Received: 19 December 2024 | Revised: 31 January 2025 | Accepted: 17 February 2025

DOI: 10.1111/ijac.15097

International Journal of Applied Ceramic TECHNOLOGY
Ceramic Product Development and Commercialization

REVIEW ARTICLE

Challenges and opportunities for increase sustainability and energy efficiency in ceramic tile industry

Carine Lourenco Alves[1] | **Julia de Oliveira Martins Müller**[2] | **Agenor de Noni Jr.**[2] | **Stefan Heinrich**[1]

[1]Institute of Solids Process Engineering and Particle Technology, Hamburg University of Technology, Hamburg, Germany

[2]Department of Chemical Engineering (EQA), Federal University of Santa Catarina, Florianópolis, SC, Brazil

Correspondence
Carina Lourenco Alves, Institute of Solids Process Engineering and Particle Technology, Hamburg University of Technology, Hamburg 21073, Germany.
Email: carine.lourenco.alves@tuhh.de

Funding information
German Research Foundation, Grant/Award Number: DFG DO 2026/6-1; German Research Foundation (GRK2462), Grant/Award Number: 390794421; DAAD Pro Bral, Grant/Award Number: 57447192; CAPES-DFG PIPC, Grant/Award Number: 88881.207634/2018-01

ABSTRACT
The ceramic tile has an estimated global warming potential of 14.4 kg CO_2 equivalent per square meter, with CO_2 emissions contributing to approximately 92.1% of the overall impact. The total emissions amount to 19 million tons of CO_2 annually, representing approximately 1% of Europe's industrial emissions that are regulated by the EU Emissions Trading System. As a result, the ceramic industry is under growing pressure to decrease carbon emissions and improve energy efficiency in accordance with Europe's new climate and energy objectives. However, this process holds a clear challenge. This work addresses the challenges and opportunities facing the ceramic tile industry in reducing carbon emissions and improving energy efficiency in line with new climate and energy goals worldwide. It highlights the importance of adopting innovative strategies across product, process efficiency, and market and supply chain aspects.

KEYWORDS
ceramic tiles, energy efficiency, sustainability

1 | INTRODUCTION

Climate change presents substantial global challenges. The worldwide scarcity of resources has become a significant policy concern, driven by projections of increasing populations and the depletion of natural resources. Consequently, the term sustainability gained significant focus, encompassing concepts such as "source reduction," recycling, recovery, waste reduction, cleaner manufacturing technologies, and industrial ecology.[1] In this context, ceramics, although made from natural materials, are recognized for their substantial energy consumption and the release of pollutants during production. Consequently, this industry has received additional attention.

Ceramic tiles are manufactures by a sequence of processing steps including raw material preparation, forming or shaping, drying, glazing, and firing.[2] The preparation of the raw materials basically occurs in either of two forms: "dry milling" or "wet milling," distinguishing between the dry and wet route, respectively.[3,4] In the wet route, after the wet milling, the suspension undergoes spray drying. The forming methods can be categorized into three main groups, based on the increasing moisture content: (1) forming through uniaxial or isostatic semi-dry pressing of a granulate material with low moisture content and/or binder addition; (2) plastic forming through extrusion, plastic pressing, wheel throwing, etc., using plastic masses; and (3) forming through air slip casting or pressure casting

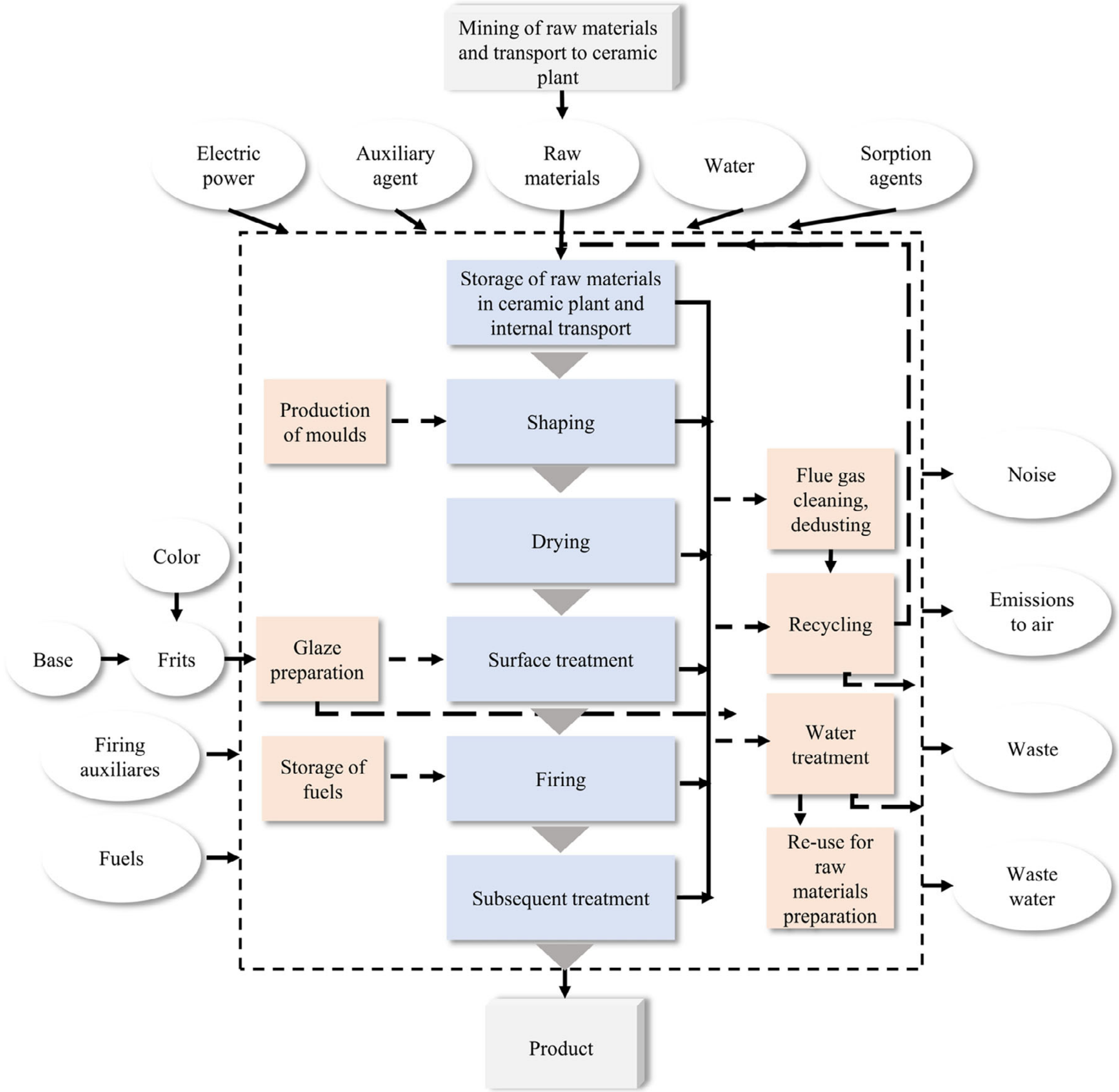

FIGURE 1 Stage steps in the manufacture of ceramic products.[6]

of suspensions.[5] Figure 1 shows schematically the manufacturing steps for the production of ceramic products including the possible or necessary supply and disposal of facilities.[6]

