
Ozone layer depletion (ODP)	kg CFC-11 eq	8.01E-07	7.87E-07
Human toxicity	kg 1.4-DB eq	6.31E-01	5.84E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	3.53E-01	3.36E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.93E+03	1.84E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	1.63E-03	1.56E-03
Photochemical oxidation	kg C2H4 eq	6.17E-04	5.97E-04
Acidification	kg SO2 eq	1.21E-02	1.17E-02
Eutrophication	kg PO4 eq	2.50E-03	2.39E-03

Table 7. Environmental Impacts of porcelain and white paste stoneware ceramic tiles (Factory)



	AD	ADPF	GWP	ODP	HTC	FET	MET	TE	POP	AP	EP
■ Water	14.04	0.05	0.08	0.03	3.42	0.76	0.44	0.41	0.16	0.20	0.49
■ Office	1.98	0.42	0.60	0.26	5.00	3.11	3.31	2.81	1.73	2.49	2.67
■ Compressor/Vacuum Cleaner	7.62	1.61	2.30	0.98	10.73	11.94	12.71	10.81	6.65	9.56	10.24
■ Packing and Storage	6.97	1.40	1.98	0.84	9.91	10.47	10.94	9.67	5.81	8.16	9.56
■ Cutting and Machining	15.36	3.25	4.63	1.98	18.58	24.07	25.62	21.80	13.41	19.27	20.65
■ Firing	14.11	76.25	72.55	79.66	22.90	18.33	16.00	25.79	48.97	33.47	28.75
■ Glazing	21.18	0.09	0.14	0.06	3.97	2.59	1.04	0.95	0.42	0.57	0.74
■ Drying	4.56	13.92	13.45	14.35	8.62	6.48	6.28	7.49	10.46	8.51	7.86
■ Pressing	14.17	3.00	4.27	1.83	16.87	22.21	23.64	20.11	12.38	17.78	19.05

Figure 6. Contribution made by the factory to each impact category (%) (Porcelain Stoneware)

	AD	ADPF	GWP	ODP	HTC	FET	MET	TE	POP	AP	EP
■ Water	15.0	0.1	0.1	0.0	2.5	0.8	0.5	0.4	0.2	0.2	0.5
■ Office	2.1	0.4	0.6	0.3	4.2	3.3	3.5	2.9	1.8	2.6	2.8
■ Compressor/Vacuum Cleaner	8.2	1.6	2.3	1.0	10.4	12.6	13.4	11.3	6.9	10.0	10.7
■ Packing and Storage	7.5	1.4	2.0	0.9	9.5	11.0	11.5	10.1	6.0	8.5	10.0
■ Cutting and Machining	16.4	3.3	4.7	2.0	19.9	25.3	27.0	22.8	13.9	20.1	21.6
■ Firing	15.1	77.8	74.1	81.1	25.5	19.3	16.8	27.0	50.6	34.9	30.0
■ Glazing	18.9	0.1	0.1	0.1	3.9	2.3	1.0	0.9	0.4	0.5	0.7
■ Drying	4.7	12.8	12.5	13.2	8.8	6.7	6.5	7.5	10.0	8.4	7.8
■ Pressing	12.1	2.4	3.5	1.5	15.5	18.7	19.9	16.8	10.2	14.8	15.9

Figure 7. Contribution made by the factory to each impact category (%) (White Paste Stoneware)

The results show that the manufacturing process of ceramic tiles produces the most environmental impacts, this is mainly because of natural gas and electricity consumption in the atomized, drying and firing stages. As shown in figures (6,7) the stage with the biggest impacts in most categories is the firing process, it can be seen in table 4 that this process has the highest fuel consumption per m^2. The Cutting and Machining stage, which has the highest electricity consumption of all the processes involved in the factory, also has significant impact in some categories.

Abiotic Depletion

Considering only the processes that occur in the factory, the stage that contributes to most of the abiotic depletion impact is the Glazing stage (21% and 19%) due to the raw materials needed for fabricating the glaze needed for the ceramic tiles, the process has an estimated impact of 1.48e-7 kg Sb eq. per m^2 (Porcelain Ceramic Tiles) and 1.38e-7 kg Sb eq. per m2 (White Paste Ceramic Tiles).

Abiotic Depletion (fossil fuels)

Counting only the factory environmental impacts, the firing (76% and 78%) is the most significant stage in the environmental impacts with an estimated impact of 109 MJ per m^2 (Porcelain Ceramic Tiles) and 107 MJ per m2 (White Paste Ceramic Tiles).

