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Comparative life cycle analysis between commercial porcelain stoneware and new ones designed by using volcanic scraps

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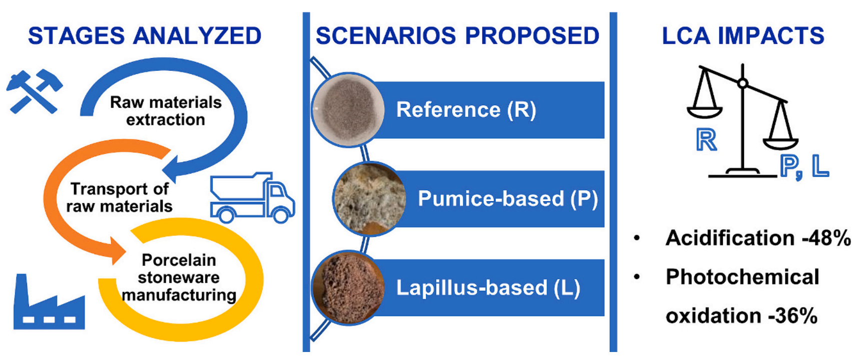
HIGHLIGHTS

- Comparative LCA was performed on three porcelain tiles, two of them with scraps
- Environmental benefits of pumice and lapillus-based products have been evaluated
- Products with scrap had a lower environmental impact than the reference product
- The pumice-based product showed lesser impacts than the same with lapillus
- "Acidification" category showed approximately 48 % reduction in impact

GRAPHICAL ABSTRACT



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ABSTRACT

To achieve carbon neutrality by 2050, many companies have started implementing sustainability policies. The aim of this work, as result of collaboration between Universities and companies, is to assess the environmental impacts associated with the production of alternative formulations of porcelain stoneware. The proposed formulations contain extraction scraps and chamotte and have promising technological properties. A comparative analysis of the life cycle in three different scenarios was carried out to assess the environmental footprint of the final products. The analyzed scenarios were a glazed porcelain stoneware (which was taken as a reference and is commercially available), a porcelain stoneware containing pumice scraps, and one containing volcanic lapillus scraps. It was observed that the transportation of raw materials has the largest environmental impact, followed by the production and extraction of the raw materials themselves. From the performed analysis, it was possible to observe that by replacing the currently used materials by the ones hereby studied, environmental benefits can be obtained. In particular, depending on the considered pollutant, the environmental impact can be reduced between a minimum of about 8 % (Freshwater Aquatic Ecotoxicity category) to a maximum of 48 % (Acidification category). In a time when raw materials supply is difficult, the use of scraps, which would otherwise be disposed of, is particularly interesting and can lead to the production of an environmentally friendly product.

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1. Introduction

The manufacturing of building materials is one of the most environmentally impactful processes globally. The decarbonization of this sector must be achieved by 2050. However, there has been an upward trend in energy consumption and emissions since 2020, due to production increases. The construction sector accounts for about 40 % of European energy demand but 80 % of the energy comes from fossil fuels. In 2021, this sector was responsible for CO_2 emissions for about 37 % globally and consumed about 34 % of the global energy demand (Anon, 2023a).

The impact of construction on the environment is not only limited to energy consumption and carbon dioxide emissions but there are also consequences on the ecosystem such as, for example, consumption of land and resources, such as water and raw materials. Further, the effects on the environment caused by the extraction, processing and transportation of these materials are to be considered. Sometimes, the effect of transportation is so important that it can make not sustainable even products that are green from a technological point of view.

Ceramic tiles belong to building materials: Italy is the seventh largest producer worldwide and second largest in Europe (Baraldi, 2023). The Italian production chain is designed with sustainability as a priority. Indeed, 100 % of raw, fired waste, and wastewater are fed back into the production cycle. Moreover, 47 % of energy is self-produced, and 99 % of dust is filtered (Anon, 2023b). Although ceramic tile production has lower CO_2 emissions than clinker production, the supply chain of raw materials must be considered: the raw materials for clinker production are located near the production plants while more than 50 % of the raw materials for ceramic tile production comes from abroad by sea, rail, or road (Anon, 2023c). Over the years, numerous studies have been carried out on the incorporation of waste into ceramic tiles. The main results regarding the effect of waste on the technological behavior and environmental impact resulting from the production of these products have been evaluated by Zanelli et al. (2021).