The entire process consumes significant amount of energy and natural resources, including water. Average water consumption per square meter of manufactured tiles is around 20 L, and energy consumption is around 32 kWh.[7] The majority of energy consumption (90%) is attributed to thermal energy consumption including the spray drying of the body suspensions, drying of the tile and the firing stage. Spray drying of the slurry accounts for ≈36% of total thermal consumption, drying of newly formed tile bodies (known as green tiles) accounts for ≈9%, and tile firing accounts for ≈55%—the highest within the manufacturing process.[8,9] Since this thermal energy is obtained from the combustion of fossil fuels, the estimated global warming potential for ceramic tile was 14.4 kg CO_2 equivalent per square meter and the CO_2 emissions account for approximately 92.1% of the overall effect.[1] It is important to notice the natural gas cogeneration facility in many European plants, which increase the overall energy efficiency on spray drying process.[10]

Despite this, there is an increase in the demand for these products worldwide. For example, the European ceramic industry generated a total revenue of €26 billion within the European Union in 2021, with over one-third of its production volume being exported to countries outside the EU.[11] The total emissions accounted 19 million tons of CO_2 per year, accounting for approximately 1% of Europe's industrial emissions regulated by the EU Emissions Trading System.[2,11] The European Union's clear trajectory toward reducing carbon emissions through initiatives like the European Green Deal and the legally binding

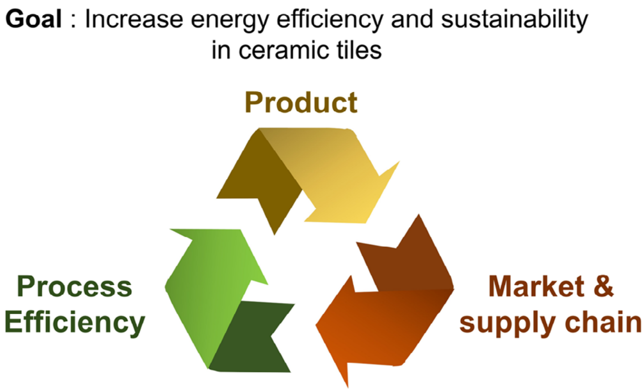

FIGURE 2 Proposed integrated approach scheme for increase energy efficiency and sustainability in ceramic tiles.

European Climate Law has brought increased focus to the sustainability of the ceramic industry.[12,13] The European Climate Law enacts the objective outlined in the European Green Deal to achieve climate neutrality for Europe's economy and society by 2050. The legislation additionally establishes a goal of decreasing overall greenhouse gas emissions by a minimum of 55% by the year 2030.[11]

This critical review focused on identifying and analyzing different sustainability strategies and opportunities using an integrated approach for the ceramic tile industry. The study centers around analyzing the supply chain of ceramic tiles, market trends, current technologies, and automation tools, with a particular emphasis on comprehending the interrelationships among key factors in ceramic tile production. Additionally, the review aims to enhance the understanding of local manufacturers regarding the adoption of low-carbon processes and digitalization tools, which are significant obstacle.[14] The integrated approach seeks to concentrate on strategies that are interconnected in three main areas: product, market and supply chain, and process efficiency. The proposed approach is seen schematized in Figure 2.

2 | STRATEGIES BASED ON CERAMIC TILE PRODUCT

The global ceramic tiles market is experiencing growth due to the rising demand for ceramic tiles that offer improved aesthetics, durability, ease of maintenance, and resistance to fire, water, and scratches.[6] Moreover, the worldwide ceramic tiles market is expected to witness expansion in the near future owing to the increasing demand for ceramic tiles in various sectors such as hospitals, laboratories, and residential buildings. The exceptional durability, low maintenance requirements, and cost-effectiveness of ceramic tiles are the reasons for this. Furthermore, ceramic tiles serve as a cost-efficient and health-conscious substitute for conventional paints.[12,13]

The technological innovation of this sector are closely related to increasing the size of the plates. Nowadays, it is possible to find since 200 × 200 mm^2 up to 1200 × 2400 mm^2. European and Brazilian markets have exhibited a greater inclination toward larger sizes, with a typical dimension of 900 × 900 × 9 mm^3. On the other hand, the American market has shown a higher tendency to purchase and manufacture smaller sizes, such as 500 × 500 × 7 mm^3.[15] This market trend influences more than just aesthetics. The larger tile sizes exhibit higher thickness in comparison to the smaller ones. For instance, a tile measuring 900 × 900 × 9 mm^3 has a specific mass of approximately 20–22 kg/m^2, whereas the "regular old" size of 500 × 500 × 7 mm^3 has a density of 15–17 kg/m^2. The additional density can be related to the general greater thickness of larger tiles, such as 900 × 900 × 9 mm^3. This increased thickness contributes directly to a higher mass per unit area (kg/m^2), even if the volumetric density of the material remains constant.

The extrapolation of higher specific mass, however, is not linear. Large size products could be made with reduced thickness and vice versa. But, the increasing of both the dimensions and the thickness of the product results in various implications for the manufacturing process and transportation, necessitating, for instance, the recruitment of additional personnel for the application of the tiles, and more complex logistic to deliver the products to end user. The alterations made to the production process have a direct impact on the emissions of CO_2 and process sustainability. It is very tough for a company do not follow the market trends, under the risk to bankrupt. This is the case of the large formats, for instance. One alternative to face both, the business and environment sustainability, is to keep the specific mass under low level, about 15–17 kg/m^2 for any size.

The compromise between large formats and low thickness can only be attained upon low porosity level, a high control of the raw material composition and the process parameters.[16,17] In this regard, porcelain tile is the best alternative as the target concept. Only porosity reduction do not guarantee the higher mechanical performance.[18] The microstructure should be robust, obtained by adequate combination of the raw materials.[16] Strong and resilient microstructure for ceramic tile is based on the control the growth of cracks below the critical threshold and the development of residual stress. When a plate is subjected to a rapid cooling rate, a residual stress profile is generated across its thickness. Additionally, the size of any flaws within the plate may increase compared to plates cooled slowly, particularly for cracks formed around quartz particles.[19,20] The magnitude of the flaw enlargement is contingent upon the rate at which cooling occurs and the characteristics of the microstructure.[20] A slower cooling rate results in a decrease in residual stress and the size of flaws. Nevertheless, the strategy is not implemented in industries due to the lack of kiln preparation. Roller kilns feature a cooling section where the rate of cooling is intentionally reduced to account for the $\alpha \rightarrow \beta$ quartz transition temperature, which occurs only between 650°C and 500°C.[17,21]

Higher mechanical strength and lower flaw size can also be achieved by ideal mullite content in the microstructure. Mullite content ranging from 14% to 17% demonstrates a more pronounced enhancement in bending strength and a decrease in subcritical crack growth.[22,23] Alternatively, Taskiran et al.[24] introduced a porcelain microstructure consisting of anorthite, which is composed of 20% clay mineral, 25% wollastonite, 30% alumina, 20% quartz, and 5% basic magnesium carbonate. Although mullite-based porcelain has been the dominant choice in the porcelain tile market, anorthite-based porcelain offers a lower average sintering temperature, 40°C lower than mullite-based porcelain.[25] This can directly contribute for a more sustainable firing operation. However, the sintering temperature range for anorthite-based porcelain is more than 40°C narrower than that of mullite-based porcelain, which is the main obstacle for the industrial application of anorthite-based porcelain. The application of combined system of the SiO_2–Al_2O_3–K_2O and SiO_2–Al_2O_3–CaO ternary systems, as well as flux consisting of both feldspar and a magnesia-containing component, may improve the firing behavior and further promote the industrial application of anorthite.[25–27] Studies in this specific field may be particular interest for the aspect of enhancing the sustainability of processes. This paper specifically examines ceramic tiles and their widely established, internationally recognized manufacturing processes. While innovative alternatives such as sustainable ceramic/polymer composites, recycled glass tiles, geopolymers, bamboo-based tiles, and bio-composite tiles demonstrate significant potential for reducing CO_2 emissions in surface covering,[28,29] they are beyond the scope of this study.