Global Warming Potential

As for the environmental impacts of the factory, the main contribution corresponds to the firing stage (73% and 74%), with an estimated impact of 6.70 kg CO2 eq. per m^2 (Porcelain Ceramic Tiles) and 6.56 kg CO2 eq per m2 (White Paste Ceramic Tiles).

Ozone Layer Depletion

Considering only the impacts of the factory, the stage that has the highest contribution to this impact category is the firing process (80% and 81%), with an estimated impact of 8.01e-7 kg CFC-11 eq, per m^2 (Porcelain Ceramic Tiles) and 7.87e-7 kg CFC-11 eq per m2 (White Paste Ceramic Tiles).

Human Toxicity

Environmental Impacts of the factory show that the key contributor stage is the firing process (23% and 26%) with an estimated impact of 6.31e-1 kg 1.4 DB eq. per m^2 (Porcelain Ceramic Tiles) and 5.84-1 kg 1.4 DB eq. per m2 (White Paste Ceramic Tiles).

Freshwater Aquatic Ecotoxicity

With an estimated impact of 3.53e-1 kg 1.4 DB eq. per m^2 (Porcelain Ceramic Tiles) and 3.36e-1 kg 1.4 DB eq. per m2 (White Paste Ceramic Tiles), the process that contributes the most to the impacts produced in the factory is the Cutting and Machining process (24% and 25%), this suggests that the electricity consumption produces the most significant impact for this category.

Marine Aquatic Ecotoxicity

The impacts of only the factory are estimated at 1.93e3 kg 1.4 DB eq. per m^2 (Porcelain Ceramic Tiles) and 1.84e3 kg 1.4 DB eq. per m2 (White Paste Ceramic Tiles). The process with the biggest contribution to this impact category is the Cutting and Machining stage (25% and 27%)

Terrestrial Ecotoxicity

The stage that has the highest contribution to this environmental impact category is the firing process (26% and 27%) with an estimated impact of 1.63e-3 kg 1.4 DB eq. per m^2 (Porcelain Ceramic Tiles) and 1.56e-3 kg 1.4 DB eq. per m2 (White Paste Ceramic Tiles).

Photochemical Oxidation

Results suggest that the firing process (49% and 51%) produces the most environmental impacts, with an estimated impact of 6.17e-4 kg C2H4 eq. per m^2 (Porcelain Ceramic Tiles) and 5.97e-4 kg C2H4 eq per m2 (White Paste Ceramic Tiles).

Acidification

With an estimated impact of 1.21e-2 kg SO2 eq. per m^2 (Porcelain Ceramic Tiles) and 1.17e-2 kg SO2 eq. per m2 (White Paste Ceramic Tiles). Results showed that the key contributor to this environmental impact category is the firing stage (33% and 35%).

Eutrophication.

The firing stage (29% and 30&) is the highest contributor with an estimated impact of 2.5e-3 kg PO4 eq. per m^2 (Porcelain Ceramic Tiles) and 2.39e-3 PO4 eq. per m2 (White Paste Ceramic Tiles).

5.3. Improvement Proposals

The ceramic process requires high heating temperatures that are provided with fossil fuels that nowadays cannot be replaced with new low-carbon technologies. According to (Furszyfer Del Rio, Dylan D. et al., 2022)there are many studies that suggest that the existing objectives for the European Ceramic industry are very demanding and unreachable if today´s technologies and policies remain exactly the same. Electrification has been proposed, but the fluctuating electricity prices and the fact that electric kilns for ceramic's mass production are not proven to be fully capable of providing the same quality as natural gas kilns, make this proposal unviable for now. Other proposals include the use of hydrogen, but as mentioned earlier, technologies requiring these fuels are not totally developed to work in the ceramic industry yet. Also, the lifespan of a kiln can be up to 40 years, and accounts for a significant capital investment, therefore, it is not economically feasible to replace them regularly. The long lifespan of these technologies makes it really hard to consider replacing the current kilns. Considering that this factory has 2 kilns which were acquired during the years 1999 and 2000, it is not economically feasible to replace them now. As (Gabaldón-Estevan et al., 2014) mentioned, the ceramic industry is now more concerned with marketing and branding strategies, than R&D for many reasons. The unwillingness to invest in energy-efficient measures with payback times over 3-5 years (9) and companies wanting to avoid being imitated by their competitors (19)