The demand for environmentally sustainable buildings is constantly increasing. Nonetheless, it is necessary to make products that can be not only environmentally friendly but with satisfying technological properties. Life cycle analysis (LCA) is a useful tool for understanding and minimizing the environmental impacts of products and services. As the world moves towards sustainability, LCA plays a crucial role in assessing and improving environmental performance by enabling the assessment of environmental impacts associated with all life stages of a product, process or service. The Society of Environmental Toxicology and Chemistry, in 1993 defined LCA as an objective process of assessing the environmental impacts associated with a product, process or activity by identifying and quantifying material and energy consumption and emissions to the environment and identifying and evaluating opportunities to reduce those impacts. Defining the boundaries of the system is very important as it allows to determine which processes, operations and flows should be taken into account: there may be several possibilities, for example, cradle to gate, cradle to grave and cradle to cradle. Referring to a product, the cradle-to-grave analysis covers the entire life cycle: from the extraction and processing of raw materials to the production, transportation, and distribution of the product, its use, reuse, and maintenance, to the recycling and final disposal of the product after use. In contrast, in the cradle-to-gate pathway the end of the scope is the factory gate (usually before the product is distributed to customers). It analyzes only up to the point where the product leaves the manufacturing facilities. The latter approach is sometimes preferred when the product can be easily recycled or composted, avoiding landfill, or simply because it is easier to track. ISO 14040 and 14,044 provide the framework for conducting LCA studies and define four main steps: 1. goal setting (ISO 14040); 2. inventory analysis (ISO 14041); 3. impact assessment (ISO 14042); 4. interpretation of results (ISO 14043). Each stage plays a key role in the analysis, enabling a detailed understanding of environmental impacts during the life of a product or service. Its application can help identify critical areas for environmental improvement, assess the environmental performance of products and services, and support decision making in the selection of alternative materials or processes, the latter coinciding with the objective of this paper. Numerous LCAs have been performed on ceramic tiles to assess their ecological footprint. Waterkemper Vieira et al. (2023) analyzed different works concerning the Brazilian ceramic tile industry identifying the relationships between the variables affecting the forming process and highlighting the areas that need measures to reduce the environmental impact of production. This study found that the transportation of raw materials from quarries to factories is the stage that causes the greatest environmental impact while the glazing of tiles is the main contributor to environmental effects in the studied industries. Almeida et al. (2016) evaluated the environmental profile of ceramic tiles produced in Portugal through LCA from cradle to grave; the most impactful processes are due to site activities, transportation, power generation and natural gas production. Tikul (2014) analyzed the impacts caused by the production processes used by small and medium-sized ceramic tile companies in Thailand, observing that small companies are more energy-intensive and more impactful than medium-sized ones. Ma et al. (2022) conducted an environmental footprint assessment on China's ceramic tile manufacturing sector through an LCA study and a view of the energy-carbon-water nexus; the greatest impact in this case was direct emissions, energy, transportation, and solid waste. Morfino et al. (2022) analyzed through LCA the impacts from the use of bleaching materials incorporated within ceramic tile mixtures to provide manufacturers with a tool to guide their choices in the selection of matting materials. Andreola et al. (2007) and Barberio et al. (2010) evaluated the environmental impacts of using end-of-life cathode ray tube glass and municipal solid waste incinerator bottom ash for ceramic glaze production and demonstrated the benefits. Assumpção de Castro et al. (2023) evaluated the life cycle and environmental contamination of cement tiles while Atılgan Türkmen et al. (2021) analyzed different scenarios for tile production to understand which process was more sustainable. Other studies can be found in the literature that use LCA to compare the production of ceramic tiles with marble (Nicoletti et al., 2002) or to assess the environmental footprint of ceramic floor and wall materials and bricks (Bovea et al., 2007; Ibáñez-Forés et al., 2011; Fullana and Palmer, 2011; Quinteiro et al., 2014; López-García et al., 2021). Moreover, LCA is becoming an increasingly popular tool in the construction industry. In fact, it is possible to find LCAs carried out on different types of mortars, cements and concretes (Farinha et al., 2019; Cuenca-Moyano et al., 2017; Tosti et al., 2020; Kul et al., 2023; Manjunatha et al., 2021; Wang et al., 2023; Colangelo et al., 2018; Ouellet-Plamondon and Habert, 2015) and even on aggregates (Pradhan et al., 2019; Tefa et al., 2022; Uzzal Hossain et al., 2016; de Bortoli, 2023).

It must be considered that this methodology has limitations because there is always a tendency to make simplifications of the system when the model is built. This is needed to enable the evaluation of the model itself, but could lead to analyses that are not always comparable. If, for example two different boundaries are considered in the same analysis, a comparison cannot be made. In addition, it is also necessary to consider the type of data such as primary (provided by company), secondary (provided by databases or literature) or tertiary (estimated data). In particular, the latter two increase the uncertainty of the final results. Some studies in literature (Cellura et al., 2011; Santos et al., 2022) deal exactly with this issue. Further, the country or the time period (or both) can influence the results, therefore they cannot be applicable in a different context. The methods used to analyze impacts are also many, and the analyses obtained by using different methods lead to results that are not comparable to each other.

The goal of this paper is to evaluate comparatively the environmental impact of three porcelain stoneware tiles by the same LCA approach and software, and using the same borders, i.e., from the cradle to the gate. Commercial porcelain stoneware was the reference for two new products formulated by replacing, in weight, foreign feldspars with approximately 50 % waste and scraps, of which 15–16 % are volcanic raw material scraps (pumice and lapillus). The technological performances of these products have already been analyzed by the authors in a previous paper (Altimari et al., 2023) and this research aims at completing the study by an environmental impact evaluation. The three types of porcelain stoneware have some raw materials in common: a German clay and some Italian raw materials. The mixture used as a reference was composed of 18 raw materials, while the mixtures based on pumice or lapillus scraps were made of 8 raw materials. In addition to the presence of pumice or lapillus, the two scraps-based bodies differ in the different percentages of used raw materials.

The novelty of this study is the application of the LCA approach to ceramic products obtained by exploiting Italian volcanic scraps, in order to help producers or customers to analyze advantages or drawbacks of these new raw materials.

2. Methodology

2.1. LCA methodology

The comparative environmental assessment described in this paper was performed according to the international regulatory reference for the execution of LCA studies represented by the ISO 14040 series of standards. The structure of LCA is divided into four main steps: objective and scope, life cycle inventory, impact assessment and interpretation of results (https://www.csqa.it/it-it/certificazioni/sostenibilita/lca-iso-14040-14044, n.d.).

2.2. Goal of the study

The focus of this work was to compare the environmental impacts of a commercial porcelain stoneware with two similar products containing mining and processing scraps of Italian volcanic minerals. The considered products have been engineered within a research and development cooperation between the academic and business worlds. The products have been technologically compared by the authors in Altimari et al. (2023). With the results that will be exposed in this work, the authors wanted to complete analysis by evaluating the environmental impact of the product with a view to promoting commercial and productive transferability, in the context of the circular economy and national productive self-sufficiency.

Porcelain stoneware is usually composed of clays, feldspars and inert materials.