The open porosity of the ceramic tiles is used to classified different products. Table 1 presents the groups from <0.5% up to >10% water absorption, according to the international standards of ceramics.[30]

The groups AIII and BIII are products for inner wall surfaces, while all other class are applied in general to floor covering. Among floor tiles, porcelain tile, BIa has the highest market value while BIIb has the lowest market value. Products from BIb to BIIa usually have low market appeal. They are not labeled as porcelain tile and cannot achieve the same level of market price, although can also rise equivalent level of durability. At the same time, those groups have higher production cost in comparison to BIIb, usually made by dry route, and cannot compete with them. After almost 40 years of successful end use mechanical performance of porcelain tile,[31] the ISO/TC 189 Ceramic Tiles Working Group has approved water absorption standard ISO13006:2018[30] has made a modification to the standard absorption test method. Instead of using the 2 h boiling water method, the new standard method involves placing the sample in a vacuum chamber before exposure to ambient water. As a result, the open porosity is more accurately measured. In the other hand, the water absorption limits were not reviewed in the same way, keeping the old values as shown in Table 1. Figure 3 shows the results of water absorption for three products for comparing the effect of the test method.

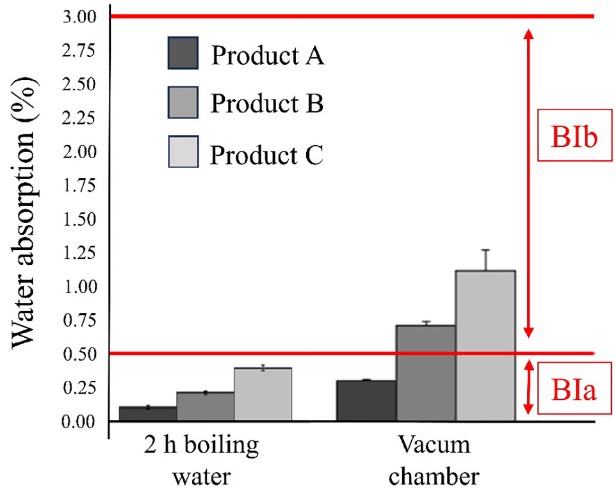

FIGURE 3 Illustration of how the implementation of the new standardized method for determining water absorption impacts the classification of labels.[30]

It can be checked the products B and C, with the new standard, are out of the range and cannot be sold as porcelain tile. The adaption to the new standards requires more energy expenditure as well as more raw materials and process restriction, which goes to the opposite direction to environmental sustainability

When comparing both categories BIa and BIb, it can be observed that they exhibit close mechanical properties. The mechanical strength is measured in terms of flexural strength. The range of values for compressive strength is greater than 35 MPa for BIa and greater than 30 MPa for BIb.[11,30] The actual mechanical strength of commercial porcelain tiles typically ranges between 30 and 90 MPa, which in many cases significantly exceeds the requirements set by the standards.[28] These strength levels can be readily achieved by tiles in the BIb category. Consequently, the BIb category has the potential to receive additional market support, as it can be manufactured

TABLE 1 Classification of ceramic tiles with respect to water absorption and shaping.[30]

Shaping	Group I ($\varepsilon \leq 3\%$)	Group IIa ($3\% \leq \varepsilon \leq 6\%$)	Group IIb ($6\% \leq \varepsilon \leq 10\%$)	Group III ($\varepsilon \geq 10\%$)
A: Extruded	Group AIa ($\varepsilon \leq 0.5\%$) Group AIb $0.5\% \leq \varepsilon \leq 3\%$	Group AIIa-1[a] Group AIIa-2[a]	Group AIIb-1[a] Group AIIb-2[a]	Group AIII
B: Dry pressed	Group BIa ($\varepsilon \leq 0.5\%$) Group BIb $0.5\% \leq \varepsilon \leq 3\%$)	Group BIIa	Group BIIb	Group BIII[b]

[a]The groups AIIa and AIIb are subdivided into two parts (parts 1 and 2) with different product requirements.

[b]Group BIII essentially applies to glazed tiles. There is a small number of dry-pressed unglazed tiles manufactured with a water absorption of more than 10% to which this product group does not apply.

using both "wet" and "dry" production routes. This context also opens up a discussion about the concept of "just-enough quality" or "sufficient quality" in product development and engineering, emphasizing the balance between meeting performance requirements and optimizing manufacturing processes.[32] This concept emphasizes the importance of delivering the precise level of quality that is necessary for a product to fulfill its intended purpose, without going beyond the specified requirements or engaging in excessive engineering. The BIb category offers a satisfactory level of quality for applications such as residential construction, while also reducing environmental impact.

An increase in the production of BIb materials would enable the use of other sources of raw materials, as the quality requirements are less stringent than those of BIa. The raw materials used are obtained from sources considered non-renewable, as they are produced through slow environmental processes and generally have limited quantity. Given this scenario and the current growth of industrial production, one possibility would be the use of certain types of waste as a source of alternative raw material for ceramic materials.[33] In this way, the recycling of industrial by-products or waste materials is seen as a waste reduction strategy as well as a way to reduce the environmental consequences arising from the extraction of conventional raw materials.

Dondi et al.[34] reported that in recent years, ceramic tile production strategies in Spain and Italy have diverged significantly. Italy has increasingly focused on porcelain stoneware, advancing toward the production of larger sizes and slabs. In contrast, Spain has adjusted its production balance, significantly increasing the share of porcelain stoneware at the expense of red-firing floor tiles. This shift has intensified the pressure on raw material supply chains, as both countries rely on the same sources for approximately 80% of their raw materials.[35] Spain, in particular, appears more exposed to the supply of highly plastic ball clays from Ukraine and sodic feldspar from Turkey, creating vulnerabilities due to growing competition with other European and global ceramic producers.

To mitigate these challenges, Dondi et al.[34] highlighted several strategies:

1. Enhancing transport logistics from raw material production centers to ceramic districts by implementing efficient rail corridors and utilizing large-tonnage ships to reduce costs.[36] For instance, German ball clays are widely used in Italy due to direct rail connections, whereas raw materials from France and the UK face higher transport costs because of road transport and low-tonnage shipping.
2. Improving the characteristics of local raw materials through beneficiation processes to remove impurities, such as iron and coarse particles, with several installations already achieving positive results.[4]
3. Replacing natural raw materials with secondary raw materials in alignment with Circular Economy principles. A notable example is the use of recycled glass as a promising substitute for feldspar in fluxes.
4. Utilizing enablers and additives, such as binders and energic fluxes, to improve process behavior and product properties. These innovations enable the use of lower-plasticity clays and feldspars with reduced fusibility.

According to Dondi et al.,[34] these measures not only address raw material supply risks but also support future research within the framework of the Circular Economy. By partially substituting natural raw materials with secondary alternatives and developing new ceramic batch concepts, the industry could more effectively exploit underutilized European deposits of ceramic raw materials, contributing to sustainability and resilience in ceramic tile production.

Numerous studies have been conducted over the past 20 years to achieve this goal in the ceramic industry. Based on their findings, it can be inferred that tile and insulation refractory industries possess significant potential for cost-effective utilization of waste ingredients compared to other ceramic industries, owing to their diverse range of properties.[37] Thus, some wastes, for example, rice husk ash,[38,39] fly ash,[40,41] blast furnace slag,[42] polished tile waste,[43] petroleum waste,[44] glass waste,[45] and many others have been recognized as potential materials to reuse in the making of different ceramics.