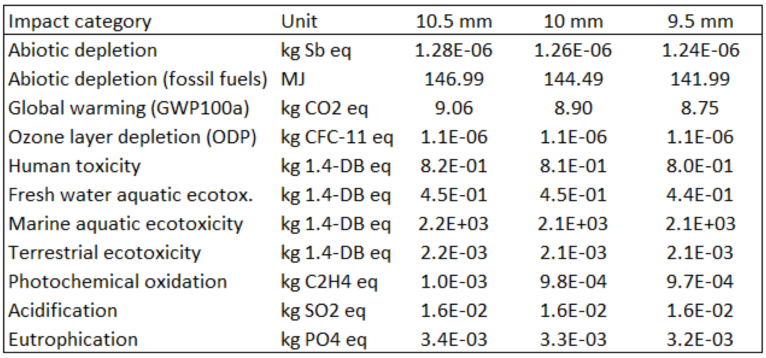
Taking into consideration some resource efficiency drivers, technological drivers and commercial trends in the ceramic tile industry, some proposals were analyzed and compared to the base case, the proposals are: Reduction of thickness, replacing Natural Gas with Biomethane, and a combination of both proposals.

5.3.1. Reduction of thickness

As shown in the results above with the porcelain stoneware and the white paste stoneware ceramic tiles, the lower the density of the ceramic tile, the less environmental impacts it has. Raw material consumption is one of the main hotspots of the process, reducing the tile´s thickness, will decrease that raw material and energy consumption as there is now less material to be dried or fired. The biggest challenge of reducing thickness is maintaining the quality, technical and functional performance of the product in terms of deformation and strength of the pieces. For this proposal, a scenario in which the thickness was reduced by 0.5 mm and 1 mm, these reductions were an estimation in which the ceramic tile keeps its technical and functional performance. These scenarios were modeled in order to compare the environmental impacts of the original scenario and the new ones proposed, the results will be discussed below.

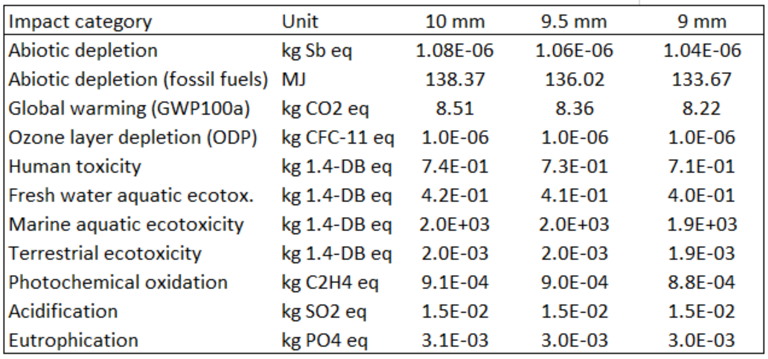
For the first scenario, considering the original thickness of both types of tiles, two processes were modeled for each, one with a 0.5 mm thickness reduction and the other one with a 1 mm thickness reduction.

As shown in tables 10 and 11, reducing the thickness 0.5 mm and 1 mm lowers the environmental impacts, in the porcelain stoneware ceramic tile production case, it shows that there is a reduction in CO2 emissions of 0.36 and 0.54 kg CO2 eq. per m^2 of porcelain ceramic tiles produced and 0.17 and 0.34 kg CO2 eq. per m^2 of white paste stoneware ceramic tiles produced. Considering current yearly production of 2,306,460 m^2 of which, the 83% corresponds to porcelain stoneware ceramic tiles and the resulting 17% accounts for white paste stoneware ceramic tiles, these reductions would save about 697.56-ton CO2 eq. and 1,032-ton CO2 eq. respectively for porcelain and 126.71-ton CO2 eq. and 191.61-ton CO2 eq. respectively for white paste.



Impact category	Unit	10.5 mm	10 mm	9.5 mm
Abiotic depletion	kg Sb eq	1.28E-06	1.26E-06	1.24E-06
Abiotic depletion (fossil fuels)	MJ	146.99	144.49	141.99
Global warming (GWP100a)	kg CO2 eq	9.06	8.90	8.75
Ozone layer depletion (ODP)	kg CFC-11 eq	1.1E-06	1.1E-06	1.1E-06
Human toxicity	kg 1.4-DB eq	8.2E-01	8.1E-01	8.0E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	4.5E-01	4.5E-01	4.4E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.2E+03	2.1E+03	2.1E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	2.2E-03	2.1E-03	2.1E-03
Photochemical oxidation	kg C2H4 eq	1.0E-03	9.8E-04	9.7E-04
Acidification	kg SO2 eq	1.6E-02	1.6E-02	1.6E-02
Eutrophication	kg PO4 eq	3.4E-03	3.3E-03	3.2E-03

Table 9. Thickness reduction scenario porcelain stoneware ceramic tile.