The products under study were a reference porcelain stoneware produced by a ceramic company that is part of the Sassuolo (MO) ceramic district (Italy), a porcelain stoneware containing pumice scraps and one containing lapillus scraps.

The raw materials used for the production of the reference sample were: two German clays, an Italian clay, an Italian kaolin, a mixture of five Italian feldspars and six Turkish feldspars, two types of Italian sands, and some raw and fired scraps from the production cycle.

The raw materials used for the production of samples containing pumice or lapillus were German clay, Italian clay, Italian kaolin, pumice or lapillus scraps (aluminosilicate raw materials that can be used as valuable raw materials in various fields (Barbieri et al., 2023)), scraps of an Italian feldspar, Italian sand, and two types of fired scraps from the production cycle. The mixture of foreign and Italian feldspars used for the reference support was replaced with pumice or lapillus scraps and Italian feldspar scraps.

The number of raw materials required to manufacture the product was reduced from 18 to 8. This led to a reduction in dye pigments while achieving good technological properties, as demonstrated in Altimari et al. (2023).

2.3. Functional unit and system boundaries

The studied system corresponds to stoneware tile. Therefore, its function is to provide coverage to the floor of a building. The chosen functional unit is 1 m^2 of tiles.

The LCA was carried out following a cradle-to-gate approach. The life cycle analysis was evaluated by several stages:

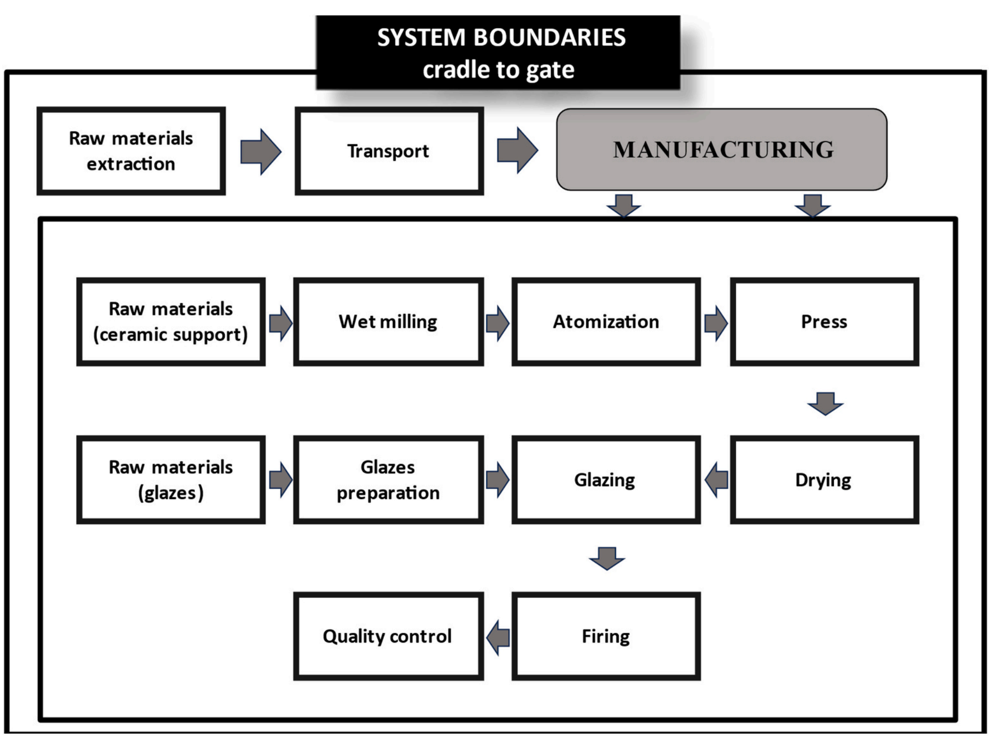


Fig. 1. System boundaries.

- Raw materials: in this phase, all materials needed to obtain support, engobe and glaze were considered. Processing scraps used as raw materials were considered to have neutral impact since they are not extracted specifically for the purpose. German and Italian clays, Italian kaolin, Italian and Turkish feldspars, pumice scraps, lapillus scraps and Italian feldspar scraps, Italian sands, scraps from the production cycle and dyes of various kinds were used to obtain ceramic support. Clays from Britain and Germany, German bentonites, German sands, Italian feldspars, northern European feldspathoids and ceramic frits from Spain were used to make engobes and glazes. In 2022, 347.5 tons of raw materials will be consumed in the plant for the production of the reference support only;
- Transportation: transportation of all raw materials from the respective quarries/mines to the production plant was considered in this phase. The routes were traveled by road, train, and sea. The distance traveled by road, to get from the quarries to the production plant, can be very different; there are local raw materials that travel about 12 km but there are also raw materials that come from abroad traveling about 1200 km. The same for transportation by sea, as Italian raw materials travel about 280 km while foreign raw materials can travel up to about 8050 km. Only one raw material, German clay, travels by train, so the distance is constant corresponding to 900 km;
- Production: this phase accounts for all the processes required to obtain the products with the related energy consumption and emissions generated to complete the process. The energy consumption considered in this phase also includes the packaging phase. The production is related to the manufacture of approximately 6.255.444 m^2 of porcelain stoneware produced in 2022 (considering that 18 kg of raw materials related to the substrate only are used for 1 m^2). In all studied cases, the considered firing cycle is the one currently used by the company, i.e. a time of 48 min at a temperature of 1210 °C.

The scenarios considered in this investigation were:

- Reference porcelain stoneware scenario (REFERENCE), which describes the sourcing and transportation of raw materials to the factory and the production of the considered product
- Scenario of porcelain stoneware containing 16 % of pumice scraps (PUMICE-BASED), which in addition to accounting for sourcing, transportation, and manufacturing of the product, goes on to consider the non-extraction of some raw materials and the decrease in the use of coloring oxides (approx. 50 %);
- Scenario of porcelain stoneware containing 15 % of volcanic lapillus scraps (LAPILLUS-BASED), which contains less sand and more feldspars than the previous one (Altimari et al., 2023).