Due to its promising properties, flying ash is widely regarded as the optimal waste material for the manufacturing of ceramic tiles. Due to its elevated alumina content, it is a viable choice for manufacturing mullite ceramics. This can be achieved by incorporating additional sources of Al_2O_3, while maintaining the Al/Si weight ratio at around 2.55. Gomes and Holanda[46] conducted a recent study to assess the potential of utilizing firewood ash waste as a sustainable source of raw materials for ceramic tiles. Gomes and Holanda[46] evaluated different formulations with firewood ash contents ranging from 0 to 10 wt.% and, consequently, from 12.5 to 2.5 wt.% of quartz to keep the appropriate alumina content in the formulation. The experiments have determined that incorporating firewood ash waste, which is abundant in CaO and also contains significant amounts of SiO_2, Al_2O_3, Fe_2O_3, MgO, and K_2O, improves the composition of ceramic floor tiles by increasing the concentration of fluxing oxides. The partial substitution of quartz with firewood ash waste had a positive impact on the technical characteristics and overall quality of the ceramic floor tiles. The study revealed that substituting up to 10 wt.% of quartz with firewood ash waste enables the manufacturing of ceramic floor tiles with reduced water absorption (classified as BIa and BIb groups) at lower firing temperatures.

3 | STRATEGIES BASED ON MARKET AND SUPPLY CHAIN

Another facet of sustainability pertains to the market and supply chain of ceramic tiles. The two Asian giants China and India and the two largest European producers Spain and Italy together accounted for 64.5% of global exports in 2022. Despite world exports accounting for 16.5% of production and 16.7% of global consumption, the majority (63.4%) of these exports were shipped within the same geographical region as their production. For instance, 80.2% of South America's exports remained within South America, 81.4% of North America's exports were sold within the NAFTA region (United States, Mexico, and Canada), and 72.5% of Asian exports were shipped to other Asian countries.[11,47] The European Union remained a partial anomaly, as 46.9% of its exports were sold in markets outside of the EU. This analysis is supported by the observation that the distribution of world production and consumption shares tends to be comparable across continents. Asia was responsible for 73% of global production and 71% of global consumption. Europe (EU + non-EU) accounted for 11.4% of production and 10% of consumption. The Americas

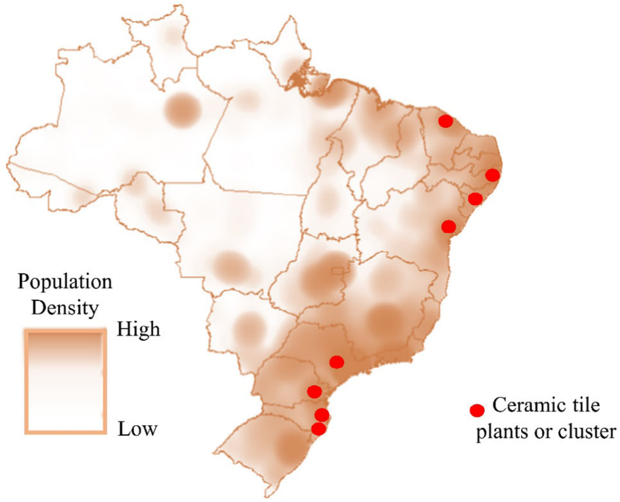

FIGURE 4 Population density analysis of Brazil in 2021 in relation to the geographical location of ceramic tile manufacturing clusters or plants.[48]

contributed 9.7% to production and 11.1% to consumption. Africa accounted for 6.2% of production and 7.6% of consumption.[6]

In terms of export inclination among different continents or macro-regions, the European Union maintained its position as the region with the highest export proportion in 2022, accounting for 76.2% of its production.[47] The remaining regions had significantly lower export volumes: non-EU Europe exported 27% of its output volumes, North America 12.7%, South America 13.2%, Asia 11%, and Africa just 6.4%.[47] The trend in import/export flows confirms the tendency for tiles to be produced close to markets.

Ceramic tile producers are frequently situated near areas of high population density for several reasons. This includes the advantage of being close to the market, which reduces transportation costs and allows for quicker delivery. Additionally, being in proximity to suppliers of raw materials helps to minimize transportation costs and lead times.[13,15] For instance, Brazil is the third top producer and consumer since 2018.[6] There is a noticeable correlation between the presence of ceramic tile plants or clusters and population density, as observed in Figure 4.

By minimizing the proximity to local producers/suppliers, the distance between raw material deposits, manufacturing plants, and markets is reduced, resulting in lower transportation costs and decreased CO_2 emissions. Furthermore, according to the life cycle assessment, the choice of raw material sources close to the factories and the use of transport with lower environmental impacts are fundamental, as the sourcing of raw materials is the stage that causes the greatest impact, both on the environment and on human health.[13,27,49,50] One of the top Brazilian ceramic company has successfully implemented this

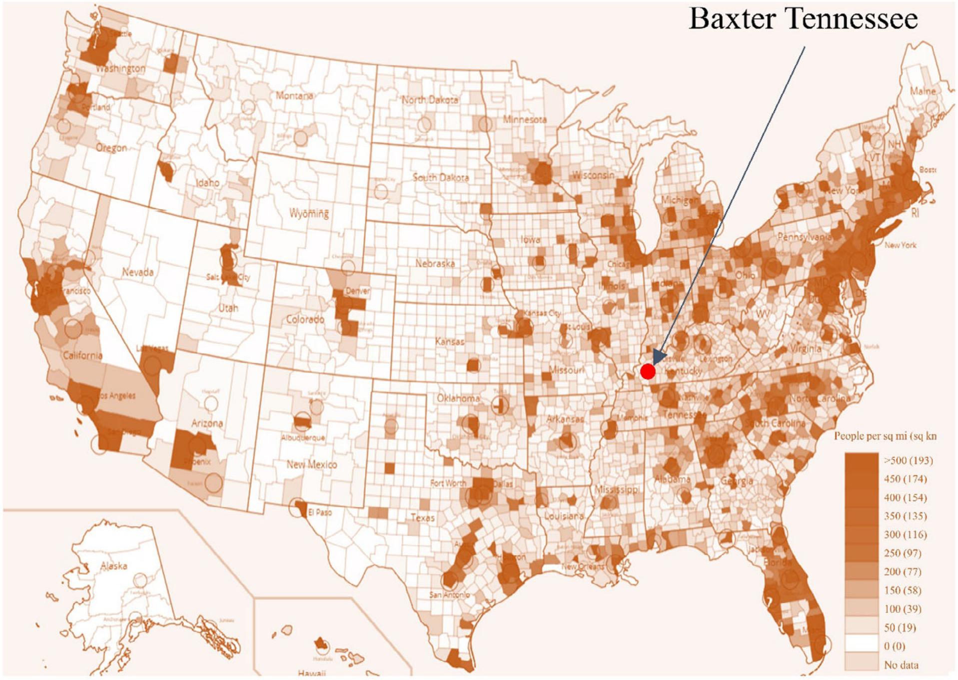

FIGURE 5 Population density analysis of EUA in 2021 in relation to the geographical location of new factory Portobello.[51]

strategy for its state-of-the-art decoration and end-of-line technology facility in Baxter, Tennessee.[6] The location of the factory compared to population density of EUA in 2021 can be seen in Figure 5. The company has allocated a substantial amount of US $180 million toward this project.[6] Multiple approaches for achieving environmental sustainability were incorporated to enhance process efficiency.

4 | STRATEGIES BASED ON PROCESS EFFICIENCY

Aiming to contribute to climate-neutrality targets, several advanced technologies may be applied to all sectors including carbon removal technologies and offsetting measures. Figure 6 presents the main technologies deployable in the ceramic industry to contribute to climate neutrality targets.[11,14]

However, it is not yet clear how, and to what extent, these technologies will be applied. Most of the technologies presented are future technologies or complete breakthroughs. For these technologies to develop and to be applied, several conditions are essential—in particular, the support of industry regulators and more studies from academia.