Impact category	Unit	10 mm	9.5 mm	9 mm
Abiotic depletion	kg Sb eq	1.08E-06	1.06E-06	1.04E-06
Abiotic depletion (fossil fuels)	MJ	138.37	136.02	133.67
Global warming (GWP100a)	kg CO2 eq	8.51	8.36	8.22
Ozone layer depletion (ODP)	kg CFC-11 eq	1.0E-06	1.0E-06	1.0E-06
Human toxicity	kg 1.4-DB eq	7.4E-01	7.3E-01	7.1E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	4.2E-01	4.1E-01	4.0E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.0E+03	2.0E+03	1.9E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	2.0E-03	2.0E-03	1.9E-03
Photochemical oxidation	kg C2H4 eq	9.1E-04	9.0E-04	8.8E-04
Acidification	kg SO2 eq	1.5E-02	1.5E-02	1.5E-02
Eutrophication	kg PO4 eq	3.1E-03	3.0E-03	3.0E-03

Table 10. Thickness reduction scenario white paste stoneware ceramic tile.

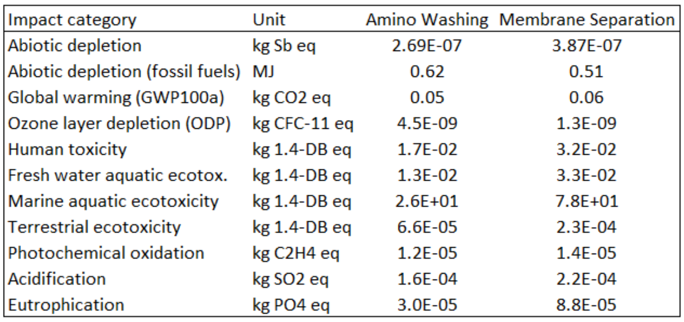
5.3.2. Replacing natural gas with biomethane

Changing from natural gas to biomethane may be the easiest solution for the ceramic sector, as it does not involve any adjustment for the process. Although the current production in Spain is 0.1 TWh, in the biomethane Roadmap, Spain´s proposal is to reach a biomethane production of 10.41 TWh. Under "ideal" regulations, biomethane is one of the most powerful tools to decarbonize the primary sector and industry, but feedstock availability appears to be a strong barrier to its deployment and its role in decarbonizing the economy. For this proposal, a scenario in which the biomethane replaces natural gas as the fuel used in the factory, therefore, it would only be used in the modelling for drying and firing processes, the results will be discussed below.

For this study, two upgrading technologies were analyzed and the environmental impacts were compared. Both technologies can be used in the biogas purification process to achieve CO2 separation and a gas methane content higher than 95%. Both are proven to be highly efficient.

- Amine Scrubbing: Amine Scrubbing is a promising biogas upgrading technology where CO2 is chemically adsorbed by backwashing the biogas in a column with an amine dilution packing. This upgrading technology has several competitive advantages over other different technologies. It does not require any pre-treatment of biogas. The amines have a highly efficient separation. The energy consumption and maintenance requirements are lower compared to other technologies and it has a lower dependence on human operators than other technologies **(11)**

- Membrane Separation: This technology is based on gas dissolution and diffusion into membranes, which are polymer materials. A differential pressure is applied on opposing sides of polymer films and biogas is circulated under pressure through polymer membranes, which are more permeable to CO2 than to CH4. The membrane separation technology has an 83% efficiency, making it the highest efficiency technology **(20)**



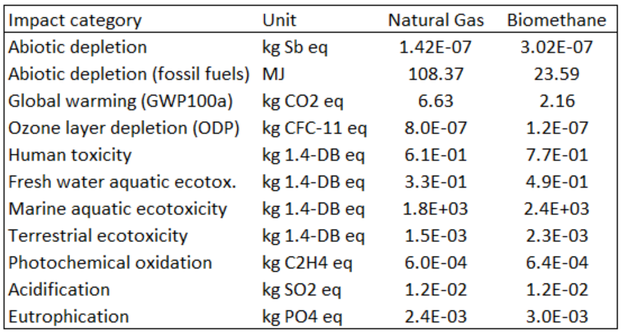
Impact category	Unit	Amino Washing	Membrane Separation
Abiotic depletion	kg Sb eq	2.69E-07	3.87E-07
Abiotic depletion (fossil fuels)	MJ	0.62	0.51
Global warming (GWP100a)	kg CO2 eq	0.05	0.06
Ozone layer depletion (ODP)	kg CFC-11 eq	4.5E-09	1.3E-09
Human toxicity	kg 1.4-DB eq	1.7E-02	3.2E-02
Fresh water aquatic ecotox.	kg 1.4-DB eq	1.3E-02	3.3E-02
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.6E+01	7.8E+01
Terrestrial ecotoxicity	kg 1.4-DB eq	6.6E-05	2.3E-04
Photochemical oxidation	kg C2H4 eq	1.2E-05	1.4E-05
Acidification	kg SO2 eq	1.6E-04	2.2E-04
Eutrophication	kg PO4 eq	3.0E-05	8.8E-05