Fig. 1 summarizes the considered life cycle stages; these are the same for all three scenarios.

2.4. Assumptions and considerations

The following assumptions were made for each scenario:

1. The amount of mix to obtain 1 m^2 of tile is 18 kg (Assopiastrelle, 1997);
2. The selected means of transportation were those with lower emission levels (Euro 6 certified trucks, electric-powered trains);
3. The coloring oxides used to color the substrate are reduced by 50 % in the case of pumice-based and lapillus-based mixture, as they naturally color the ceramic piece (brown for pumice-based, black for lapillus-based);
4. All raw and fired waste is fed back into the production cycle.

Since there is no direct or good quality data, nor high interest because they are the same in all scenarios, the following parameters were not considered within the process:

1. Emissions related to dust and fume removal systems (Soliroc™ process (Commissione delle Comunità Europee, 1997));
2. Waste production and disposal (for example insulators);
3. Water consumption, as this is recycled within the production cycle (https://www.ceramica.info/articoli/ceramica-italiana-scelta-sostenibile-video-brochure/, n.d.);
4. The energy produced in cogeneration;
5. Fuels used for vehicles loading hoppers.

2.5. Life cycle inventory analysis

Life cycle inventory analysis is a phase that includes the collecting and processing of data on all inputs and outputs of the production system under consideration. In order to obtain a valid model, the inventory must be as complete as possible.

Data on raw material extraction and transportation (not km traveled but related to fuels, emissions, …) come from the Ecoinvent v3 database (Weidema et al., 2013; Frischknecht and Rebitzer, 2005). In this regard, the data on the processes that most closely resemble the objective and scope of this study were selected, with a global scope and sintering temperatures similar to those used in this life cycle study; data on transportation (km traveled), quantities of raw materials used, and energy consumption were primary data, i.e., provided directly by the tile maker company involved in this study.

Data on the quantities (kg) of raw materials needed for the annual production of porcelain stoneware were provided by the manufacturing company. Carriers deliver the raw materials needed for production every week; upon entering the company these are mandatory to declare the quantities delivered, which are then certified by the operators. The quantities are recorded and make it possible to obtain very reliable estimates of the raw materials purchased and used. The unit of measurement related to the quantities of raw materials was “kg”.

Raw material transport data, on the other hand, were provided by the mining companies. Distances were estimated on the basis of actual kilometers traveled by transporters (in the case of road routes), trains or ships. However, the data were checked and confirmed through the use of high-accuracy maps. The unit of measurement related to transportation was “tkm” (ton per km).

Regarding energy data, it must be considered that ceramic companies, being highly energy-intensive companies, are subject to mandatory energy diagnosis in accordance with Legislative Decree 102/2014. Energy diagnosis is defined as a procedure aimed at providing adequate knowledge of the energy consumption profile of industrial plant. Thus, the diagnosis is the most qualified tool for analyzing the energy management framework of an activity: it highlights the level of management efficiency, starting from the analysis of significant energy flows, to identify the most energy-intensive process steps and machines.

Electrical and thermal equipment consumption data were collected or calculated by:

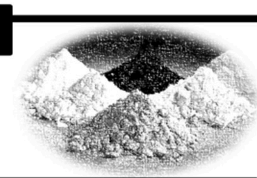
- Field measurements of consumption (continuous meters, periodic readings of parameters for industrial management/accounting, …);
- Spot readings of consumption by instrumentation inserted for periods deemed significant to the interpretation of the consumption trend of the equipment under consideration;
- Estimation of consumption based on nameplate powers, time of use of the equipment and the sensitivity of the department head in defining possible correction factors (average power consumed versus nameplate power).

In this case, for electricity consumption, the company has tax counters for purchase and production (co-generator); a tax counter also measures the consumption of natural gas taken from the pipeline.

The company in 2023 carried out the energy diagnosis, and the

INVENTORY

RAW MATERIALS



Kg	REFERENCE	PUMICE-BASED	LAPILLUS-BASED
CLAYS	8.7	8.1	8.1
FELDSPARS	7.6	-	-
SAND	0.8	0.9	0.5
MIX FELDSPARS SCRAPS	-	5.9	6.1
CHAMOTTE	0.9	3.1	3.2

TRANSPORT

Transport, freight, lorry, 16-32 tons, EURO6 {RER} I market for transport I Alloc Def, U
Transport, freight train {Europe without Switzerland} I transport, freight train, electricity | Alloc Def, U
Transport, freight, sea, container ship, (GLO) transport, freight, sea, container ship | Alloc Def, U

	REFERENCE	PUMICE-BASED	LAPILLUS-BASED
CLAYS (km)*	2504	1587	1587
FELDSPARS (km)**	13458	-	-
SAND (km)	655	55	55
MIX FELDSPARS SCRAPS (km)	-	619	614
CHAMOTTE (km)	71	71	71

MANIFACTURING

Electricity, medium voltage {Europe without Switzerland} I market group for electricity, medium voltage I APOS, U
Heat, district or industrial, natural gas {RoW} I heat and power co-generation, natural gas, lean burn I APOS, U

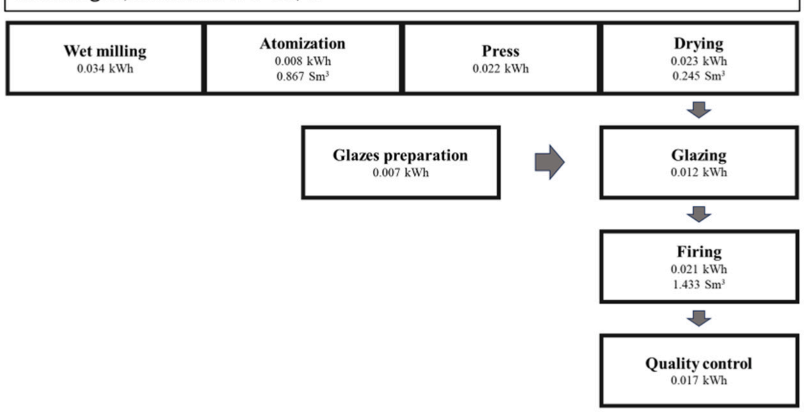


Fig. 2. Inventory data.