Considering the case of the Baxter plant as an example, significant feature stands outs regarding new sustainable technologies, such as the continuous modular mills (MMC) and an atomizer for mold flux production line (ATM) spray dryer. These advanced technologies are highly efficient according to the supplier, offering significant reductions in water and energy consumption. The multichannel horizontal with seven-tier (E7P) dryer and a new modulated air-gas kiln named as FMA Maestro were set up to carry out the tasks of drying and firing. In addition, super-heated combustion air recovery system (SPR) was integrated to guarantee low energy consumption and emissions in accordance with Tennessee's strict atmospheric emissions regulations.[52]

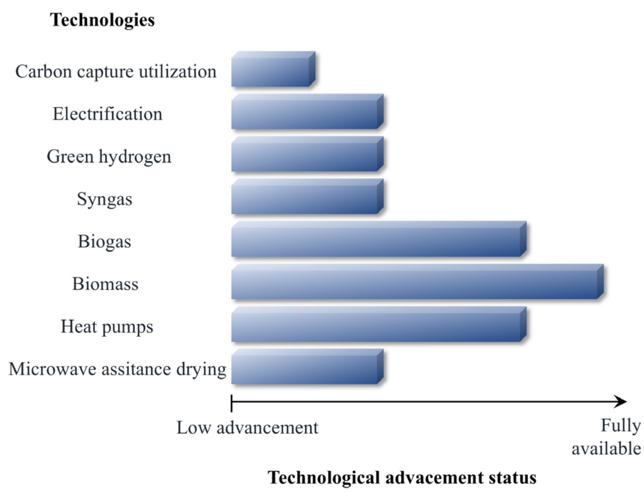

FIGURE 6 Comparison of new technologies and technological advancement status.[11]

In addition, the adopting of renewable energy sources, such as renewable electricity, green hydrogen, green synthetic gas, or biofuels, will significantly decrease emissions. Thus, the challenge relies on a systematic reduction of carbon emissions in the power sector and a greater accessibility of environmentally friendly hydrogen, synthetic gas, and biofuels. Depending on the type of plant and availability of resources options, some plants could switch to decarbonized electricity. Alternatively, they may eventually adopt biofuels, green hydrogen, or green synthetic gas as alternative energy sources. Given that kilns have a lifespan of over 40 years and changing the fuel type requires a significant financial investment (except when switching from natural gas to biogas), it is crucial to carefully consider the energy source and ensure a consistent and affordable fuel supply. In the worldwide scenario, Brazil is a global leader in the use and production of biofuels. Diesel in Brazil contains 12% biodiesel, with plans to increase this to 15% by 2026.[53] Gasoline blends include approximately 27% ethanol, demonstrating the country's significant biofuel integration.[54] Additionally, more than 80% of Brazil's electricity is sourced from renewable energy, primarily hydropower, supplemented by wind, solar, and biomass.[55]

Based on this, one of the largest manufacturer of ceramic tiles in Europe, has decided to proceed with the eCombustible project, which is a new, clean energy source based on hydrogen. This energy source has the capability to replace natural gas without requiring any modifications to the current plant and machinery.[6,56] The initial practical application of this technology can be seen in the spray drying facility at the Onda factory. This facility is the world's first to carry out spray drying without any CO_2 emissions, representing a significant milestone in the gradual elimination of natural gas usage in the entire production process. The company aims to completely transition away from natural gas by 2025 or 2026, with an investment of €250 million.[56] eCombustible employs an electrolysis process and electromagnetic fields to convert water into fuel using electrical energy. The resulting fuel is tailored to specific requirements. The water undergoes treatment in a plant where substances such as heavy metals are eliminated. It then proceeds to the fuel production module, where it is divided into hydrogen and oxygen. Every module consists of 36 cells and operates on electrical pulses with precise frequencies that greatly decrease energy usage. Subsequently, the hydrogen undergoes a process in a magnetic reactor, wherein it is tailored to align with the energy composition and flame properties of the fuel it is substituting. The hydrogen and oxygen are stored in separate tanks and later transported to the burner, where they combine to form the final molecule of eCombustible. The patented eCombustible process generates a fuel that is both clean and efficient. When this fuel is burned, it only releases water vapor, completely eliminating carbon emissions.[6,11,14,47]

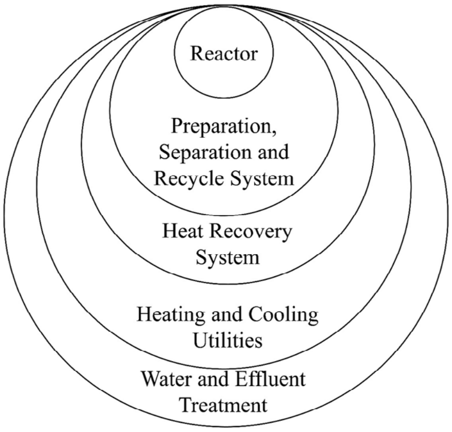

FIGURE 7 Onion ring approach for determination of sustainability strategies for ceramic tile processing.[23]

The above cases demonstrate the ceramics industry's commitment to reducing carbon emissions. However, in order to achieve carbon neutrality, all factories must migrate to renewable energy sources. To do this, the EU industry will require approximately 50 000 terajoules of green hydrogen, biogas, and green electricity each by 2050.[11] The current availability of these quantities is not accessible to the industry, and their supply is contingent upon various factors, including infrastructure and the appropriate legal and policy framework. According to the European Ceramic Industry Association, the investment required to achieve carbon neutrality will significantly increase over time, reaching €500 million by 2030 and exceeding €1.5 billion annually by 2050.[6,11] Therefore, optimizing the process is essential for cost reduction.

The kiln is responsible for over 80% of our industry's emissions, which are primarily caused by energy consumption. The process flowchart development by Onion's ring approach[32] illustrates the strategies for achieving more sustainability in the ceramic tiles firing, as schematized in Figure 7.

According to this process flowchart, in order to achieve sustainability in the ceramics sector, the strategy must be to reduce the impacts caused by the firing stage. Based on this, alternatives are sought that directly or indirectly influence this stage, such as the addition of a heat recovery system, optimization of the heating and cooling system, new formulations, among others. However, increasing the efficiency of this stage presents some challenges that need to be overcome. Table 2 shows the requires challenges involving the kiln for increase sustainability and the parameter to be changed.

Over the past century, single firing has become the dominant process in ceramic tile production, largely replacing the traditional double-firing method.[8,57] This transition has significantly improved energy efficiency by reducing

TABLE 2 Challenges for increase sustainability during firing in ceramic tile manufacturing and their strategy.

Challenge	Strategy
Lowering firing temperature	Batch composition
Lowering firing time	Particle size reduction
Improving kiln productivity and stability	Bottleneck management
Lowering flue gases flux	Lowering O_2 in the kiln
Increasing heat recovery	Refluxing heat
Lowering heat loses	Insulation

the thermal energy required for firing. Furthermore, it has expanded the possibilities for product innovation, enabling the development of larger tile formats and a broader range of water absorption characteristics.[14,58] While this work focuses specifically on ceramic tiles, similar energy efficiency challenges and product design opportunities are encountered in other ceramic sectors, such as whiteware and bricks. These industries face parallel demands for sustainable production methods and innovative approaches to meet evolving market and environmental requirements.

