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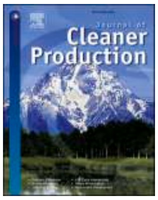

Review

Strategies and pathways to improve circularity in ceramic tile production

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ABSTRACT

This review investigates how the ceramic tile industry can advance its transition toward a circular economy, emphasizing waste recycling as a core focus. The ceramic sector faces increasing challenges in managing waste, both from its production processes and external sources, while seeking innovative methods to minimize environmental impact. Furthermore, there is growing interest in evolving production techniques from traditional commercial practices to incorporating waste materials into ceramic manufacturing. Key themes explored include zero-waste manufacturing models and measures addressing different stages of production, such as optimizing raw material sourcing, implementing best practices, and improving the management of end-of-life products. The review examines the hurdles of integrating waste from other industries and highlights the potential for developing ceramic products derived from recycled materials. Emerging strategies, including the optimization of material formulations and the enhancement of production processes, are highlighted as key drivers for the large-scale utilization of waste materials. To support this shift, the review recommends developing standardized protocols for waste characterization and establishing cross-sector partnerships to streamline resource exchange. These practical measures can help stakeholders enhance sustainability while maintaining product performance and regulatory compliance. In addition to technological innovation, regulatory incentives and market-driven policies are essential to promote circularity within the ceramic industry. Integrating environmental criteria into product standards, encouraging green labelling, and supporting research-industry collaborations can further drive the adoption of recycled materials. These combined efforts can foster long-term resilience and position the ceramic tile sector as a proactive contributor to global sustainability goals.

1. Introduction

The production of ceramic tiles is currently estimated globally at around 16 billion square meters per year (Baraldi, 2024), a total of which includes various types of products (ISO 13006, 2018). Top manufacturing countries are China, India, Brazil, Iran, Indonesia, Egypt and Vietnam, which account for 73 % of the world's production. The technological leadership in tile-making is held by countries (Italy, Spain, Turkey) that account for 7 % of global output (Baraldi, 2024). The prevailing typologies are tiles with vitrified to semi-vitrified support (porcelain stoneware and red stoneware) which are presumed to represent the main share of the total (Conte et al., 2024a). The remaining tiles pertain to a range of products (*e.g.*, monoporosa) with semi-porous to porous support (Dondi et al., 2014). The terminology used for ceramic tiles and their production is shortly explained in the nomenclature reported as supplementary material.

The ceramic industry has undertaken initiatives to improve environmental sustainability and reduce energy consumption and greenhouse gas emissions through targeted actions (ISO 17889-1, 2021; Cerame-UNIE, 2021). Since ceramic production implies energy consumption that is "hard-to-abate", inevitably linked to thermal processes, the transition to a Circular Economy has long been underway (Rambaldi, 2021). Among the various "R" actions envisaged by the Circular Economy (Kirchherr et al., 2017; De Pascale et al., 2021), waste recycling is the most suitable for ceramic tile production and also the one practised more extensively and for a longer time (Dondi, 2022).

The ceramic tile industry consumes, globally, a quantity of raw materials estimated at around 300–350 million tonnes per year

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(García-Ten et al., 2024). These raw materials are mainly represented by batch components, which are mostly clay materials and quartz-feldspathic fluxes (Dondi et al., 2014, 2021). This huge volume of raw materials therefore offers the opportunity to insert considerable amounts of waste into a circular process that can significantly contribute to improving the environmental and socioeconomic sustainability of ceramic tile production. The industrial target is primarily to use any waste as if it were a conventional raw material, adjusting process settings, if necessary, without substantially changing the technology used to manufacture ceramic tiles (Zanelli et al., 2021a). This is undoubtedly an important limitation since the technological behaviour of waste materials can be very different from the raw materials usually employed (constraining the amount of waste that can be utilized). In the case of waste-based formulations, a dedicated technology must be also developed to manufacture tiles that represent *de facto* novel products.

Waste recycling has become a popular topic, as it is one of the parameters required by the international standard on the sustainability of ceramic tile production, as well as by green labels, *e.g.,* LEED (Dondi, 2022). Nevertheless, it is essentially carried out as a reuse of in-house residues, to a degree that varies with the type of production and legal requirements in each country. Waste from external sources is seldom introduced into the batch and is normally limited to a few percentage units (Zanelli et al., 2021a). Current research highlights numerous studies focusing on the incorporation of diverse waste materials into ceramic tiles, demonstrating promising results in enhancing their properties and reducing reliance on virgin raw materials. Extensive experimentation has been conducted on different types of waste, showcasing their potential as viable substitutes or additives in ceramic formulations. A comprehensive list of waste materials and the permissible quantities that can be incorporated is provided in the supplementary material (Table S1).

Knowledge of waste recycling in the production of ceramic tiles has been recently reviewed, both at a technological level and in terms of environmental issues (Andreola et al., 2016; Zanelli et al., 2021a). The framework is a patchwork of case studies, which together help define the TRL (i.e., Technology Readiness Level) and the recommended percentage for each waste type. The level of development is very different depending on the technological, technical, and environmental constraints that still exist for the majority of residues proposed as ceramic raw materials.

What is missing in the literature is an analysis reversing the point of view, from the particular to the general: going beyond individual case studies that were already reviewed (Andreola et al., 2016; Hossain and Roy, 2020; Zanelli et al., 2021a). To fill this gap, it is necessary to look at the most pressing needs, in terms of quantities of waste to be disposed of, and at the problematic issues that waste recycling raises in industrial practice, especially in terms of batch design and influence on the product performance and market value. Systemic approaches turn out to be a key to assessing the environmental, economic and social performances of ceramic tile production when waste is utilized as a secondary raw material, because of the growing complexity of the supply chain and the need to balance circular economy and sustainability (Garcia-Muiña et al., 2019).

The goal of this paper is to critically discuss, based on a review of scientific literature and industrial practices, how the circularity of the ceramic tile industry can be enhanced through waste recycling. The novelty of this work lies in a comprehensive analysis of potential pathways, carried out for the first time across the entire life cycle. This analysis begins with efforts to achieve a zero-waste target in ceramic tile manufacturing and extends to actions that should be undertaken both upstream and downstream of ceramic tile production, encompassing the supply chain of raw materials and the management of end-of-life products. Furthermore, technological challenges that the ceramic tile industry has to face will be examined, both as regards the incorporation of waste from other industrial sectors, as well as the development of waste-based ceramic products. In parallel, general strategies to improve waste recycling will be discussed with particular attention to systemic approaches, based on resource efficiency criteria and operational tools. Along with that, new technological solutions to facilitate waste recycling will be critically discussed as well as batch design tactics to be applied in industrial practices.

2. Methodological approach

The state of the art on the application of circular economy in the ceramic tile industry, with emphasis on waste recycling, was realized through a review of both scientific literature and industrial practices.

Bibliographical research has considered all pertinent contributions that address specifically the challenge of improving circularity in the tile industry (Scopus database, combining several keywords for the various actions under examination) as well as reviews on waste recycling in ceramic tiles (*e.g.*, Andreola et al., 2016; Hossain and Roy, 2020; Zanelli et al., 2021a), the bibliographic research has been therefore directed essentially towards recent contributions, useful for outlining the current picture of the tile industry that is facing the challenge of increasing circularity. This has been possible, particularly in the case of pathways for which there is substantial scientific production, such as the development of waste-based ceramic tiles, incorporation of waste from other industrial sectors, and systemic approaches based on resource efficiency criteria.

On the other hand, when actions aimed at improving circularity take place within the ceramic tile production cycle, scientific contributions are generally scarce and industrial know-how must be considered. In this case, together with the literature search, interviews were carried out with a panel of a dozen experts, who were consulted (individually and confidentially, to prevent conflicts of interest) in the period between mid-2023 and the beginning of 2024. The panellists are technical managers of leading companies, operating in Italy, that produce ceramic tiles and raw materials. This is because Italy is globally renowned for its technological expertise and innovative practices in waste recycling processes, particularly in the production of ceramic tiles (Boschi et al., 2023). The objective was to confirm the actual situation at an industrial level, with specific regard to the identification of the best available technologies and practices for zero-waste manufacturing as well as novel technological solutions and tactics of batch design to facilitate waste recycling.

When the actions to be undertaken are outside the usual range of action of ceramic companies – *i.e.,* upstream and downstream of their manufacturing cycle – specific contributions for ceramic tiles are very scarce. In this case, in addition to the information from the panel of experts, the bibliographic search pointed to the most current and significant case studies, developed at a high technology readiness level, which can constitute an example of industrial practices applicable to ceramic tiles.

3. Results

Pathways to enhance waste recycling in ceramic tile production are critically reviewed to get an up-to-date picture of the problems and possible solutions. The entire industrial value chain of tilemaking is considered with diversified objectives: from zero-waste manufacturing in-house to the ceramic factory, to actions to be undertaken upstream and downstream of the tile production. Attention is dedicated to the incorporation of urban and industrial residues in ceramic bodies, distinguishing the target of improving waste recycling within current products from that of maximizing the use of residues by creating new products based on waste.