Table 11. Environmental Impacts of Upgrading Techniques. (F.U. 0.10465 Nm^3)

As presented in Table 11, the impacts of membrane separation upgrading technique are greater in nine out of eleven environmental impact categories. Amino washing upgrading technique has greater environmental impacts in abiotic depletion (fossil fuels) and Ozone Layer Depletion. As mentioned before, both techniques are really efficient and do not require great amounts of energy. Biomethane processes considered in this study come from biogas with the following composition CH4 (63.3%), CO2 (33.4%), N (3.2%), H2S (0.0005%). This biogas was obtained from three different treatments with the following composition, anaerobic digestion of manure (1.6%), biowaste (37.3%) and sewage sludge (61%).

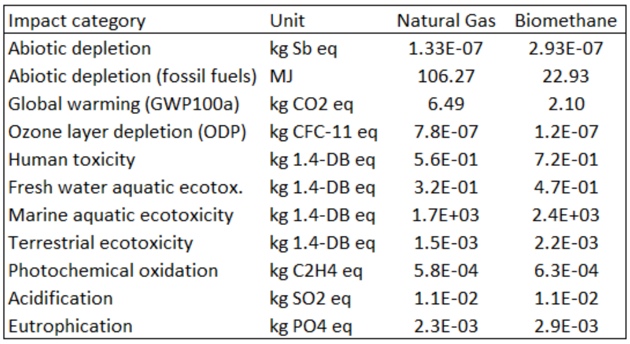
For this replacement of natural gas with biomethane scenario, the process was modeled with a Biomethane made of a mix of 4 different upgrading techniques with the following compositions, amino washing (57%), membrane separation (26%), pressure swing adsorption (15%), and from synthetic gas (2%).

This scenario, considers the replacement of natural gas with biomethane only in the processes in the factory, which are drying and firing, and as shown in tables 12 and 13, this measure reduces the environmental impacts in three out of seven impact categories, there is an evident reduction in CO2 emissions of 4.47 kg CO2 eq. and 4.39 kg CO2 eq. Considering current yearly production of 2,306,460 m^2, of which 1,914,361.8 m^2 correspond to porcelain ceramic tiles and the other 392,098.2 m^2 correspond to white paste ceramic tiles. Replacing natural gas with biomethane would save 1,700.59 ton CO2, and 335.75 ton CO2 eq. respectively, and a total of 2,036.35 ton CO2 eq.



Impact category	Unit	Natural Gas	Biomethane
Abiotic depletion	kg Sb eq	1.42E-07	3.02E-07
Abiotic depletion (fossil fuels)	MJ	108.37	23.59
Global warming (GWP100a)	kg CO2 eq	6.63	2.16
Ozone layer depletion (ODP)	kg CFC-11 eq	8.0E-07	1.2E-07
Human toxicity	kg 1.4-DB eq	6.1E-01	7.7E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	3.3E-01	4.9E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.8E+03	2.4E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	1.5E-03	2.3E-03
Photochemical oxidation	kg C2H4 eq	6.0E-04	6.4E-04
Acidification	kg SO2 eq	1.2E-02	1.2E-02
Eutrophication	kg PO4 eq	2.4E-03	3.0E-03

Table 12. Biomethane scenario porcelain stoneware ceramic tile

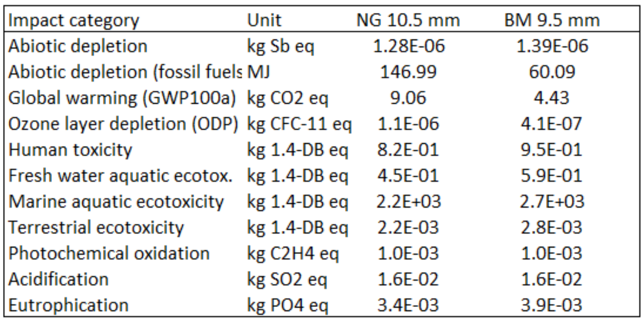


Impact category	Unit	Natural Gas	Biomethane
Abiotic depletion	kg Sb eq	1.33E-07	2.93E-07
Abiotic depletion (fossil fuels)	MJ	106.27	22.93
Global warming (GWP100a)	kg CO2 eq	6.49	2.10
Ozone layer depletion (ODP)	kg CFC-11 eq	7.8E-07	1.2E-07
Human toxicity	kg 1.4-DB eq	5.6E-01	7.2E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	3.2E-01	4.7E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	1.7E+03	2.4E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	1.5E-03	2.2E-03
Photochemical oxidation	kg C2H4 eq	5.8E-04	6.3E-04
Acidification	kg SO2 eq	1.1E-02	1.1E-02
Eutrophication	kg PO4 eq	2.3E-03	2.9E-03

Table 13. Biomethane scenario white paste stoneware ceramic tile.