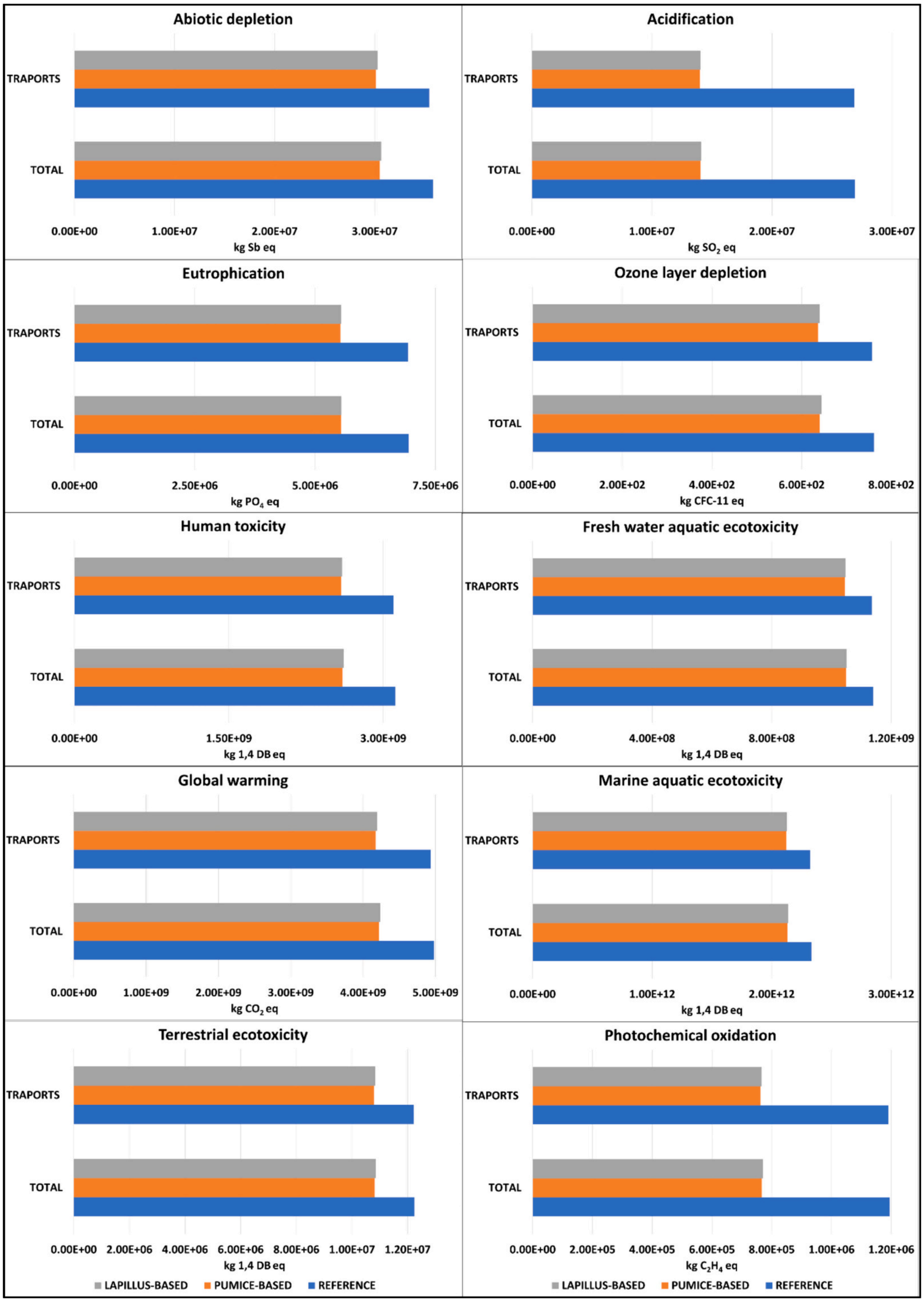


Fig. 3. Impact categories for the three scenarios.

expert staff who dealt with it validated the data reported in this paper. However, all data were rechecked to be sure of the quality of the input data and consequently have reliable output data. The unit of measurement related to energy was “kWh” and “Sm^3” (Standard cubic meter).

Fig. 2 shows some inventory data for raw material, transportation and energy. It shows the quantities of raw materials needed to produce 1 m^2 of product and the distances traveled from the quarries to the factory. In terms of distances, the raw materials marked with an asterisk (*) are transported by road and rail, those marked with two asterisks (**) are transported by road, by rail and by sea, and all others are transported by road. “Mix feldspars scraps” means the sum of pumice or lapillus scraps and Italian feldspar scraps.

Regarding the data on the consumption of electricity (kWh) and natural gas (Sm^3) needed to produce 1 m^2 of product (data provided by the ceramic company), they are again visible in Fig. 2. Consumption was considered to be the same for every type of porcelain stoneware. The figure does not show consumption data for auxiliary and general services, which are 0.99 kWh and 0.06 Sm^3 and 0.06 kWh and 0.004 Sm^3, respectively.