3.1. Zero-waste manufacturing of ceramic tiles

The production of ceramic tiles physiologically creates residues in different steps of the manufacturing process (Fig. 1). Some residues arise

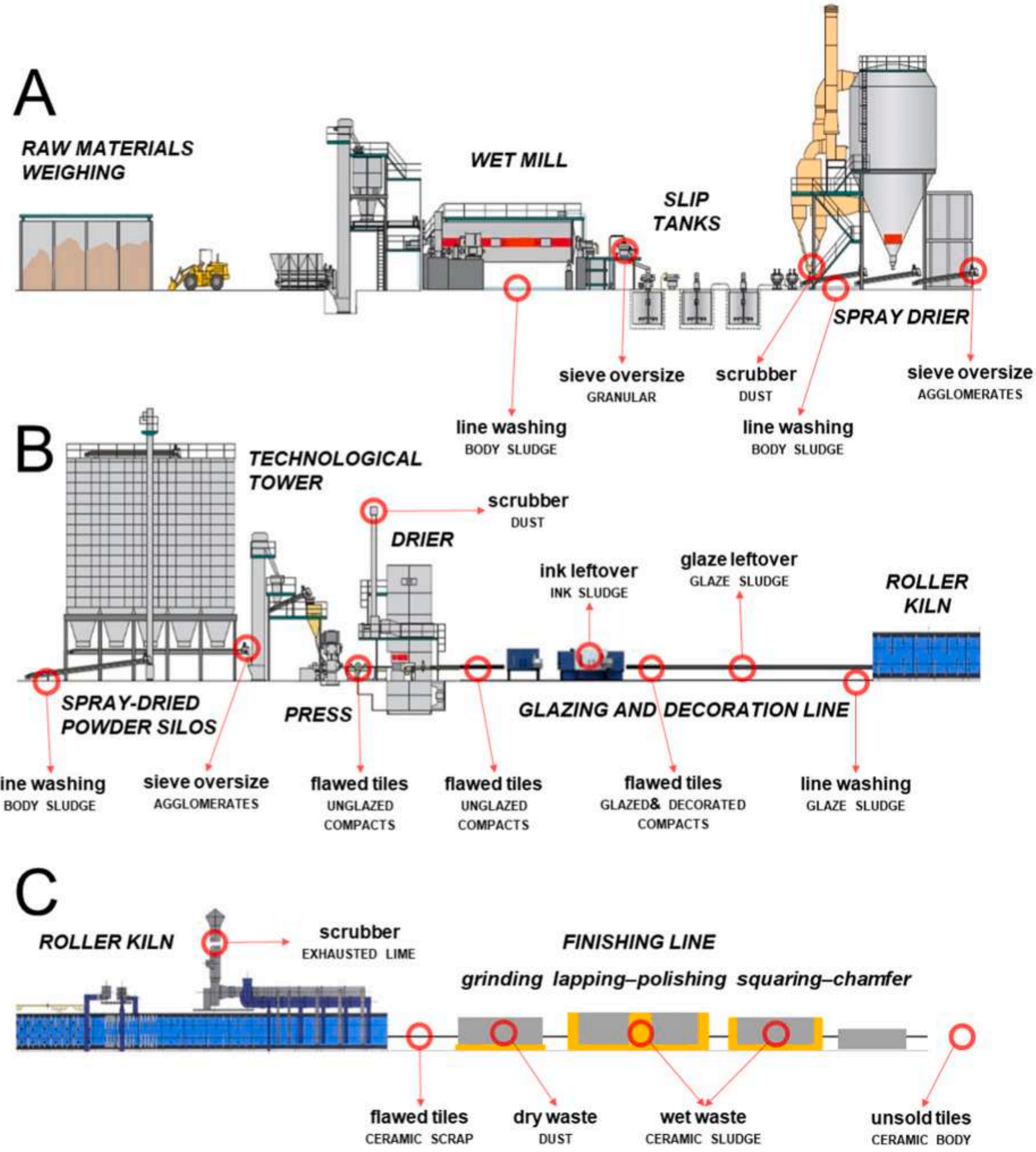

Fig. 1. Origin and physical state of residues along the ceramic tile manufacturing cycle.

from production controls, where there is a go-no-go screening, such as in the case of slip or powders sieving (originating granular waste) and scrapping of flawed tiles, both unfired and fired (as a solid waste). Others come from cleaning the grinding, spray-drying and pressing departments as well as the glazing, decoration and finishing lines (giving rise to both solid residues and wastewater). Further residues are obtained by air purification in the areas where dust is produced (spray drying, pressing, drying, dry finishing) or treatment of fumes of the roller kiln (exhaust lime from scrubbers). In addition, there are exhaust consumable parts (degraded ceramic rollers and grinding media, solid waste) and ink and glaze leftovers (oil or water suspensions). Such residues have a physical state and compositional characteristics that make more or less easy their recycling through cannibalistic loops within the same manufacturing line of ceramic tiles. Four separate cases can be identified as detailed hereafter.

Direct recycling can be carried out for residues with composition and physical state similar to the material in production (unglazed and unfired tiles, oversize from sieving of spray dried powders). Simple preliminary operations consist of tile crushing or powder/sludge disagglomeration prior to reintroduction in the mill or the slip tank before spray-drying (El-Fadaly et al., 2010; Garcia-Ten et al., 2015; Rambaldi et al., 2018; Valença and Ferranço, 2018; Amin et al., 2019).

Direct recycling by adjusting the processing parameters concerns mixed residues in which both support and coating are present, as a mixture of body, glaze and decoration, like in glazed unfired tiles and sludge from line washing (Manfredini et al., 1991). These residues are generally cannibalised at the milling stage, and this makes it necessary to check the rheological behaviour of slips, along with the firing behaviour of tiles and the final colour of the ceramic body (Andreola et al., 2004; Rambaldi et al., 2016; Ergin et al., 2023). Similar drawbacks can affect residues having a physical state that requires careful handling (like dust from drying operations).

Recycling after chemical or mechanical treatments is usually necessary when the residue must be purified or clarified (wastewater) or because it was consolidated during processing (broken, flawed or unsold tiles; scraps, dust and sludge from the finishing line). Fired tiles and scraps must be previously crushed to the usual grain size of raw materials acceptable as milling feed (Monfort et al., 2000; Karamanov et al., 2006; Tarhan et al., 2017; Kabiraj et al., 2018). Also, in this case, an adjustment of the processing parameters (*e.g.*, milling time) is commonly needed. In addition, continuous control of the quality of wastewater is recommended, before introducing it in the slip, in terms of pH, solid load, concentration of electrolytes, organic matter and bacteria (Manfredini et al., 1991; Zannini, 2020).

Problematic recycling due to contamination affects those residues in which acid pollutants and heavy metals volatilised during firing are concentrated, like in the exhaust lime from kiln scrubbers (Andreola et al., 1992a, 1992b, 1993; Garcia-Ten et al., 2015). The challenge is to avoid the release of fluorine, chlorine, sulfur and hazardous elements at high temperatures, once the waste is introduced into a ceramic batch and fired (Dondi et al., 1990; Rambaldi et al., 2016, 2018). Most exhaust lime is still landfilled (Boschi et al., 2020) despite its fluorite content being similar to cement-grade fluorspar. A different issue is that of body contaminants, for example, the undesired phases (micas, rubber, grinding medium fragments, etc.) enriched in the oversize from slip sieving. Another example is regarding the sludge from surface polishing operations of porcelain stoneware tiles, which is contaminated by abrasive (SiC or diamond) and binders (Shui et al., 2011; Ke et al., 2016; Wang et al., 2021). Further problematic waste is the ink leftover from digital decoration because inkjet printing is too demanding to allow direct recycling (Gardini et al., 2015). In any case, these leftovers are small amounts that can consist of oil or water-glycol emulsions containing heavy metals from pigments and several additives.

The amount of the above-mentioned residues depends on the product type (glazed or unglazed tiles; porous or vitrified body; dark-colored or light-colored body) and specific features (tile thickness, finishing, etc.) along with the factory layout. Indeed, there are differences between the full cycle (sectors A-B-C in Fig. 1) and partial cycle (sectors B and C only), particularly in the case of plants producing spray-dried powders also for industries with the partial cycle (full cycle with sector A overdimensioned). It is known, thanks to continuous monitoring of the Italian ceramic tile manufacturers over the last decades, that the total amount of process residues amounts to approximately 13 % of production (Resca et al., 2015; Boschi et al., 2023). This amount can be almost entirely utilized, as demonstrated by recycling factors that express the amount reused as a percentage of the total solid waste and wastewater (Boschi et al., 2023). These factors vary according to the different production layouts (Fig. 2): both the full cycle and the partial cycle allow a degree of recycling close to 100 % of wastewater and solid waste, while the factories that produce spray-dried powders also for third parties have fluctuating factors averaging 125 % for solid waste and 115 % for wastewater (Boschi et al., 2023).

Recycling of in-house residues is a well-established practice in the Italian ceramic tile industry that has, for a long time, made available technological solutions alternative to landfilling (Timellini et al., 1983; Busani et al., 1995; Palmonari and Timellini, 2000; Boschi et al., 2023). Since the manufacturing technologies are substantially the same throughout the world, a global quantity of recyclable residues can be estimated from the world tile production, which was on average about 16 billion square meters in the latest years (Baraldi, 2024) roughly corresponding to 350 million tonnes per year (García-Ten et al., 2024). This leads to a global amount, supposing a percentage of in-house residues as high as 13 %, close to 45 million tons. However, as these residues can be readily recycled, for the most part, they do not fall into the category of waste (*i.e.,* materials that the industry wants to get rid of). The fate of these residues is not as well-known on a global scale, and it would therefore be useful to understand the state of implementation of the best available technologies in other ceramic manufacturing countries.

Future research on zero-waste manufacturing of ceramic tiles is likely to focus on advancing direct recycling techniques, particularly by fine-tuning processing parameters to accommodate varying waste compositions. Investigations of chemical or mechanical treatments of residues are essential to enhance the recycling rate in ceramic production. Addressing challenges such as contamination remains critical, as it can hinder the effective recycling of certain materials. Furthermore, strategies for recycling in-house residues hold significant potential for improving resource efficiency, although optimizing their reuse without compromising product quality remains a key challenge.