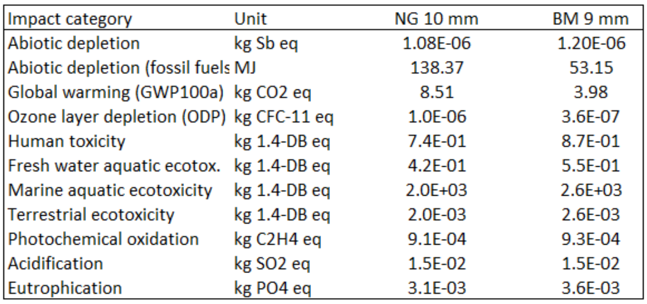
5.3.3. Combination of both

Last modelling considers not only the replacement of natural gas with biomethane, but a 1 mm reduction in the thickness of both types of ceramic tiles. The combination of both measures shows a much more significant reduction in kg CO2 eq. emitted, for porcelain ceramic tiles, there is a reduction of 4.63 kg CO2 eq. which would save a yearly amount of 8852.93 ton CO2 eq. whereas for white paste ceramic tiles there is a 5.53 kg CO2 eq. which would avoid a yearly amount of 1774.57 ton CO2 eq.



Impact category	Unit	NG 10.5 mm	BM 9.5 mm
Abiotic depletion	kg Sb eq	1.28E-06	1.39E-06
Abiotic depletion (fossil fuels	MJ	146.99	60.09
Global warming (GWP100a)	kg CO2 eq	9.06	4.43
Ozone layer depletion (ODP)	kg CFC-11 eq	1.1E-06	4.1E-07
Human toxicity	kg 1.4-DB eq	8.2E-01	9.5E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	4.5E-01	5.9E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.2E+03	2.7E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	2.2E-03	2.8E-03
Photochemical oxidation	kg C2H4 eq	1.0E-03	1.0E-03
Acidification	kg SO2 eq	1.6E-02	1.6E-02
Eutrophication	kg PO4 eq	3.4E-03	3.9E-03

Table 14. 3rd Scenario comparison porcelain stoneware ceramic tile.



Impact category	Unit	NG 10 mm	BM 9 mm
Abiotic depletion	kg Sb eq	1.08E-06	1.20E-06
Abiotic depletion (fossil fuels	MJ	138.37	53.15
Global warming (GWP100a)	kg CO2 eq	8.51	3.98
Ozone layer depletion (ODP)	kg CFC-11 eq	1.0E-06	3.6E-07
Human toxicity	kg 1.4-DB eq	7.4E-01	8.7E-01
Fresh water aquatic ecotox.	kg 1.4-DB eq	4.2E-01	5.5E-01
Marine aquatic ecotoxicity	kg 1.4-DB eq	2.0E+03	2.6E+03
Terrestrial ecotoxicity	kg 1.4-DB eq	2.0E-03	2.6E-03
Photochemical oxidation	kg C2H4 eq	9.1E-04	9.3E-04
Acidification	kg SO2 eq	1.5E-02	1.5E-02
Eutrophication	kg PO4 eq	3.1E-03	3.6E-03

Table 15. 3rd Scenario comparison white paste stoneware ceramic tile.

6. Sustainable Development Goals in the Ceramic Sector

For some years now, the ceramic sector has been a really good example of excellence at international level in the management of the critical environmental aspects that characterize the product and the process. In previous years, ceramic companies have carried out different research projects and have collaborated with local institutions to reduce the environmental impacts of the activity. The results achieved have been very positive, for example, a lower energy consumption, complete recycling of waste and water, and utilization of waste from other supply chains from a circular economy perspective, pollutant emissions have been contained under the best available techniques in the sector. Environmental certifications of products and processes have developed sectoral analyses of life cycle impacts to facilitate the diffusion of environmental declaration products **(21)**

SDGs can be an opportunity for every company to:

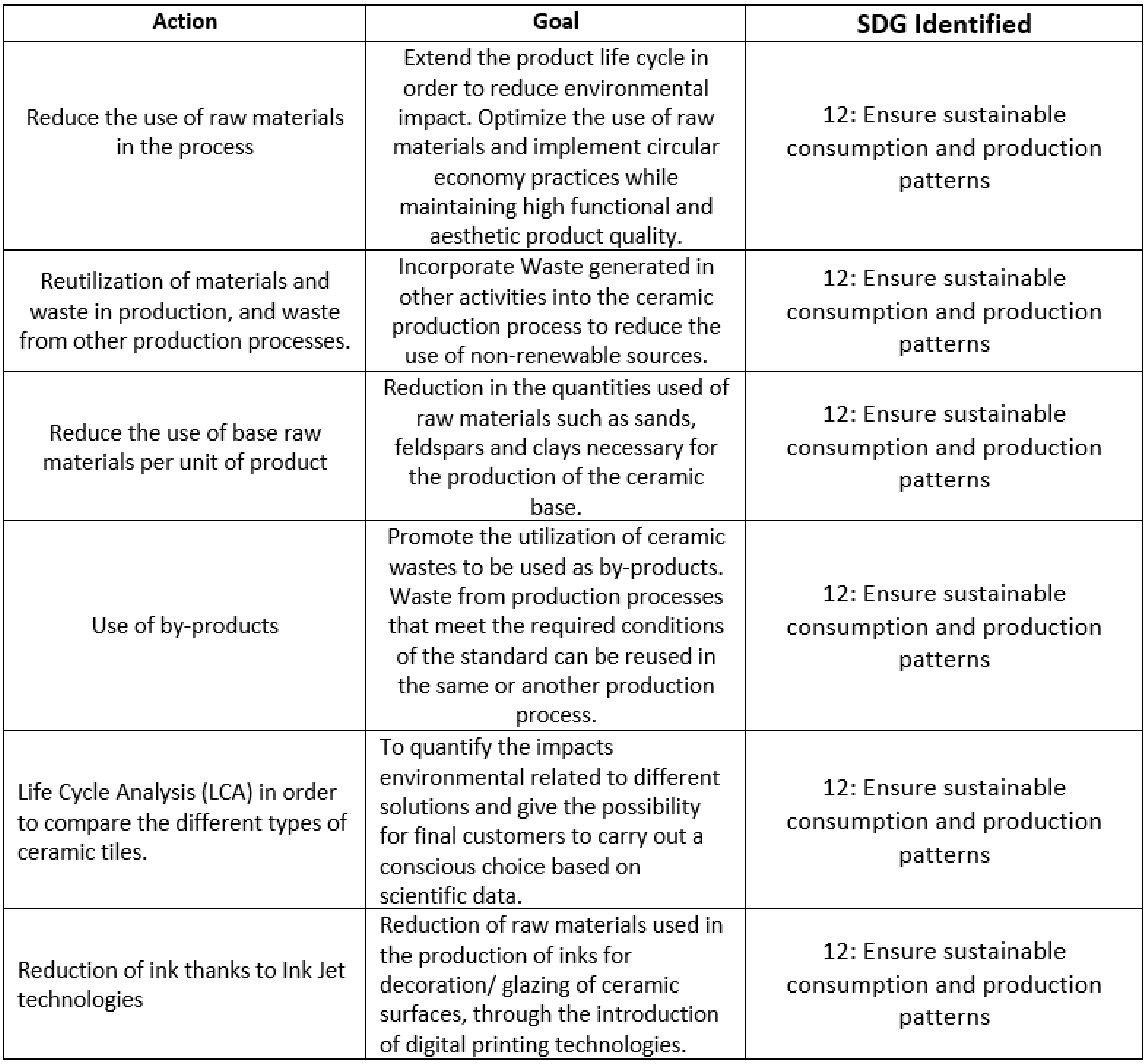
- Identify new business areas and opportunities.
- Ensure the conditions for long-term success by improving the economic and social context which these companies are operating.
- Identify, prevent and manage risks and relative costs.
- Improve business performance in terms of Sustainability, CSR and ESG.
- Strengthen relationships with stakeholders and enhance reputation and brand.
- Create new partners locally and globally.
- Integrate business strategy with sustainability.
- Improve the quality and competitiveness of the area.

This study focuses primarily on 2 SDGs, the most important one is SDG 12: Responsible Consumption and Production, and SDG 7: Affordable and Clean Energy. Different actions and proposals have been mapped consistently with the different SDGs.

The above-mentioned actions are mainly focused on two main areas:

- **The ceramic product**, which due to its intrinsic characteristics guarantees a reduced environmental impact in the life cycle and lends itself to circular economy approaches during production and disposal and was the subject of a strong innovation effort on the environmental performance front, which has become a distinguishing feature along with design and quality.

- **The production process and system activity**. In this we see a combination of optimization and green innovation approaches on the technological front and the adoption of management practices that enable environmental management system certifications to be obtained.