For simplicity of visualization, the merged data have been shown in

Table 1
Impact percentages corresponding to raw materials (RM), transportation (T), and manufacturing (M).

	Reference (%)			Pumice-based (%)			Lapillus-based (%)		
	RM	T	M	RM	T	M	RM	T	M
Abiotic depletion	0.07	98.93	1.00	0.05	98.78	1.17	0.05	98.78	1.17
Acidification	0.08	99.76	0.16	0.09	99.60	0.31	0.09	99.60	0.31
Eutrophication	0.10	99.80	0.09	0.09	99.79	0.12	0.09	99.79	0.12
Global warming	0.07	99.06	0.87	0.05	98.93	1.02	0.05	98.93	1.02
Ozone layer depletion	0.08	99.46	0.46	0.07	99.38	0.54	0.07	99.39	0.54
Human toxicity	0.17	99.52	0.31	0.17	99.46	0.37	0.17	99.46	0.37
Fresh water aquatic ecotoxicity	0.18	99.66	0.16	0.18	99.65	0.18	0.18	99.65	0.18
Marine aquatic ecotoxicity	0.21	99.56	0.24	0.20	99.54	0.26	0.20	99.54	0.26
Terrestrial ecotoxicity	0.11	99.80	0.09	0.10	99.80	0.10	0.10	99.80	0.10
Photochemical oxidation	0.07	99.61	0.32	0.07	99.43	0.50	0.07	99.43	0.50

Fig. 2. As mentioned in Section 2.2, in the case of both quantities and transports, when it comes to clays, it must be considered that we are dealing with 4 types of them in the case of the reference and 3 in the other two cases while, in the case of feldspars, 11 were considered for the reference and 2 (mix feldspars scraps) in the other two scenarios. The sands included in the slurries were 2 in the reference scenario and 1 in the other two cases while for chamotte 1 type was used in the reference and 2 types for the pumice based or lapillus based scenarios.

Energy data have also been merged; the data visible in the Figure below refer to the sum of the data from the departments considered. For example, the grinding department refers not only to the operation of grinding raw materials, but to all the machinery that contributes to this stage: conveyor belts, automatic loading and unloading of raw materials, monitoring booths; the atomization department takes into account the stage of mixing raw materials with water, sieving, etc…

2.6. *Life cycle impact assessment methodology*

The used impact assessment methodology is CML 2000 version 2.05, developed by Centre for Environmental Studies (CML), Leiden University (Netherlands) in 2001, replacing the CML 1992 method. CML-IA is a database that contains characterization factors for life cycle impact assessment (LCIA) (https://www.universiteitleiden.nl/en/research/research-output/science/cml-ia-characterisation-factors, n.d.). This methodology allows the following impact categories to be analyzed: Abiotic Depletion, Acidification, Eutrophication, Global Warming Potential, Ozone Layer Depletion, Human Toxicity, Freshwater Aquatic Ecotoxicity, Marine and Terrestrial Aquatic Ecotoxicity, and Photochemical Oxidation. The validity of the results is global in scope, but the Acidification and Photochemical Oxidation categories are based on average values for the European region (De Bruijn et al., 2002).

This methodology provides information on human health, natural resources and the environment and has been used in numerous works in the literature (Ibáñez-Forés et al., 2013; Özkan et al., 2016; Muñoz et al., 2018; Uceda-Rodríguez et al., 1917). The evaluation of impact indices against an average European in one year is standardized.

The software SimaPro 8.3.0.0 (PRé Consultants) enabled the model construction and data processing.

3. Results and discussion

Fig. 3 shows the impacts associated with total tile production (m^2) compared to the year 2022. For each impact category and scenario, the comparison of total inputs and raw material transportation inputs can be seen.

It is evident that over 95 % of the impacts are from the transportation of raw materials from quarries to the manufacturing site; this is even more evident in Table 1. As mentioned in Section 2.3, impacts related to raw material extraction, transportation and manufacturing were considered for each scenario. Table 1 shows the percentage influence of each analyzed phase on the related impacts.

Ibáñez-Forés et al. (2013), in a 2013 paper on tile production in Spain, observed that recovering heat from the production cycle can achieve environmental improvements of more than 90 %. In this case study, combined heat and power (CHP) significantly reduced the impact of manufacturing, as shown in Table 1. Ceramic companies are energy-intensive companies; in fact, if combined heat and power were not considered, most likely the production phase would be the most impactful in agreement with other studies (Almeida et al., 2016; Ibáñez-Forés et al., 2013).

In all cases, the pumice and lapillus scenarios show a decrease from the reference. The categories that show a greater decrease in impacts are “Acidification” and “Photochemical oxidation” while those that are close to the values of the reference scenario are “Freshwater aquatic ecotoxicity” and “Marine aquatic ecotoxicity”. Although the relative improvement is less evident, the absolute decrease in “Marine aquatic ecotoxicity” and “Freshwater aquatic ecotoxicity” is still relevant, as they are in the order of E12 kg 1,4 DB eq and E9 kg 1,4 DB eq respectively.

In all scenarios, the greatest impacts occur in the categories “Marine aquatic ecotoxicity”, “Human toxicity”, “Fresh water aquatic ecotoxicity,” and “Global warming.”

From a comparison between the pumice-based and lapillus-based scenarios, it is possible to say that the differences are very small. Nonetheless, pumice-based products have slightly lower impacts in most indicators. Probably the difference between the pumice-based and lapillus-based scenarios is due to the variation in the percentages of raw materials required to obtain the ceramic piece.