3.2. *Actions upstream of ceramic tile production*

The actions upstream of tile production essentially concern the supply of raw materials, both for the body and for the glaze, which can therefore be considered as an extension of ceramic production, in the cradle-to-gate perspective of a life cycle analysis (Hellweg and Milà i Canals, 2014). These actions comprise a series of operations with their efficiency and impact (environmental, economic, social). While the strategy to improve resource efficiency and life cycle impacts will be discussed in section 4.1, here we want to evaluate the actions aimed at increasing circularity, therefore mainly related to residues that are generated, on the one hand, by the extraction and processing of raw materials (clays, fluxes, sands, etc.) and, on the other hand, by the production mainly of frits. Since the fractions that are discarded are objectively difficult to reuse in ceramic production, as they can generate defects and are considered contaminants, the ultimate goal is the valorization of such mining residues in any application, therefore, not exclusively along the ceramic tile value chain. This is reflected in the policy for sustainable mining, which includes the reuse of mining residues towards the target of full exploitation of resources (Moran et al., 2014; Dondi, 2018; Dino et al., 2020; Mancini et al., 2024).

An example of full exploitation is illustrated in Fig. 3, which is

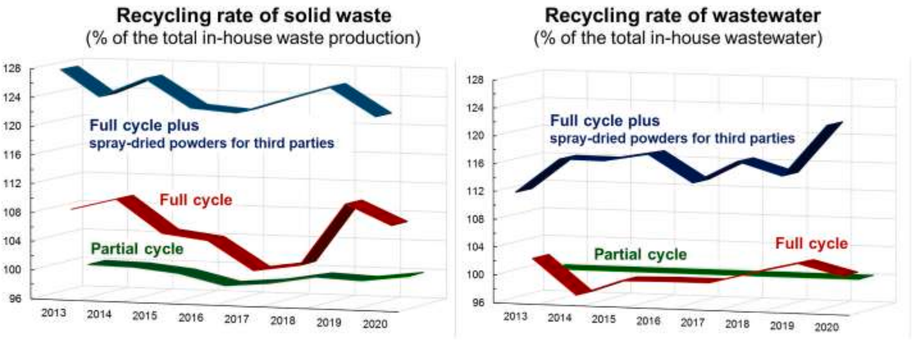

Fig. 2. The recycling rate of in-house residues by the ceramic industry (solid waste and wastewater) for the three production layouts in the period 2013–2020 (modified after Boschi et al., 2023).

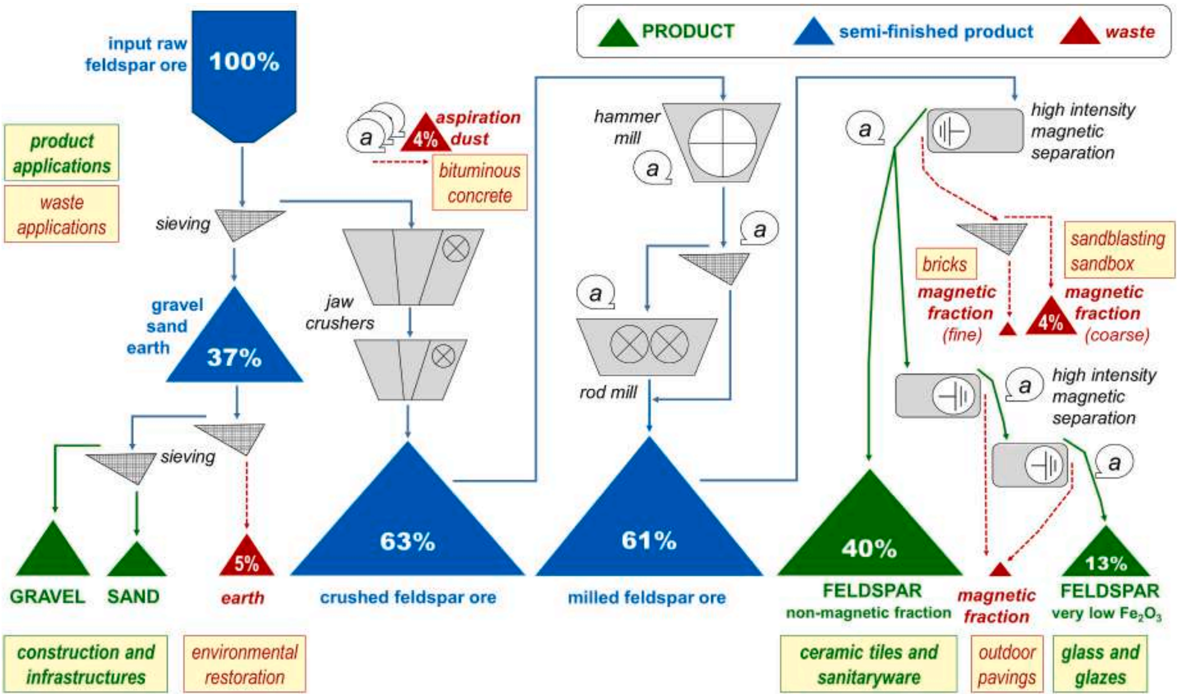

Fig. 3. Example of full exploitation of a feldspar deposit (adapted from Dino et al., 2012; Dino et al., 2020). Flow diagram illustrating the various processing steps (primary and secondary grinding, magnetic separation) and the quantitative breakdown of the input (raw feldspar ore) into semi-finished and finished products, and waste. Applications are indicated for the different products and types of waste.

particularly relevant because it concerns a raw material commonly used in ceramic tile production (feldspar). This case study demonstrates how a zero-waste option is feasible, to the benefit of the ceramic industry, which does not have to take over, albeit indirectly, the environmental and economic costs arising from the residues produced in the extraction and processing of raw materials (Dino et al., 2012; Mancini et al., 2024). Beneficiation of feldspar inevitably entails the separation of mineral fractions that are not suitable for the production of ceramic tiles (*e.g.*, magnetic fractions or dust from air cleaning operations). These residues can in turn be treated to meet market requirements, for instance, gravel and sand (to be used in the construction sector), coarse-grained magnetic fractions (suitable for sandblasting or train sandbox), and "granite dust" (useable in bituminous concrete).

A limitation of residues from carbonate rocks is their emission of CO_2 or other volatile gases when burned. These are greenhouse gases, often taxed in developed countries, so the application of carbonate-bearing waste in ceramics is discouraged, unless for porous tiles (*e.g.*, monoporosa) where carbonatic raw materials are desired batch ingredients.

Another recovery path for mining waste, along with the restoration of extractive sites, is to produce recycled aggregates. In some circumstances, residues derived from quarry dumps and working operations were utilized for armour stones and aggregates for concrete, embankment, filling, railway ballast, etc. Whether such recycled aggregates offer any significant advantage in reducing emissions compared to natural aggregates, could be determined by transit distances, processing needs, and product demands (Jones and Gutiérrez, 2023). For instance, a new firm was established in the Apuan basin, bringing together the majority of marble quarries to recover and reuse quarry waste. The goal was to enhance the environmental, social and economic performance of local businesses. New research is being conducted to illustrate that quarry waste represents an innovative economic potential; this method is well aligned with the circular economy, transforming industrial actions into tangible environmental and safety improvements (Dino et al., 2017). Fine-particle residues are the mineral wastes that have the poorest recovery options available. The need for clean, single-sized aggregates from both primary and recycled sources led to considerable amounts of undersized waste material generated during the crushing, grading, and washing operations. These materials are most commonly used in quarry recovery and backfilling operations, however, because of the small particle size, they do not need any additional milling for ceramics applications and might be well utilized by the industry (Jones and Gutiérrez, 2023).

The case studies of Montorfano and Baveno (Dino et al., 2012, 2020) and Monte Bracco (Dino et al., 2021) in Northern Italy exemplify challenges and innovative solutions in resource management and environmental stewardship. In Monte Bracco, historical mining practices focused on extracting only the most economically viable portions of ore deposits, leaving significant potential resources underutilized in abandoned quarry benches and old landfills. Dino et al. (2021) highlight the opportunity to recover valuable materials, such as quartz from landfill waste, for commercial purposes. On the other hand, around Lago Maggiore, granite quarrying has produced substantial waste, impacting the local environment. Remediation was undertaken in 1995 to valorise granite quarry waste, rich in quartz and feldspar, as secondary raw material (SRM). This initiative illustrates a successful strategy to mitigate environmental impacts while meeting rising demands for feldspar in Italy, a mineral whose consumption increased significantly since 1975, particularly in the last decades. These efforts by mining industries underscore the feasibility and economic viability of integrating SRMs into industrial processes, contributing to sustainable resource management and environmental sustainability in the region (Dino et al., 2012).

Several mining waste materials, such as intrusive (*e.g.*, granite) and volcanic rocks from the dimensional stone industry, can be used in place of feldspar when making ceramic tiles (Zanelli et al., 2021a). Substantial amounts of industrial waste from coal mining, energy production, metal ore extraction, and rock raw material processing are rich in alkali ($K_2O + Na_2O$) and Fe_2O_3 and are crucial for producing feldspar used in various products, including ceramics, building materials, bituminous concrete, and external pavements (Lewicka, 2020). Some volcanic rocks, like pumice and lapilli, are rich in alkali, so they can contribute to the porcelain stoneware fusibility (Altimari et al., 2023). Extraction of ornamental stone, such as aplitic granite generates waste materials containing quartz and feldspars, with trace amounts of micas and kaolinite, which are common constituents of ceramic tile bodies. Therefore, mining waste from granite dumps could be utilized as flux in ceramic batches (Vasić et al., 2022).