One crucial requirement to accomplish optimization is the digitization of plants, which can yield significant advantages in terms of process control, uniform quality, and intelligent management of production flows. Several advancements are being implemented, such as enhancing conventional controls (such as size, flatness, density, edges, etc.) by incorporating process feedback mechanisms (where upstream machines can automatically rectify defects).[12] Toward the digitalization of ceramic tiles and establishing a digital twin for the complete manufacturing sequence, an integrated flowsheet process model has been developed and utilized to simulate the porcelain tile manufacturing process by flowsheet simulations.[16]

The concept of flowsheet simulation involves solving material and energy balances numerically, as well as determining intensive state variables for various process structures. Flowsheet simulation tools have become widely accepted in the field of chemical engineering for processes involving fluids. Nevertheless, the utilization of such instruments is still relatively uncommon for procedures that involve solid materials, particularly ceramic powders. The development and application of tools for the solid process were initiated only in recent years.[59] One of the reasons is the increased complexity resulting from a more detailed description of solids, which involves the use of multidimensional distributed parameters. Particles can be distributed based on different property dimensions, such as size, density, moisture content, and so on. Therefore, in order to accurately compute material streams that are described by multidimensional parameters, it is necessary to utilize specialized techniques such as transformation matrices.[60]

An open-source simulation framework called Dyssol has been developed for performing dynamic and steady-state flowsheet calculations of solids processes.[61] Alves et al.[16] utilized Dyssol to implement semi-empirical models for the entire processing plant for porcelain tiles. The flowsheet simulation was validated based on industrial data Brazilian porcelain factories. The simulation results demonstrate a strong correlation with the experimental data, considering various compositions and processing parameters. The simulation methodology was further extended beyond the modeling of process behavior and sensitivity analysis—to the energy optimization of the entire production process.[62] Different case studies were evaluated including the different cost productions for both Brazilian and Spanish scenarios, which are significant as leading global producers.[63,64] By keeping the final open porosity of tiles between 4.8% and 5.1%, same firing time, longer milling times can result in lower firing temperatures to retain the same final porosity range, which can considerably save thermal energy, resulting in the same production, but at a lower cost. In contrast, the same firing temperatures can be maintained for shorter firing times if longer milling times are used, resulting in increased productivity for the same thermal energy consumption. Increased milling times did not compromise the overall costs in both Brazil and Spain, even though there is an increase in electrical energy consumption. Similarly, longer milling times can reduce the CO_2 emission rate due to the reduced firing temperature.[64] Figure 8 shows the results from the simulation case study (a) comparing the production rate and CO_2 emissions for different milling times and (b) comparing the costs of the Spanish scenario and milling time for different firing temperatures.

In another case study, Alves et al. integrated the composition data of raw materials into a simulation framework.[64] This allowed for a precise evaluation of how different compositions affect the overall process and its resulting CO_2 emission rate. The batch composition was adjusted to achieve stable process and ensure product quality based on the mullite content.[17] Even though talc has been associated with higher prices, this flux contributes to lowering total production costs and CO_2 emissions in both Brazilian and Spanish scenarios.[64] Figure 9 shows the simulation results comparing CO_2 emissions according to different compositions and its influence on total costs in the Spanish scenario.

The simulation methodology is highly relevant in decision making, even before the acquisition of raw materials and the modification of the manufacturing sequence. Manufacturers can evaluate the optimal raw material

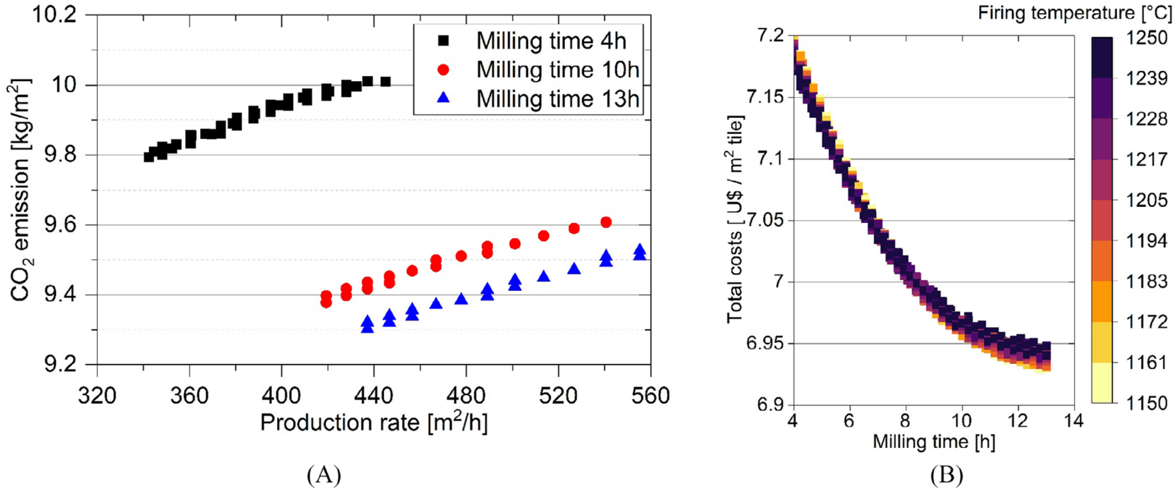

FIGURE 8 (a) Comparison between the production rate and CO_2 emissions for different milling times. (b) Comparison between the costs of the Spanish scenario and milling time for different firing temperatures.[63]

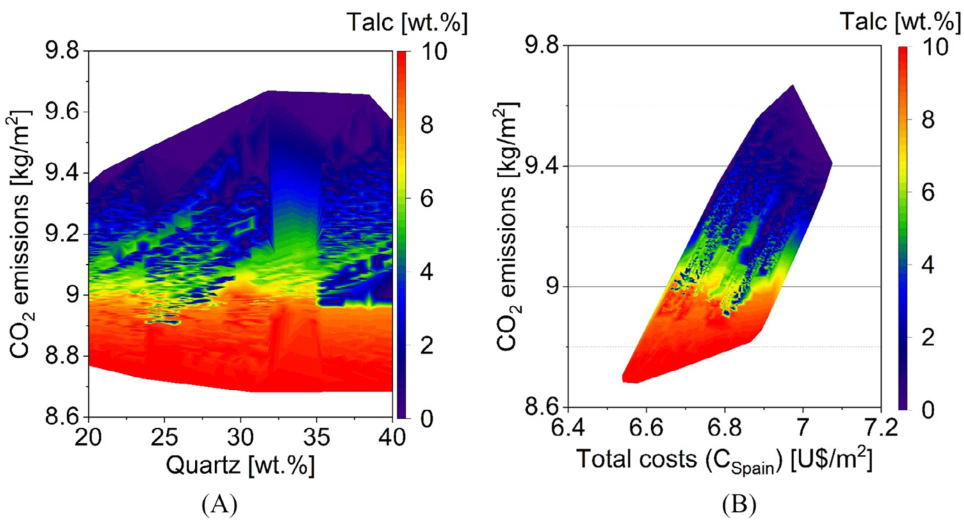

FIGURE 9 Analysis from flowsheet simulations (a) comparison between CO_2 emissions, quartz, and talc content. (b) Comparison between CO_2 emissions and total costs on Spanish scenario based on different talc content.[64]

composition that minimizes production costs and CO_2 emissions by employing simulation. Additional research is necessary to assess the supply chain, specifically in regards to purchase costs and the sustainability as additional emissions linked to raw materials. Moreover, it is imperative to analyze the possible consequences of modifying the equipment and how the modifications on the processing sequence influences the life cycle of the equipment. The utilization of these tools holds promise for decision-making models, digitalization, and the development of digital twins is essential for streamlining processes, improving efficiency, and maintaining competitiveness. Nevertheless, although these technologies possess significant potential, their extensive adoption necessitates additional incentives from the industry.