The impact of transportation is very high. According to literature data (Waterkemper Vieira et al., 2023; Almeida et al., 2016; Ma et al., 2022) transportation is very impactful and therefore these data could be confirmed, although normally the greatest impacts are related to production. In the case study, however, the model did not consider the real quantity of energy needed to produce the amount of porcelain stoneware manufactured by the company in 2022. This is due to the presence of a cogeneration plant capable of producing almost all the needed energy, so the company is self-powered. On the other hand, there are raw materials that travel over 8000 km to get to their destination.

Fig. 4 shows only the data on raw material impacts. This is to better highlight the difference between the three scenarios. In the previous figures, there is no contribution related to raw materials or production because they are negligible compared to transportation, as evident in Table 1.

The categories “Freshwater aquatic ecotoxicity” and “Photochemical oxidation” do not show a clear change from the life cycle of the reference sample. The trend in data for raw materials alone is comparable to the total data (raw materials, transport and production): there is a decrease in all categories in the case of pumice-based and lapillus-based products. Comparison of the pumice-based and lapillus-based scenarios shows that the latter scenario showed indicators with slightly lower impacts except for the case of “Fresh water aquatic ecotoxicity”.

There has been a conscious focus on transportation and raw

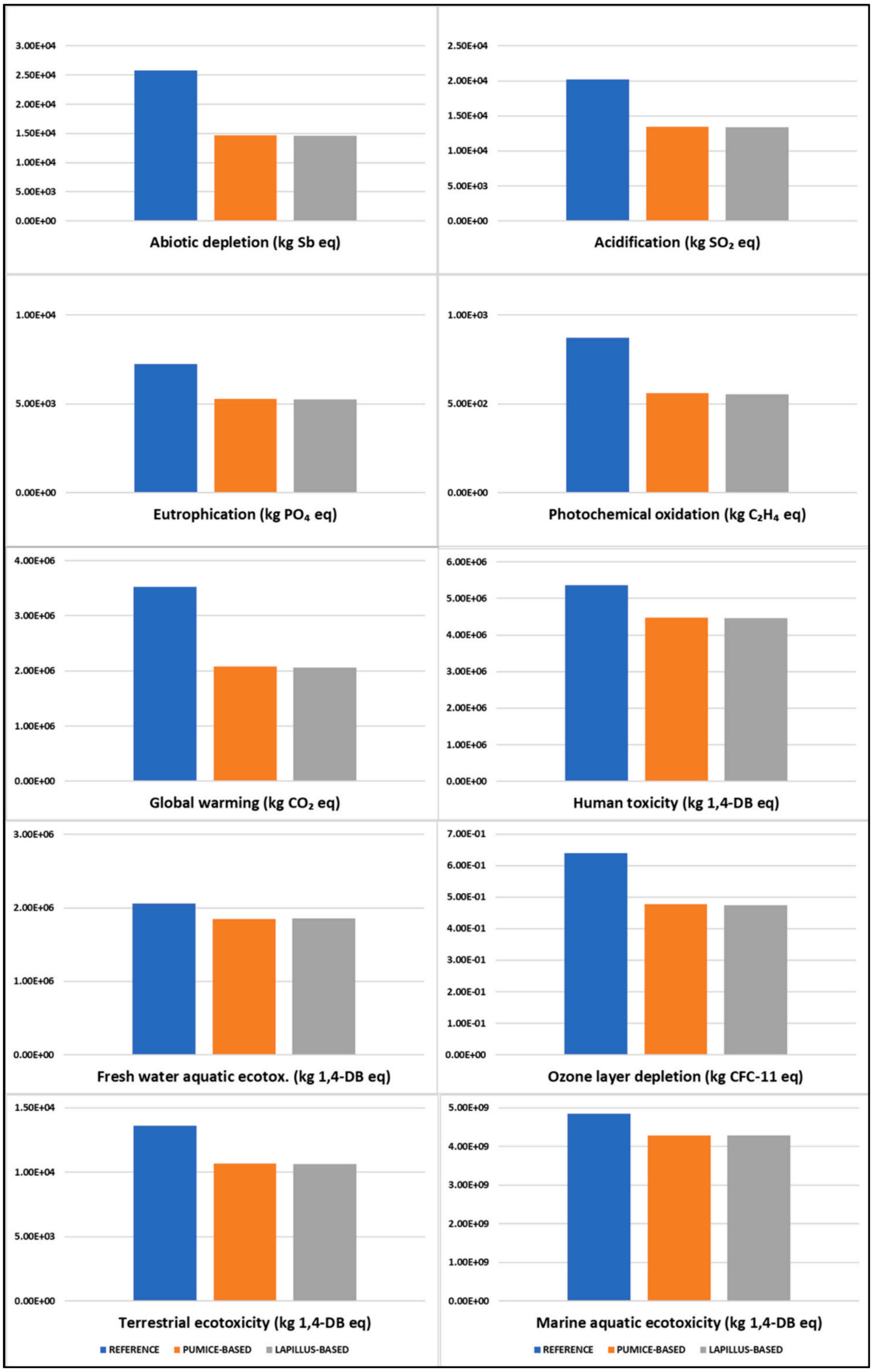
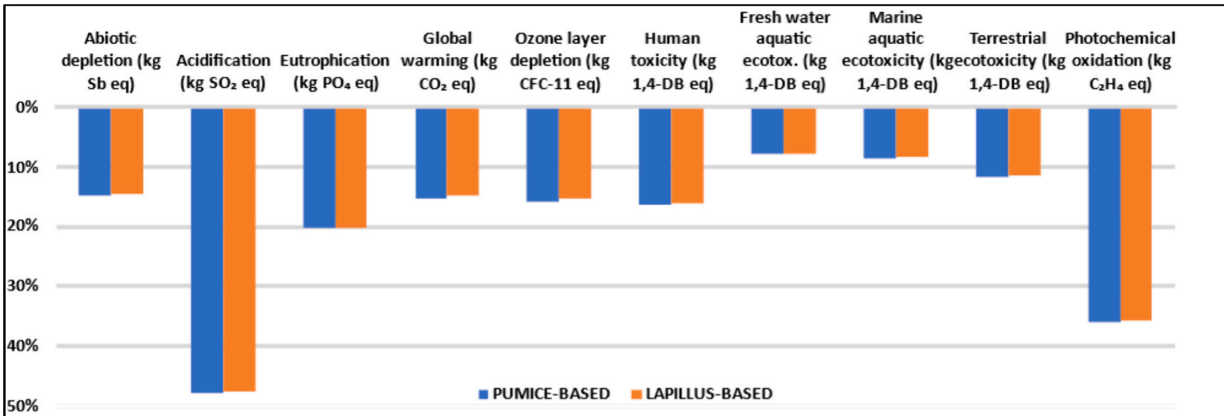