Action	Goal	SDG Identified
Reduce the use of raw materials in the process	Extend the product life cycle in order to reduce environmental impact. Optimize the use of raw materials and implement circular economy practices while maintaining high functional and aesthetic product quality.	12: Ensure sustainable consumption and production patterns
Reutilization of materials and waste in production, and waste from other production processes.	Incorporate Waste generated in other activities into the ceramic production process to reduce the use of non-renewable sources.	12: Ensure sustainable consumption and production patterns
Reduce the use of base raw materials per unit of product	Reduction in the quantities used of raw materials such as sands, feldspars and clays necessary for the production of the ceramic base.	12: Ensure sustainable consumption and production patterns
Use of by-products	Promote the utilization of ceramic wastes to be used as by-products. Waste from production processes that meet the required conditions of the standard can be reused in the same or another production process.	12: Ensure sustainable consumption and production patterns
Life Cycle Analysis (LCA) in order to compare the different types of ceramic tiles.	To quantify the impacts environmental related to different solutions and give the possibility for final customers to carry out a conscious choice based on scientific data.	12: Ensure sustainable consumption and production patterns
Reduction of ink thanks to Ink Jet technologies	Reduction of raw materials used in the production of inks for decoration/ glazing of ceramic surfaces, through the introduction of digital printing technologies.	12: Ensure sustainable consumption and production patterns

Action	Goal	SDG Identified
Sustainable Transportation	Use of train for transportation of raw materials and shipping final product instead of road transport.	12: Ensure sustainable consumption and production patterns
Environmental Product Declaration (EPD)	EPD is a verified certification, that transparently communicates the environmental performance or impact of any product or material over its lifetime.	12: Ensure sustainable consumption and production patterns
Management of Energy Consumption (Fossil Fuels)	Increase energy efficiency of the process, reducing natural gas consumption, in addition to electricity consumption in the different phases of the productive process. Energy efficiency is key for competitiveness, especially in an energy-intensive sector.	7: Affordable and Clean Energy
Use of renewable energies and energy recovery processes.	Renewable energy production and energy recovery systems are important elements for competitiveness and energy costs reduction.	7: Affordable and Clean Energy

Table A1. SDGs in the Ceramic Sector **(21)**

7. Conclusions

This study has discussed the environmental impacts of porcelain and white paste stoneware ceramic tiles of a factory located in Castellón de la Plana through a Life Cycle Assessment. Seven environmental impacts have been estimated using LCA tool SimaPro. The total energy consumption of the facility is 60.68 GWh and had a total production of 2,306,460 m^2, this means that they needed 26.30 kWh for every m^2 produced. Findings in the study indicated that for every $1m^2$ of ceramic tiles produced, CO2 emissions are estimated at 10.51 kg CO2 eq. for porcelain ceramic tiles and 9.93 kg CO2 eq. for white paste ceramic tiles. The total energy requirement for $1m^2$ of ceramic tiles produced is 146 MJ for porcelain ceramic tiles and 140 MJ for white paste ceramic tiles. The following conclusions were drawn out of the study:

- The ceramic tiles manufacturing stage is the main hotspot for 10 out of 11 environmental impact categories considered in this study due to the electricity and natural gas consumption.
- The ceramic industry not only has a lot of environmental impacts as mentioned during this study, but it also has social impacts, starting from the extraction of raw materials
- The ceramic process requires high heating temperatures that are provided with fossil fuels that nowadays cannot be easily replaced with new low-carbon technologies, but changing from natural gas to biomethane may be the easiest solution for ceramic industries because it does not involve any adjustment for the process like hydrogen. The modelled scenario in which biomethane replaced natural gas as the primary fuel for the firing and drying, showed that using biomethane as a substitute of natural gas would be a big step for the decarbonization of the ceramic industry.
- The use of raw materials is also one of the hotspots identified in this study, reducing the thickness and therefore the density of the tiles, not only lowers the use of raw materials, but also decreases the energy consumption during the whole process, because there is less material to be dried or fired, so it does not require the same energy.

- Many efforts have to be made to decarbonize the ceramic sector, the biggest obstacles are not in terms of innovation, there are many ideas and solutions, the biggest obstacles are mostly because the industry is more concerned about other things than investing in energy and resource efficiency solutions due to return investment times. Sustainability of ceramic industry should also consider economic costs and social impacts to integrate them with environmental impacts.
- Three different scenarios were studied in this study that have the potential to improve the environmental performance of the factory analyzed, although there are more effective solutions out there, the proposed solutions were taken into account and chosen considering the context of the company and its requirements.

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