5 | CONCLUSION

The ceramic industry is dedicated to ongoing enhancements in the energy efficiency of its installations in order to decrease the overall demand for energy and consequent CO_2 emissions. A comprehensive review was conducted to address the current state of ceramic tile production and explore strategies for reducing carbon emissions in the ceramic industry, in line with the new climate and energy goals in Europe. For this, a review based on three pillars have been proposed: product, market and supply chain, and process efficiency.

Regarding the product aspect, strategies include the increased application of recycled material as well increase the concept of best fit product to its application, adopting the concept of "sufficient quality" that highlights the significance of providing the exact level of quality required for a product to meet its intended purpose. In this sense, the products from BIb category provides a commendable standard of excellence for applications such as residential construction, while simultaneously mitigating impacts on the environment, without the requirement of category BIa of porcelain tiles that demands higher energy costs.

From a market and supply chain perspective, it is evident that local suppliers should be prioritized. Additionally, conducting an analysis of raw material purchases can help avoid transportation costs and unnecessary emissions that are unrelated to the actual manufacturing of the product. To achieve the new European climate and energy targets, it is crucial to adopt advanced technology and management strategies, as well as embrace innovative technologies. Nevertheless, the impact of these new technologies on product quality remains uncertain, requiring additional research.

The key improving efficiency relies on optimizing sintering/firing operation. While the primary barriers may be related to finances and economics, additional obstacles can be observed. An important obstacle is the limited understanding among local manufacturers regarding the adoption of low-carbon processes and the lack of understanding how the modification of process operations influence the entire manufacturing chain. Simulations and digitalization can be highly significant in this regard. Although simulation approaches have been proposed as effective tools for decision making and the development of digital twins, it is crucial to acquire additional industry support to progress in this direction. By providing incentives for the implementation of these advanced simulation techniques, the industry can discover fresh prospects for growth, innovation, and environmentally friendly progress.

ACKNOWLEDGMENTS

We gratefully acknowledge the financial support from the German Research Foundation (DFG). Project ID: 418788750 (DFG DO 2026/6-1) and DFG Graduate School GRK 2462 "Processes in natural and technical particle fluid systems (PintPFS)" (project no. 390794421) as well the DAAD (Pro Bral 57447192) and CAPES-DFG program (PIPC 88881.207634/2018-01).

ORCID

Carine Lourenco Alves https://orcid.org/0000-0002-7144-6152
Julia de Oliveira Martins Müller https://orcid.org/0009-0007-8976-5235
Agenor de Noni Jr. https://orcid.org/0000-0001-9713-5283
Stefan Heinrich https://orcid.org/0000-0002-7901-1698

REFERENCES

1. Türkmen BA, Duhbacı TB, Özbilen ŞK. Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey. Clean Techn Environ Policy. 2021;23:1295–310.
2. Boschi G. Sustainability and environmental impact of the Italian ceramic tile industry. AMSDottorato. 2023.
3. Nassetti G, Timellini G. Granulation of powders for Whitebody ceramic tiles. Materials & Equipment/Whitewares: Ceramic Engineering and Science Proceedings. 1991. p. 328–42.
4. Soldati R, Zanelli C, Cavani G, Battaglioli L, Guarini G, Melandri C, et al. Powder rheology and compaction behavior of novel micro-granulates for ceramic tiles. Powder Technol. 2020;374:111–20.
5. Monfort E, Mezquita A, Vaquer E, Celades I, Sanfelix V, Escrig A. Ceramic manufacturing processes: energy, environmental, and occupational health issues. Comprehensive Mater Process. 2014;8:71–102.
6. Ceramic World Web. Ceramic world review. Available from: https://ceramicworldweb.com/en/tag/ceramic-world-review Accessed 30 Apr 2024.
7. Monfort E, Mezquita A, Granel R, Vaquer E, Escrig A, Miralles A, et al. Analysis of energy consumption and carbon dioxide emissions in ceramic tile manufacture. Bol Soc Esp Ceram Vidr. 2010;49:303–10.
8. Ferrer S, Mezquita A, Aguilella VM, Monfort E. Beyond the energy balance: exergy analysis of an industrial roller kiln firing porcelain tiles. Appl Thermal Eng. 2019;150:1002–15.
9. Chitwaree S, Tiansuwan J, Thavarungkul N, Punsukumtana L. Energy saving in sintering of porcelain stoneware tile manufacturing by using recycled glass and pottery stone as substitute materials. Case Stud Thermal Eng. 2018;11:81–88.
10. Branchini L, Bignozzi MC, Ferrari B, Mazzanti B, Ottaviano S, Salvio M, et al. Cogeneration supporting the energy transition in the Italian ceramic tile industry. Sustainability. 2021;13:4006.
11. The European Ceramic Industry Association. Ceramic roadmap to 2050: continuing our path towards climate neutrality.
12. Mezquita A, Monfort E, Ferrer S, Gabaldón-Estevan D. How to reduce energy and water consumption in the preparation of raw materials for ceramic tile manufacturing: dry versus wet route. J Cleaner Product. 2017;168:1566–70.
13. Ros-Dosdá T, Fullana-i-Palmer P, Mezquita A, Masoni P, Monfort E. How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective. J Cleaner Product. 2018;199:554–64.
14. Furszyfer Del Rio DD, Sovacool BK, Foley AM, Griffiths S, Bazilian M, Kim J, et al. Decarbonizing the ceramics industry: a systematic and critical review of policy options, developments and sociotechnical systems. Renew Sustain Energy Rev. 2022;157:112081.
15. Boschi G, Masi G, Bonvicini G, Bignozzi MC. Sustainability in Italian ceramic tile production: evaluation of the environmental impact. Appl Sci. 2020;10:9063.
16. Alves CL, de Noni Jr. A, Janssen R, Hotza D, Neto JBR, Gómez González SY, et al. Integrated process simulation of porcelain stoneware manufacturing using flowsheet simulation. CIRP J Manuf Sci Technol. 2021;33:473–87.
17. de Noni Jr. A, Canever SB, Henrique P, Da Silva RR. Microstructure-oriented porcelain stoneware tile composition design. Ceram Int. 2023;49(14):24558–65.