In summary, the valorization of mining waste demonstrates the potential for sustainable practices in the mining industry. By transforming waste into valuable secondary raw materials, these initiatives reduce environmental impacts, conserve natural resources, and provide economic benefits, presenting a viable model for other regions facing similar challenges.

Future research should aim at improving resource efficiency upstream of ceramic tile production. The main line of action is to minimize the production of mining waste through the full exploitation of deposits, which implies the valorization of residues as secondary raw materials, looking at all possible applications, not only in the glass and ceramic sectors.

3.3. Actions downstream of ceramic tile production

At the end of the product's useful life cycle, ceramic tiles are usually included in Construction and Demolition Waste (CDW). This is an extremely uneven waste, given the current demolition practices that involve the selective removal of only certain materials (wood, metals, glass). Thus, CDW commonly encompasses concrete, mortar, brick, plasterboard, stone, and possibly other materials, along with ceramic tiles of various types (Bianchini et al., 2005; Rodrigues et al., 2013; Galderisi et al., 2023). Recycling such a mixed CDW is challenging unless properly sorted because the materials that can be obtained by current technologies have worse technical performance compared to natural aggregates (Silva et al., 2014; Galán et al., 2019; Caro et al., 2024). For this reason, ceramic-bearing CDW is generally backfilled or utilized in road subbases and embankments (Zhao et al., 2021; Caro et al., 2024).

The actual possibilities of selective ceramic recovery seem to be limited to a few applications (floating floors, ventilated façades) but it has been rarely put into practice. In the absence of selective demolition or deinstallation of buildings, there is a need for enabling technologies that allow for the effective separation of ceramic materials from the rubble (Galán et al., 2019; Ulsen et al., 2021; Trotta et al., 2021; Marín-Cortés et al., 2023). An advanced technology, currently in development, is based on the high selection capacity that ensures hyperspectral analysis of individual CDW fragments, i.e., by combining information from different spectral bands, such as visible light, infrared, and ultraviolet frequencies (Hollstein et al., 2016; Bonifazi et al., 2019; Suciu et al., 2020; Wang et al., 2020; Klewe et al., 2023; Radica et al., 2024). These procedures involve the acquisition of hyperspectral libraries (Fig. 4) possibly supplemented by chemical analysis techniques, such as XRF or LIBS (Klewe et al., 2022). These libraries can be used, with a statistical approach, like exploratory data analysis (Bonifazi et al., 2021) or via machine learning (Klewe et al., 2023) for the classification of the

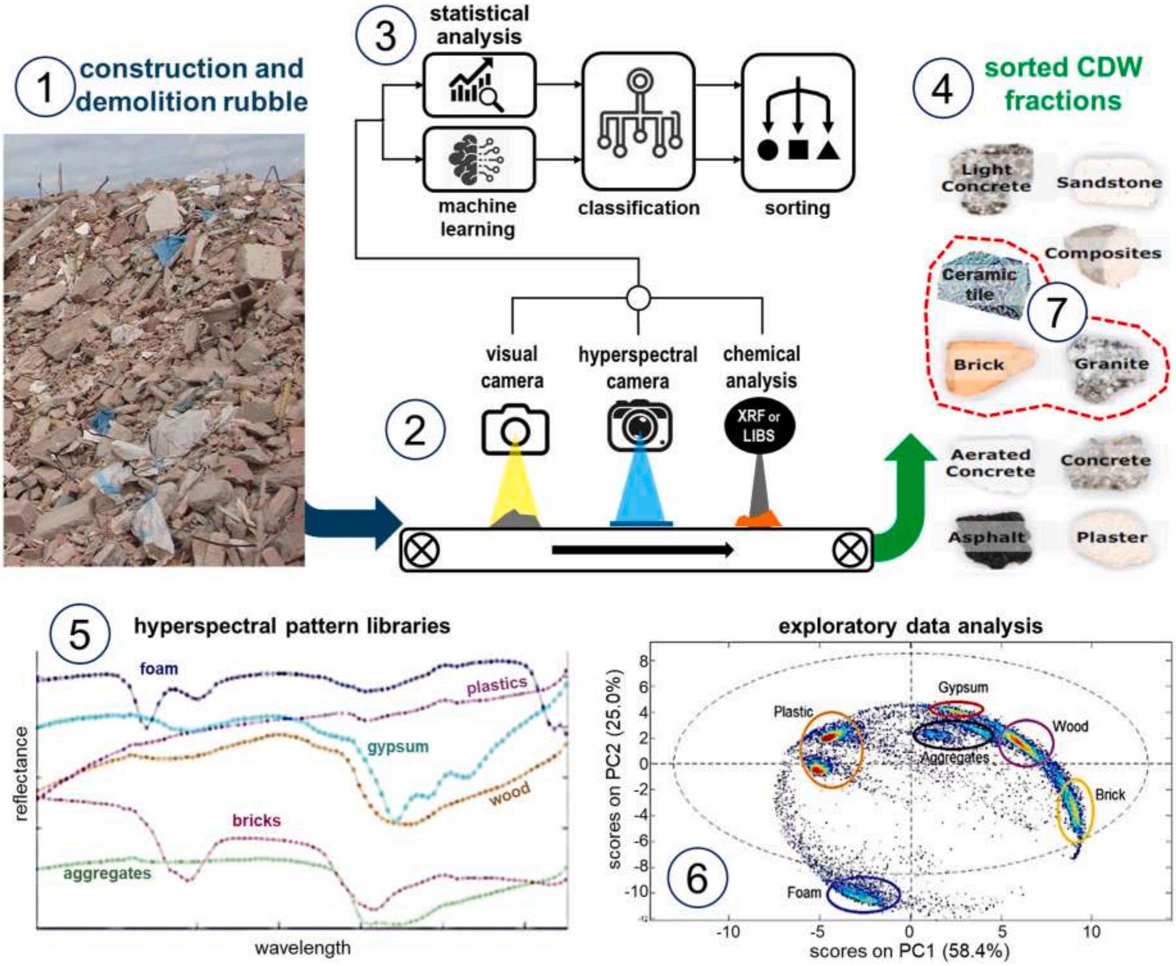

Fig. 4. Flow diagram illustrating the advanced technology for sorting of CDW envisaged to obtain ceramic-rich fractions (modified after Bonifazi et al., 2019; Klewe et al., 2023). The construction and demolition rubble (1) is analyzed using hyperspectral and spectroscopic techniques (2), which allow a selection by advanced data processing methods (3) of the various building materials (4). An effective separation is possible by training the sorting system with hyperspectral pattern libraries, specific to each material (5), associated with exploratory data analysis (6) to sort fractions suitable for ceramic applications (7).

different materials constituting the CDW (Bonifazi et al., 2022). In this way, it is possible for their separation in a flow of rubble (Bonifazi et al., 2023; Klewe et al., 2023; Radica et al., 2024).

Surely, the heterogeneity of CDW, both in particle size distribution and composition (Bianchini et al., 2005; Rodrigues et al., 2013) represents an obstacle to its recycling (Zanelli et al., 2021a). However, even having residues enriched in ceramic tiles, the problem of handling old types would arise, since the latter are made up of materials (majolica, earthenware, cottoforte) that have not been produced for decades (Dondi et al., 2014). These old tiles have a composition of both the support and the glaze that are very different from those employed in the current ceramic production. In the case of the substrate, the obstacle is mostly represented by high iron and calcium contents; for glazes, the problem is the probable occurrence of hazardous elements, primarily lead and boron. In addition, there can also be significant levels of Cd, Se, Sb, *i.e.,* elements now practically eliminated from the formulations of frits and glazes (Casasola et al., 2012; Eppler, 2012).

According to a recent study on the environmental and socioeconomic implications of CDW recycling, the recovery rate in the European Union (EU) is 89 %, which is high in comparison to other waste streams. However, this comparatively high statistic might be deceiving because it often corresponds to "poor" levels of circularity rather than high-value material recovery. Indeed, recycling concrete, bricks, gypsum, and ceramic tiles provides an excellent environmental performance but is also the most expensive option. However, shifting from waste to recycling reduces total societal expenses in the EU, primarily due to lower external expenditures. Concrete and bricks are the fractions that have the most potential to improve present waste management techniques concerning environmental benefits (Caro et al., 2024).

Incorporating CDW into ceramic production can offer significant advantages and varied applications. CDW serves as a filler in brick manufacturing by reducing clay mineral content, decreasing plasticity, and minimizing drying shrinkage (Zanelli et al., 2021b; Dubale et al., 2022, 2024). Research indicates that up to 30 wt% of roof tile waste can be added to produce third-class bricks and up to 35 wt% for second-class bricks, thus conserving natural resources. However, leaching procedure tests proved that the material may exceed US EPA concentration limits, suggesting it is preferable to mix it with raw materials for further production (Dubale et al., 2022).

Furthermore, CDW can constitute up to 50 wt% in red tiles and brick ceramics without compromising processing or quality. For instance, adding 40 % CDW increases compressive strength meeting acceptable standards. Even at 20 wt% in commercial clay-based mixes, CDW maintains essential properties for brick production. This versatility underscores CDW's potential across sectors such as sand production, road construction, concrete, and ceramics/bricks. To fully exploit CDW's benefits in ceramic brick manufacturing, additional research is essential for optimizing technology, assessing economic viability, evaluating environmental impacts, and establishing regulatory guidelines (Dos Reis et al., 2021).