Fig. 4. Raw materials impacts.

materials, as these are the life cycle stages that vary from one product to another. One point should be made: the number of raw materials in the pumice-based and lapillus-based scenarios is significantly reduced when compared with the reference. Consequently, impacts are reduced. However, they remain very high because many of the raw materials in the reference scenario travel by rail and se, while Italian raw materials travel by road. Hence, most of the transportation means used in the reference case are less impactful than those used in the other two cases.

If we shift our attention to energy consumption, it is possible to see that it is very low. Normally most of the impacts are due to the production process, as shown by other authors (Frischknecht and Rebitzer, 2005). In the case under study, the company works in cogeneration, recovering heat and producing electricity, avoiding buying electricity from fossil sources. Energy consumption generates somewhat higher impacts than those generated by raw materials but manages to be limited.

Fig. 5 shows the avoided impacts in the two alternative scenarios compared to the reference. The data refer to the tons of impacts avoided



	PUMICE -BASED	LAPILLUS-BASED
Abiotic depletion	14.85%	14.45%
Acidification	47.77%	47.60%
Eutrophication	20.28%	20.14%
Global warming	15.30%	14.91%
Ozone layer depletion	15.89%	15.43%
Human toxicity	16.39%	16.10%
Fresh water aquatic ecotoxicity	7.93%	7.77%
Marine aquatic ecotoxicity	8.59%	8.41%
Terrestrial ecotoxicity	11.69%	11.40%
Photochemical oxidation	35.82%	35.58%

Fig. 5. Avoided impacts.

in the corresponding categories.

The two scenarios are very similar to each other. As mentioned earlier, pumice waste-based tile production has slightly lower impacts in most categories, and this results in a higher percentage of avoided impacts. There are environmental benefits in each category. The categories that had less environmental benefits were “Fresh water aquatic ecotoxicity” and “Marine aquatic ecotoxicity”. The greatest environmental benefits, with a net decrease in impacts, were in the categories “Acidification” and “Photochemical oxidation.” The other categories showed improvements between about 11 % and 20 %. The obtained environmental benefits are in the range of about 20 % in both scenarios.

4. Conclusions

In this work, the life cycle of three products was analyzed: a reference product (which is a porcelain stoneware tile currently on the market), a porcelain stoneware tile containing pumice scraps, and a porcelain stoneware tile containing volcanic lapillus scraps. The inventory analysis made it possible to evaluate the impacts deriving from the extraction and transportation of raw materials and from product manufacturing. Impact categories were evaluated with a focus on raw materials and their transportation, as they differentiated one scenario from another. The manufacturing process remained the same in all three scenarios.

It was observed that:

a) For each scenario, transportation is responsible for more than 95 % of the generated impacts, followed by the production process and finally by the raw material extraction process, which only in one case generated impacts greater than 0.2 %;
b) In the two scenarios in which volcanic scraps were among the raw materials, the impacts decreased in any analyzed category;
c) The reduction in impacts ranges from a minimum of about 8 % in the “Fresh water aquatic ecotoxicity” and “ Marine aquatic ecotoxicity” categories, to a maximum of about 48 % in the “Acidification” category;
d) The influence of transportation is still high in the two proposed case studies, because:

- notwithstanding the raw materials come from Italy, they travel mainly by road, with a corresponding high impact;
- the impact associated with energy consumption is low because the factory is almost energy self-consistent, so the impact produced by the transportation is emphasized.

Impacts could be further reduced by:

- evaluating more environmentally friendly means of transportation, as Italian raw materials currently travel by road. It would be better if they traveled by train;
- evaluating raw materials located close to the production site.

It was very difficult to compare the present study with others in the literature. Points of agreement were found, such as the high impact of transportation, and others in disagreement, such as the impacts generated by manufacturing. Working with a specific plant and at an industrial level has the advantage of being at an advanced stage of scale-up; on the other hand, there are limitations due to the inherent nature of the considered plant, in particular the cogeneration aspect, which greatly reduces the impact of the manufacturing phase. In any case, it is still possible to state that pumice and lapillus-based tiles, in addition to having good technological performance, are more environmentally and human health friendly than the considered reference. Although the impacts can be further reduced, the obtained results strengthen the importance of using these types of scraps for the production of porcelain stoneware.

CRediT authorship contribution statement

F. Altimari: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **F. Andreola:** Writing – review & editing. **I. Lancellotti:** Writing – review & editing, Conceptualization. **L. Barbieri:** Writing – review & editing, Conceptualization.

Teresa Cotes-Palomino: Writing – review & editing, Supervision, Resources, Conceptualization. **Carmen Martínez-García:** Writing – review & editing, Resources, Conceptualization. **Manuel Uceda-Rodríguez:** Investigation, Formal analysis. **Ana Belen López-García:** Writing – review & editing, Validation, Supervision, Resources, Conceptualization.

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.

Data availability

The data that has been used is confidential.

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