18. Dondi M. Mechanical and tribological properties of ceramic tiles: a reappraisal: seramik karolarin mekanik ve tribolojik özellikleri. Conference: 4th SERES '07. 2007.
19. de Noni Jr. A, Hotza D, Soler VC, Vilches ES. Influencia del enfriamiento de la etapa de cocción sobre las propiedades mecánicas del gres porcelánico. Bol Soc Esp Ceram Vidr. 2007;46:163–70.
20. de Noni Jr. A, Hotza D, Soler VC, Vilches ES. Influence of macroscopic residual stresses on the mechanical behavior and microstructure of porcelain tile. J Eur Ceram Soc. 2008;28:2463–69.
21. Mezquita A, Boix J, Monfort E, Mallol G. Energy saving in ceramic tile kilns: cooling gas heat recovery. Appl Thermal Eng. 2014;65:102–10.
22. de Noni Jr. A, Hotza D, Soler VC, Vilches ES. Influence of composition on mechanical behaviour of porcelain tile. Part III: effect of the cooling rate of the firing cycle. Mater Sci Eng A. 2011;528:3330–36.
23. Magagnin D, Dos Santos CMF, Wanderlind A, Jiusti J, de Noni Jr. A. Effect of kaolinite, illite and talc on the processing properties and mullite content of porcelain stoneware tiles. Mater Sci Eng A. 2014;618:533–39.
24. Taskiran MU, Demirkol N, Capoglu A. A new porcelainised stoneware material based on anorthite. J Eur Ceram Soc. 2005;25:293–300.
25. Li K, Cordeiro EDS, de Noni Jr. A. Comparison between mullite-based and anorthite-based porcelain tiles: a review. Eng. 2023;4:2153–66.
26. Capoglu A. A novel low-clay translucent whiteware based on anorthite. J Eur Ceram Soc. 2011;31:321–29.
27. Vasić MV, Velasco PM, Bueno-Rodríguez S, Grubeša IN, Dondi M, Villarejo LP, et al. State and perspectives of sustainable production of traditional silicate ceramics. Open Ceram. 2024;17:100537.
28. Fukushima M, Ohji T. Macroporous ceramics for the sustainable development goals (SDGs): review. Int J Appl Ceram Technol. 2023;20:660–80.
29. Eterigho-Ikelegbe O, Trammell R, Bada SO. Novel ceramic composites produced from coal discards with potential application in the building and construction sectors. J S Afr Inst Min Metall. 2022;122:1–8.
30. ISO 13006:2018. Ceramic tiles—definitions, classifications, characteristics and marking. 01.040.91 91.100.23. 2018. Available from: https://cdn.standards.iteh.ai/samples/63406/15e46e89b1ca44098a24ce182c51bcc0/ISO-13006-2018.pdf
31. Sánchez E, García-Ten J, Sanz V, Moreno A. Porcelain tile: almost 30 years of steady scientific-technological evolution. Ceram Int. 2010;36:831–45.
32. Towler G, Sinnott R. Chemical engineering design: principles, practice and economics of plant and process design. Butterworth-Heinemann; 2021.
33. Soldati R, Zanelli C, Cavani G, Battaglioli L, Guarini G, Dondi M. Improving the sustainability of ceramic tile-making by mixing spray-dried and dry-granulated powders. Bol Soc Esp Cerám Vidr. 2022;61:325–35.
34. Dondi M, García-Ten J, Rambaldi E, Zanelli C, Vicent-Cabedo M. Resource efficiency versus market trends in the ceramic tile industry: effect on the supply chain in Italy and Spain. Resour Conserv Recycl. 2021;168:105271.
35. Dondi M. Clay materials for ceramic tiles from the Sassuolo District (Northern Apennines, Italy). Geology, composition and technological properties. Appl Clay Sci. 1999;15:337–66.
36. Sánchez E, García-Ten J, Regueiro M. Materias para la industria cerámica española. Situación actual y perspectivas. Bol Soc Esp Ceram Vidr. 2006;45:1–12.
37. Hossain SS, Roy PK. Sustainable ceramics derived from solid wastes: a review. J Asian Ceram Soc. 2020;8:984–1009.
38. Liu X, Chen X, Yang L, Chen H, Tian Y, Wang Z. A review on recent advances in the comprehensive application of rice husk ash. Res Chem Intermed. 2016;42:893–913.
39. Prasara-A J, Gheewala SH. Sustainable utilization of rice husk ash from power plants: a review. J Cleaner Product. 2017;167:1020–28.
40. Luo Y, Ma S, Zheng S, Liu C, Han D, Wang X. Mullite-based ceramic tiles produced solely from high-alumina fly ash: preparation and sintering mechanism. J Alloys Compd. 2018;732:828–37.
41. Luo Y, Zheng S, Ma S, Liu C, Ding J, Wang X. Novel two-step process for synthesising β-SiC whiskers from coal fly ash and water glass. Ceram Int. 2018;44:10585–95.
42. Ozturk ZB, Gultekin EE. Preparation of ceramic wall tiling derived from blast furnace slag. Ceram Int. 2015;41:12020–26.
43. Ke S, Wang Y, Pan Z, Ning C, Zheng S. Recycling of polished tile waste as a main raw material in porcelain tiles. J Cleaner Product. 2016;115:238–44.
44. Pinheiro BCA, Holanda JNF. Reuse of solid petroleum waste in the manufacture of porcelain stoneware tile. J Environ Manage. 2013;118:205–10.
45. Hossain SS, Mathur L, Majhi MR, Roy PK. Manufacturing of green building brick: recycling of waste for construction purpose. J Mater Cycles Waste Manag. 2019;21:281–92.
46. Gomes FPS, Holanda JNF. Recycling of firewood ash waste in ceramic floor tiles with low water absorption. Mater Res. 2023;26.
47. European Commission. Best available techniques (BAT) reference document for ceramic manufacturing industry.
48. Brazilian Government. Instituto Brasileiro de Geografia e Estatística. Available from: https://www.ibge.gov.br/ Accessed 7 May 2024.
49. Liu F, Shafique M, Luo X. Literature review on life cycle assessment of transportation alternative fuels. Environ Technol Innovation. 2023;32:103343.
50. Ferrari AM, Volpi L, Settembre-Blundo D, García-Muiña FE. Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and enterprise resource planning (ERP) in an industry 4.0 environment. J Cleaner Product. 2021;286:125314.
51. American Community Survey. Maps of US Census data: US population density. 2021. Available from: https://ecpmlangues.unistra.fr/civilization/geography/map-us-population-density-2021
52. Ceramic World Web. Portobello begins production in the USA using Sacmi technology 2023. May 2023. Available from: https://ceramicworldweb.com/index.php/en/news/portobello-begins-production-usa-using-sacmi-technology
53. Biofuels International. Brazil's biodiesel blend increases to 12%. 2003. Available from: https://biofuels-news.com/news/brazils-biodiesel-blend-increases-to-12/

54. IEA Bioenergy Technology Collaboration Programme. Compare-and-contrast transport biofuels policies (2021-2023 update).
55. International Energy Agency: IEA. Electric energy source worldwide. Available from: https://www.iea.org/. Accessed 7 May 2024.
56. Ceramic World Web. Pamesa Group acquires best surfaces (now Ascale) and invests in clean energy 2023. September 2023. Available from: https://ceramicworldweb.com/en/news/pamesa-group-acquires-best-surfaces-now-ascale-and-invests-clean-energy
57. Gliozzo E. Ceramic technology. How to reconstruct the firing process. Archaeol Anthropol Sci. 2020;12:260.
58. Peng J, Zhao Y, Jiao L, Zheng W, Zeng L. CO_2 emission calculation and reduction options in ceramic tile manufacture—the Foshan case. Energy Procedia. 2012;16:467–76.
59. Dosta M, Litster JD, Heinrich S. Flowsheet simulation of solids processes: current status and future trends. Adv Powder Technol. 2020;31:947–53.
60. Skorych V, Das N, Dosta M, Kumar J, Heinrich S. Application of transformation matrices to the solution of population balance equations. Processes. 2019;7:535.
61. Skorych V, Dosta M, Heinrich S. Dyssol—an open-source flowsheet simulation framework for particulate materials. SoftwareX. 2020;12:100572.
62. Alves CL, Skorych V, de Noni Jr. A, Hotza D, Gómez González SY, Heinrich S, et al. Improving the sustainability of porcelain tile manufacture by flowsheet simulation. Ceram Int. 2023;49:24581–97.
63. Alves CL, Skorych V, de Noni Jr. A, Hotza D, González SYG, Heinrich S. Application of flowsheet simulation methodology to improve productivity and sustainability of porcelain tile manufacturing. Machines. 2023;11:137.
64. Alves CL, Skorych V, de Noni Jr. A, Hotza D, González SYG, Heinrich S. Optimizing raw material composition to increase sustainability in porcelain tile production: a simulation-based approach. J Am Ceram Soc. 2024;107: 2110–2127.

How to cite this article: Lourenco Alves C, de Oliveira Martins Müller J, de Noni Jr A, Heinrich S. Challenges and opportunities for increase sustainability and energy efficiency in ceramic tile industry. Int J Appl Ceram Technol. 2025;e15097. https://doi.org/10.1111/ijac.15097