Ceramic tile demolition waste (CTDW) could also be used as an alternative to Portland cement. CTDW lowers particle spacing in cement due to its increased surface area and particle concentration. In comparison to limestone, CTDW increased the cement's hydration process. It raised the primary heat flow peak and cumulative heat values at 24 and 168 h by 5–8 %, using the same amounts of CTDW and limestone. Between 1 and 7 days, cement containing CTDW demonstrated up to 5 % greater compressive strength than cement with limestone at comparable replacement levels. Although research on cement made from ceramic waste frequently focuses on its hardened qualities and pozzolanic potential, with CDW no substantial pozzolanic reaction of CTDW was seen within the first seven days. This was demonstrated by the comparable strengths of mixes comprising either CTDW or limestone (de Matos et al., 2021).

Future research on downstream actions in ceramic tile production must delve into advanced strategies for integrating construction and demolition waste (CDW) into ceramic formulations. Key challenges lie in addressing the heterogeneity, contamination, and unpredictable material properties of CDW, which can affect product quality and performance. Overcoming these obstacles requires innovative solutions, such as enhanced preprocessing technologies, precise material characterization, and the development of robust industrial processes to ensure scalability and sustainability.

3.4. *Incorporation of waste from other sectors in ceramic tile bodies*

The technological feasibility of waste incorporation into ceramic tile batches has been recently critically reviewed (Andreola et al., 2016; Hossain and Roy, 2020; Zanelli et al., 2021a). An extremely variegated picture emerges, with clear differences from waste to waste in terms of knowledge of the behaviour in the ceramic process and level of technological readiness. A detailed analysis of waste behaviour in every stage of ceramic tile manufacturing led to pointing out technological bottlenecks to be overcome to enable actual recycling (Zanelli et al., 2021a).

The environmental feasibility of waste incorporation in ceramic bodies has been already reviewed in general (Coronado et al., 2015; Ardit et al., 2022) and for specific residues (Cheeseman et al., 2003; Andreola et al., 2007; Andreola et al., 2016; Jordán et al., 2021; among others). These studies contributed to the awareness that waste ceramization offers potentially effective solutions for immobilization, in particular of hazardous elements. However, there are distinctive features to be taken into account, depending on the type of ceramic body, waste materials, etc.

In contrast to how primary natural resources are used, the value-adding of industrial waste and its upgrading to alternative raw materials can offer several benefits, including a decrease in the volume of natural raw materials extracted (preserving resources), a decrease in energy consumption during subsequent processing (lowering costs), and a decrease in pollutant emission levels, so improving safety and environmental sustainability (Akpınar and Anlı, 2023). Theoretically, recycling in ceramic tile manufacturing can be advantageous since it can absorb large amounts of waste (sometimes including hazardous materials) that would otherwise have to be disposed of in landfills. The large volume of ceramic tile production can result in waste valorization, even if this integration is done in tiny amounts. A lot of research on waste recycling in ceramic tile production has been published (Zanelli et al., 2021a); nevertheless, the transfer of technology to manufacturing processes is not straightforward. There are numerous conditioning factors, including.

- the degree to which the waste and the ceramic batch are chemically compatible;
- the type of cycle (wet or dry route) into which the waste will be involved (Mezquita et al., 2017);
- the nature of the finished product, whether porous or vitrified (Borja et al., 2022; Cengizler, 2022);
- the waste supply in terms of available quantities and constancy of composition;
- the pre-treatments to match raw materials requirements for ceramic tile-making (Teoh et al., 2021);
- the transportation expenses that must be kept under control.

Whenever the percentage of waste used in tile production is significant, repurposing of bodies and glazes is advised to comply with standard prescriptions and market demand. On the other hand, this effort can be awarded an environmental certification of "green materials"; for instance, a given percentage of post-consumer waste in ceramic tiles can contribute to award buildings with LEED Certification, *i.e.,* Leadership in Energy and Environmental Design (Andreola et al., 2016; Boschi et al., 2020).

Although the use of waste in the production of ceramic tiles has been the subject of several studies (Zanelli et al., 2021a), technological innovation is leading to a continuous evolution of commercial products (increasing dimensions to over 5 square meters, thin or thick slabs, etc.). This situation makes waste recycling even more challenging, as the target is moving, and new and increasingly demanding technological requirements must be fulfilled.

Nonetheless, certain types of waste have a remarkable potential to take the place of traditional natural resources in ceramic production (Hossain and Roy, 2020). The majority of the literature that has been reviewed concentrated on the firing process, even though ceramic bodies had to meet all specifications—from milling to firing—to be employed in the production of tiles. Specifically, the behaviour of powder during compaction and the rheological behaviour of slips often represent the bottleneck in the scaling up from laboratory to factory. Although it may not seem significant, the requirement for early treatments is essential to the viability of waste utilization since it could reveal a shortage of supplies that inhibits recycling. It is not a coincidence that successful cases typically have minimal supply gaps, allowing residues to be sent directly to the tile manufacturing facility. If managed by the waste provider or the end user, a basic preliminary treatment such as drying or comminution represents a small gap, *i.e.*, pre-treatment waste for the preparation of glass-ceramics (Liu et al., 2023). But when the need arises to remove unwanted components selectively, beneficiation procedures need to be set up with certain plans and know-how. This is usually a serious obstacle that calls for a coordinated response, involving raw material suppliers (whenever able to transform waste into industrial minerals) or collecting places where residues can be treated and converted into secondary raw materials for ceramic tiles. Depending on the production process and the type of tile, a TRL for recycling, waste by waste, could be assigned thanks to the integration of accessible literature data with recognized industrial successes (Zanelli et al., 2021a). The waste with composition and technological behaviour similar to those of ceramic raw materials, such as granite recovered from quarry dumps or glass cullet from sorting municipal solid wastes, are associated with greater TRLs when compared to industrial practice.

Any waste that can be recycled but has not yet been used in industrial production is considered to be at an intermediate stage. The main causes of this incomplete development were technological barriers, like shortages in supply, challenges in batch design brought on by unusual compositions (such as high Ba and Sr in screen glass), or dangerous emissions during firing. Additional residues, such as coal fly ash (Luo et al., 2019), spent foundry sand (Mymrin et al., 2023), asbestos-containing demolition waste (Stevulova et al., 2020), cathode tube glass (Karaahmet and Cicek, 2019), sewage sludge (Amin et al., 2018), ornamental stone cutting (Souza et al., 2010) and sawing sludge (Subashi De Silva et al., 2022), were investigated in industrially relevant environments (pilot or full scale). The problems that hinder their recycling range from the way they behave during the ceramic process and the requirement for precautionary measures due to the presence of potentially harmful components and emissions during the firing process (Yuan et al., 2023).

When only assessed at the laboratory scale, waste recycling has a low TRL. Mining tailings (Almeida et al., 2021), oil refining sludge (Jagaba et al., 2022), galvanic sludge (Castañeda et al., 2023), and coal bottom and fly ash (Yuan et al., 2023) are a few examples. The environmental concerns (managing issues related to foul odours, fermentation, acid releases, or potential leaching of dangerous compounds or harmful gaseous emission) and waste pre-treatment appear to be more significant in these cases than the ceramic behavior. At low TRL, a suggested percentage of recyclable waste is typically overestimated. This means that projecting technical viability based only on laboratory-scale outcomes must be done with extreme caution (Zanelli et al., 2021a).

The practical application of waste in ceramic tiles is technically possible and already exists for residues that show a high affinity for the raw materials to be replaced, according to the circular economy perspective. This situation opens the door for ceramic tile manufacture, which uses huge amounts of raw materials globally, to become an important waste recycling goal. However, clay materials account for approximately half of the raw material demand, while just a few kinds of waste being studied can provide plasticity. Examples are limited to mining residues that contain enough clay minerals, and extremely fine-grained industrial waste. Therefore, the most promising applications seem restricted to flux and filler substitutes in complex ceramic bodies. Many residues can function as flux or filler (Ngayakamo et al., 2022), and more kinds may be selected for these functions in the event of a suitable technological characterisation. Many scientific and technological studies can be conducted to close this knowledge gap and advance our understanding of residues evaluated at lower TRLs (Andreola et al., 2016; Zanelli et al., 2021a).

Nevertheless, it is necessary to consider the constraints resulting from the compositional compatibility of any waste to be incorporated into the ceramic body. There is indeed a substantial difference between the composition of natural raw materials and that of most of the residues that can be used as secondary raw materials (Conte et al., 2024a). Taking the production of porcelain stoneware as an example, both the raw materials and waste data can be plotted in the Na_2O-Al_2O_3-SiO_2 system that best represents porcelain stoneware bodies (Fig. 5). While natural raw materials approach the compositional field of porcelain stoneware, waste materials are more or less markedly distant from it, according to alumosity and silica or iron oxide amounts. The exceptions are certain mining residues, the recycling opportunities of which are reviewed in section 3.2. Apart from the technological constraints mentioned in section 3.3, it is difficult to introduce large quantities of waste materials that are compositionally far from the ceramic batch because the resulting body composition would fall off the target. By keeping the field of porcelain stoneware as a target, most waste materials are compatible with up to a small percentage of the ceramic batch; by a lever rule approach, the eligible amount is inversely proportional to the distance from waste to the target. The combination of different types of waste is also a challenge, precisely because it is not easy to find residues whose points are located on opposite sides of the field of porcelain stoneware so that they can reciprocally compensate for the different compositions. Not to mention that, in any case, technological and environmental feasibility must be maintained.

Future research in incorporating waste from other sectors into ceramic tile bodies should focus on optimizing formulations to ensure performance and durability while maximizing waste utilization. Challenges include addressing variability in waste composition, scaling up laboratory findings to industrial levels, and ensuring compliance with environmental and safety regulations. Advancements in analytical tools and processing technologies will be key to overcoming these hurdles and unlocking new opportunities for sustainable innovation.

3.5. Development of novel waste-based ceramic products

The limitations highlighted in the previous section, due to the compositional differences between residues and ceramic batches, make it appropriate to look for alternative ways to increase the quantities of recycled waste materials. One promising approach is to combine residues and raw materials to create new waste-based ceramic products. The main advantage is the possibility of using significantly higher waste amounts than can be incorporated into standard tile bodies. The necessary condition is to engineer the batch design according to the characteristics of waste and raw materials. There are several studies in the literature that have paved the way for this (Segadães, 2006; Junkes et al., 2012; Dal Bó and Hotza, 2013; Galán-Arboledas et al., 2019).

The strongest limitation is that these new ceramic materials generally do not meet the technical and aesthetic requirements that the flooring and covering markets require. It is not a coincidence that Green Public Procurement has often been invoked for these waste-based products (Monfort, 2012; Andreola et al., 2016). Other substantial constraints come from production efficiency, given that in many cases the waste-bearing products proposed in the literature are obtained with

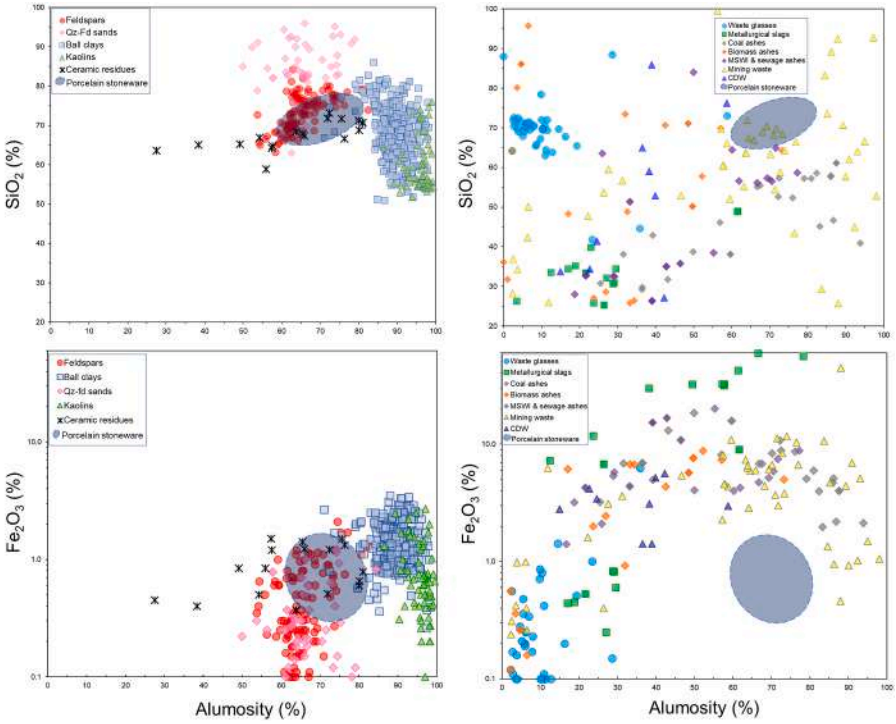

Fig. 5. Alumosity [(Al_2O_3+Fe_2O_3)/(Al_2O_3+Fe_2O_3+Na_2O + K_2O + MgO + CaO)] *versus* silica (above) or iron oxide (below) diagrams to compare the composition of porcelain stoneware body and raw materials (left) with the main waste materials proposed as secondary raw materials in ceramic tiles (right).

shaping and firing technologies that suffer from lower throughput, higher cost, and technological limitations (*e.g.,* small size of tiles). It is true, however, that it is not fair to compare mature products – such as wall and floor coverings, which underwent decades of process optimization – with brand-new products, still under development. In any case, considerable R&D efforts are required since novel waste-based ceramic tiles have only been achieved at a rather low technology readiness level (Zanelli et al., 2021a) and only a few studies are known at TRL 5–7 for mining residues (Campos et al., 2004), fly ash (Luo et al., 2018) and glass cullet (Skerratt, 2001).

Recent research has explored the use of unconventional materials as substitutes for traditional raw materials in ceramic and stone production, aiming to enhance sustainability and efficiency (Table S1). For example, hazardous industrial waste, such as methanol synthesis catalyst (MSC), red sludge from bauxite processing (RM) and ferrous slag (FS) have shown potential as alternatives to natural resources like clay and sand (Mymrin et al., 2022). In ceramic production, a mixture of 70 % MSC and 30 % RM demonstrated good mechanical properties at 1050 °C, with flexural resistance of 25–26 MPa (Mymrin et al., 2022). Similarly, blast furnace slag and ceramic sludge can be used to prepare parawollastonite and gehlenite minerals without chemical additives. With blast furnace slag, up to 83 wt% could be incorporated, resulting in decreased porosity and improved suitability for building materials applications (Khater et al., 2022). This demonstrates how different types of industrial waste can be effectively utilized to produce high-performance, sustainable ceramic products, emphasizing the versatility and potential of these alternative materials (Khater et al., 2022).

On the contrary, the fabrication of artificial stones using industrial waste materials has demonstrated significant sustainability and performance benefits. For example, granite particle waste (80–90 %) from quarries, combined with epoxy resin, has been used to create artificial stones with impressive flexural rupture stresses around 30 MPa (Carvalho et al., 2018). Additionally, incorporating 80 % of quarry dust and chamotte from brick industries into epoxy resin produced ornamental stones with similar mechanical strength. These properties not only meet but often exceed the required standards for ornamental stones used in civil construction. This innovative approach effectively repurposes industrial by-products, fulfilling stringent mechanical and aesthetic requirements for construction materials and underscoring the feasibility and practicality of integrating industrial waste into high-value products (Gomes et al., 2018). Overall, these studies underscore the potential of utilizing waste materials in novel ways to enhance sustainability in construction materials, offering both environmental benefits and meeting industry standards effectively.

The future of waste-based ceramic products lies in developing dedicated tile-making technologies to expand the range of compatible waste materials. Key challenges include overcoming inconsistencies in waste quality, adapting production methods for seamless integration, and achieving mass production adaptability. Research must also focus on developing efficient preprocessing techniques and economically viable approaches to encourage broader implementation in the ceramic sector.

4. Discussion

Strategies to improve waste recycling in ceramic tile bodies are discussed here as something transversal to the above-reviewed pathways. Any improvement of the circular economy in the ceramic tile industry must address significant challenges in sectors with distinct but interconnected objectives: managing waste recycling within the complexity of the supply chain, expanding the technological arsenal, and accrediting ceramic tile as a receiver of hard-to-dispose waste.

4.1. *Waste recycling within resource efficiency*

This strategy aims to adopt resource efficiency criteria and operational tools to measure and monitor the environmental, economic and social performances of ceramic tile production employing waste as secondary raw materials. This stems from the need to manage the growing complexity of the supply chain, where it is necessary to find a balance between circular economy (waste recycling in particular) and sustainability (Garcia-Muiña et al., 2019). Recently, various methodologies have been proposed and applied to the supply chain of ceramic tiles, which provide different approaches and operational tools that can also be useful for improving circularity and recycling.

Among the latter, the joint use of different life cycle tools, namely Life Cycle Assessment (LCA), Life Cycle Costing (LCC) and Social Life Cycle Assessment (S-LCA), addressing respectively environmental, economic and social issues, has been proposed, leading to the Life Cycle Sustainability Assessment (LCSA) framework (Settembre Blundo et al., 2018, 2019, Huertas-Valdivia et al., 2020; Ferrari et al., 2019; Medina-Salgado et al., 2022; Vieira et al., 2023). These tools can support decisions to reach significant reductions of the impacts potentially associated, for example, energy consumption or the distance travelled as well as the way of transportation employed for raw materials, including recycled wastes, demonstrating that the upstream supply chain represents a competitive factor to pursue less resource intensive and more sustainable manufacturing of ceramic products (Settembre Blundo et al., 2018, Huertas-Valdivia et al., 2020; Settembre-Blundo et al., 2018b). Indeed, the intrinsic holistic characteristics of these tools allow for avoiding shifting burdens among different phases of the whole life cycle of the studied process, as well as among different environmental, economic and social issues, thus obtaining more reliable comparisons between conventional ceramic tiles and those derived instead from wastes. To cite some recent examples, LCA was applied by Quereda et al. (2024), to compare the potential environmental impacts of producing porcelain tiles using conventional raw materials *versus* incorporating foundry by-products. The study examines the replacement of feldspathic sand in porcelain tile bodies with both uncalcined and calcined foundry by-products. The authors calculated only small reductions in the associated environmental impacts when using foundry by-products, mainly due to the limited contribution of the raw materials within the overall environmental footprint of ceramic tile production (*i.e.,* instead dominated, for more than 80 %, by the manufacturing phase). Nevertheless, a theoretically estimated reduction of 8500 t CO_2-eq per year was calculated for the Spanish situation with the results obtained.

LCA was also applied together with LCC by Yuan et al. (2024), to evaluate the environmental and economic impacts of replacing potash feldspar with industrial waste, fly ash (IWA), in ceramic tile manufacturing.

A systematic comparison of the environmental impacts across five ceramic tile manufacturing scenarios, each incorporating different proportions of IWA (0 %, 5 %, 10 %, 20 %, and 30 % by weight), revealed that replacing even as little as 5 % of potash feldspar with IWA can reduce potential impacts in key categories. These include climate change, terrestrial acidification, freshwater eutrophication, human toxicity, terrestrial ecotoxicity, and fossil depletion, with reductions ranging from approximately ca. 1 % to ca. 4 %. These reductions approached 10–20 % for selected impact categories when a 30 wt% of IWA replacement is considered. Concurrently, LCC highlighted a cost decrease per square meter ranging from ca. 2 % to ca. 11 %, when replacing potash feldspar by 5 wt% and 30 wt% of IWA respectively, mainly associated with reductions in raw material and transport costs compared to traditional formulations.

Overall, the results reported by Quereda et al. (2024) and Yuan et al. (2024) demonstrate and support, using quantitative holistic Life Cycle-based metrics, the effective potential for ceramic industries to reduce the environmental and economic impacts associated with tile manufacturing by replacing feldspar-based raw materials with selected wastes. The above mentioned tools (*i.e.,* LCA, LCC and S-LCA) can also be merged, and the corresponding assessment carried out dynamically, due to the complete digitalization of ceramic manufacturing and the full exploitation of Internet of Things (IoT) technologies within the Industry 4.0 paradigm. This allows to continuously monitor the performance of the supply chain over time, thus verifying sustainability objectives and quantifying any deviations or needs of implementation (Hervas-Oliver et al., 2019; Ferrari et al., 2019; Vacchi et al., 2021; Raffaeli et al., 2024). A representative example of how the digitalized ceramic tile manufacturing process can be continuously monitored and assessed in terms of its environmental sustainability is reported in Fig. 6 (similar approaches can be applied by integrating LCC- and S-LCA-based calculation tools).

The above mentioned LCA, LCC and S-LCA life cycle tools can also be applied in a predictive way thus under an eco-design perspective, to include sustainability among the conventionally considered industrial criteria for product development like quality, functionality, aesthetics and profit. This was, for example, the case of six alternative supply scenarios that were simulated, assessed (in terms of the potential associated environmental, economic and social impacts) and compared, *ex ante* with the reference one (Garcia-Muiña et al., 2019).

The validation of the potential offered by eco-design and digital technologies to serve as operational tools or approaches to promote circular business models and competitiveness was also empirically verified for an Italian ceramic manufacturer (Garcia-Muiña et al., 2019). In particular, the progressive reduction in the supply of extra-EU clay and feldspar in favor of European and local sources (delivered via more environmentally sustainable transport systems, *e.g.*, by train) contributed to significant reductions in most of the impact categories considered, compared to the reference composition (*e.g.*, more than −30 % for respiratory inorganics and land occupation environmental indicators). Similar findings were also demonstrated when quantifying externalities, showing a progressive decrease (up to −0.41 €/m^2) associated with the reduced utilization of extra-EU raw materials and increased transport by train. Reductions of up to −0.52 €/m^2 were also observed for industrial costs, primarily due to the lower cost of raw materials. Furthermore, a reduction of approximately −8 % in social impacts was quantified by applying Societal Life Cycle Costing (S-LCC).

A further approach within the eco-design of porcelain tiles was proposed by Alves et al. (2023), which coupled flowsheet simulation with MATLAB to create a digital twin of the manufacturing chain to promptly ascertain the necessary adjustments in the processing parameters as a consequence of modifications in raw materials composition, concurrently evaluating the potential reductions of cost and CO_2 emissions.

The environmental sustainability performances of the ceramic supply chain can also be improved by implementing lean and quality management practices. A statistical multivariate analysis performed on data referred to 233 ceramic enterprises showed that the adoption of these practices allows enhancing the operational and environmental performances, while typically decreasing the economic ones (Choudhary et al., 2022).

The environmental, economic and social impacts associated with particularly resource-intensive supply chains, such as the ceramic sector, can significantly be negatively affected by geopolitical and sanitary crises, as those faced during the last years. A potential solution, recently highlighted, could be the configuration of reshoring and nearshoring scenarios for ceramic raw materials locations and sourcing. This was quantitatively demonstrated by Fernández-Miguel et al. (2022) through the application of a transdisciplinary approach, comprising a sectoral scenario analysis, a strategic design of alternative scenarios, a technological assessment of the alternative scenarios and their environmental impact assessment (the latter performed by LCA methodology). This approach led to the development of five different compositions of ceramic bodies, characterized by lower degrees of sourcing criticism and lower environmental impacts with respect to the reference composition and all complying with the ISO requirements for ceramic tiles (as experimentally determined at a lab scale). Particularly, the novel nearshoring and reshoring scenarios proposed demonstrated the possibility of achieving reductions in the global warming potentials associated with the extraction and delivery of raw materials to factories (for the production of 1 m^2 of porcelain tiles) of −1.03 kg CO_2 eq. and −1.33 kg CO_2 eq., respectively (Fernández-Miguel et al. 2022).

Although the strategy described in this section, employing efficiency criteria and selected operational tools can contribute to assessing and

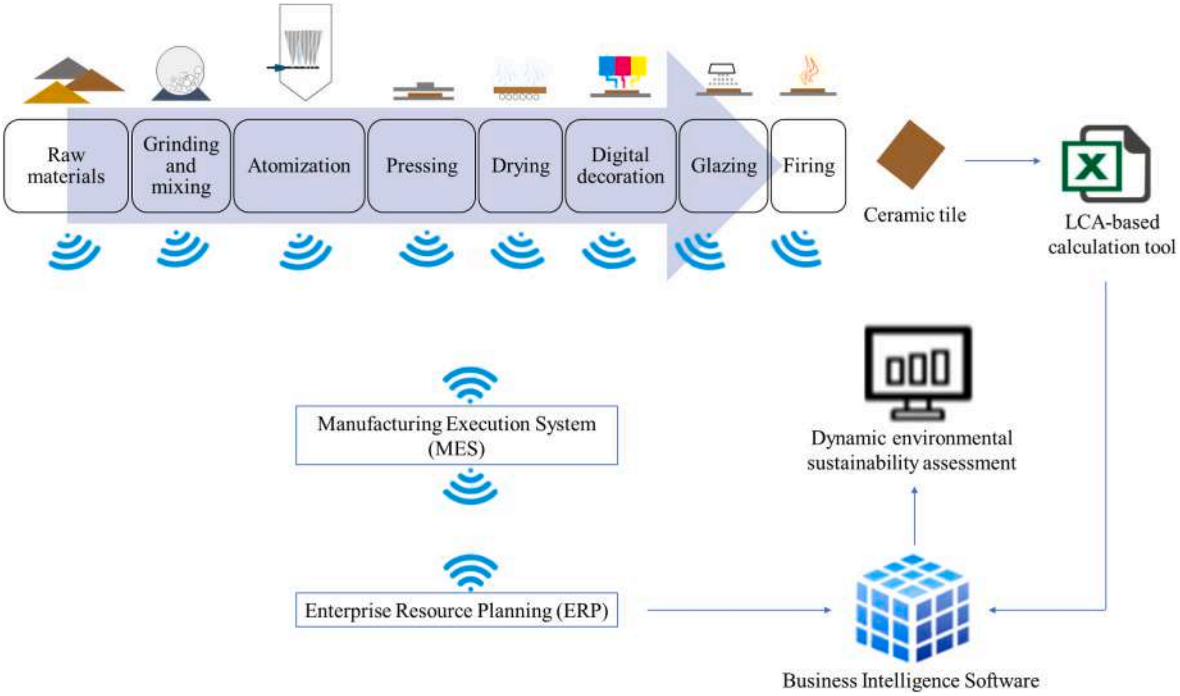

Fig. 6. Simplified representation of how to perform a dynamic LCA-based environmental sustainability assessment by exploiting full digitalization and automation of ceramic tile manufacturing.

monitoring the potential reductions in the environmental, economic and social impacts associated with the use of recycled wastes, further research is still needed to manage waste recycling more reliably within the complexity of the ceramic sector supply chain. Particularly, manufacturing enterprises operating in the ceramic sector significantly struggle in sourcing primary inventory data related to the extraction and production of the employed raw materials, necessary for the sustainability assessment. This difficulty in implementing the cradle-to-grave life cycle approach due to the unavailability of primary data shared by most of the supply chain actors is typically overcome by employing secondary data from scientifically recognized databases, that are generally not specific to the analyzed sector, thus making the obtained results not completely reliable.

This issue was, at least partially, addressed by the REDiRECT (2024) project, recently funded by the Ministry of Enterprises and Made in Italy. Indeed, the main objective of this project was to develop a new manufacturing model for the ceramic and mining industry called Circular Enterprise 4.0, employing industrial symbiosis as a tool for cooperation and collaboration between the operators of the supply chain. This could make the life cycle approach effective because companies will be able to exchange not only material resources but also information and knowledge in a context of mutual trust.

4.2. New technological solutions to ease waste recycling

This strategy consists of the development of new processes and management solutions to maximize waste recycling. There are several possible pathways to implement these solutions in ceramic tile production, which are briefly illustrated hereafter.

The reuse of waste can be managed in different ways, and this can take place either within the single tilemaking plant within factories of the same manufacturing group or at a ceramic district level. There are regulatory constraints on the transport of waste, which vary from country to country, as well as limitations related to logistics, which must be taken into account. Some in-house residues are easily recyclable along the same production line, as illustrated in section 3.1, with a continuous, automated process. Others are instead accumulated in temporary stocks and then processed in recycling campaigns. The latter, as well as waste materials from outside the ceramic supply chain, can be reused with various tactics (Fig. 7), of which the simpler is their dilution in the same standard batch (option A: all residue in). Another chance is splitting residues between two different productions (option B in Fig. 7) like for example unglazed and glazed porcelain stoneware, as the former has stricter technical and aesthetic requirements, in particular about body coloration, while the latter can tolerate greater amounts of residues (Rambaldi, 2021; Zanelli et al., 2021a). Taking this strategy even further, it can be decided to keep the main production almost waste-free (except for some easily and directly recyclable in-house residues) and concentrate all remaining waste, including those from other industrial sectors, in "green" products (option C in Fig. 7) that represent only a fraction of the overall output of the factory or manufacturing group. For waste from external sources, it becomes crucial to have effective forms of industrial symbiosis to ensure supplies in quality and quantity constant over time at affordable cost. Another recycling tactic is to manage the distribution of waste within the ceramic tile and thus create appropriate product architectures. Commonly, a batch can contain all the waste materials with which the tile support is manufactured. This has the undoubted advantage of managing only one formulation, but also the disadvantage of exhibiting any unwanted aesthetic aspects (for example, dark coloring). Alternatively, two distinct formulations can be developed: ideally, one containing residues and the other free of waste. To minimize undesirable aesthetic effects, products can be designed with two-layer or sandwich architectures, taking care to place the waste-based formulation in the lower layer or the central one in the case of a sandwich. These architectures can be realized through double loading the powders in the mould (in conventional hydraulic presses) or double or triple loading the powders on the belt (in presses and compactors for large formats). A pressing need aims at overcoming technological bottlenecks in the introduction of waste materials into the ceramic tile production cycle which are crucial limiting factors for increasing circularity (Zanelli et al., 2021a). The main bottlenecks are in both the body preparation and the firing stages. The main problems in body preparation concern the wet route (*i.e.,* the wet milling and spray drying process) and are essentially related to the rheological behaviour

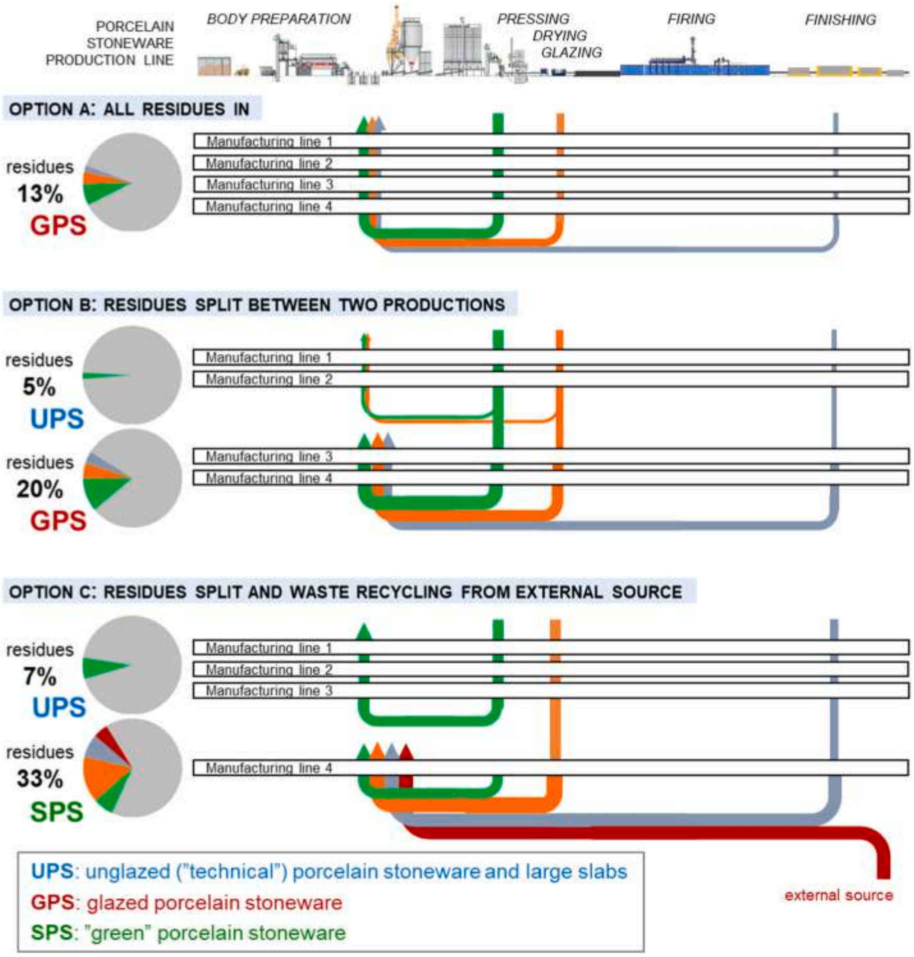

Fig. 7. Examples of waste recycling tactics in the production of ceramic tiles.

of slips. A typical disadvantage of waste addition may be the increase of slip viscosity and thixotropy. This leads to a consequent reduction in grinding efficiency with a detrimental domino effect downstream in tile processing. These problems are managed in industrial practice by limiting the percentage of waste and accepting higher costs, due to less efficient process conditions and/or increased amount of deflocculant additives (Manfredini et al., 1991; Andreola et al., 2001, 2020). The dry route, which consists of body preparation by grinding and granulation in dry conditions, allows to overcome these limitations (Melchiades et al., 2010; Gil et al., 2012; Mezquita et al., 2017).

In this way, general advantages can be achieved – such as lower water, energy and additive consumption (Nassetti and Palmonari, 1993; Melchiades et al., 2010; Mezquita et al., 2017) – and specific advantages for waste recycling, since avoiding aqueous suspensions removes the bottleneck of rheological problems. Recently, the technological solutions of dry routes have been enriched, including hybrid routes, to achieve the performance of granulates closer and closer to those of spray-dried powders (Shu et al., 2010; Soldati et al., 2020). Thanks to these advances, it is possible to have greater flexibility in the process, which can therefore use entirely the wastewater from the line washing (target not reachable with a full dry process) or insert the waste materials in the granulation stage (Melchiades et al., 2011). In perspective, it can be envisaged to mix spray-dried powders (made with waste-free formulations or with a low waste amount) with microgranulates obtained with waste-based batches (Soldati et al., 2022).

Limitations regarding firing behaviour have emerged, for example, in the sintering of vitrified tiles containing waste materials, which may suffer from a lower densification efficiency and/or poor dimensional stability at high temperatures (Sánchez et al., 2019; Conte et al., 2022). This is the major technological bottleneck in the case of glassy waste, which used in quantities greater than a few percent can significantly worsen pyroplasticity and reduce bulk density (Conte et al., 2020). Solutions to overcome the problem of excessive deformation of tiles at high temperatures should be sought through a microstructural product design. In a material such as porcelain stoneware, where at the maximum firing temperature the amount of liquid phase can attain 60–70 % in volume, this can be pursued by modulating batch formulation and processing parameters to keep under control, such as the quantity, size and shape of the crystalline grains (Dos Santos Conserva et al., 2017; Sánchez et al., 2019) as well as number and size of the microstructural defects (De Noni Junior et al., 2023; Dal Bó et al., 2023). Another standpoint concerns the bulk viscosity of the tile (the so-called effective viscosity), which depends on the viscosity of the liquid phase and the amount of solid load (Costa, 2005; Giordano, 2019). The effective viscosity can be controlled by a buffering effect: if quartz is stable at high temperature, it ensures an adequate amount of solid load; if it melts, it increases the viscosity of the liquid phase while still allowing to maintain a sufficiently high effective viscosity (Conte et al., 2018). The introduction of waste materials can irremediably compromise this buffering effect and therefore the design of the batch must consider the bulk composition and firing behaviour of the waste components.

The circularity can be promoted by waste materials that favor a consistent lowering of the firing temperature, with consequent advantages in thermal energy savings (Dong et al., 2020; Gualtieri et al., 2018; Peng and Qin, 2019). Along with these advantages, however, there are pending issues, such as the development of glazes and engobes that, for low temperatures, must necessarily include critical raw materials in larger quantities (*e.g.,* boron and/or lithium). Therefore, these solutions seem valid for niche applications, where environmental performance is emphasized through green labeling.

4.3. Ceramic bodies for waste inertization

This strategy is based on the fact that ceramics can be an important receiver of waste, thanks to the firing process that can guarantee an adequate level of inertization also for hazardous elements (Andreola et al., 2019; Ardit et al., 2022; Conte et al., 2024a). This paved the way for the ecodesign of new formulations of "green" ceramic tiles and also for the development of tailored batches with a high content of waste materials (Skerratt, 2001; Luo et al., 2018; Rambaldi et al., 2018; Rambaldi, 2021). To have full control over the technological and environmental repercussions, however, implies the need to have a deep understanding of how the introduction of waste affects the firing behaviour of ceramic tiles.

At the moment, batch design takes into account only the technological response of the various raw materials and this approach is maintained in industrial practice and also in the design of formulations containing waste. It would be very useful to have a “compositional compass” that allows to correctly address the batch design both in the option to maximize waste recycling in current ceramic productions (as reviewed in section 3.4) and in the case of novel waste-based products (as considered in section 3.5). The knowledge of compositional fields of the main ceramic materials used in tilemaking is limited and there is no agreement on the compositional parameters to be adopted in batch design, so the indications are often contradictory (Dondi et al., 2014; De Noni Junior et al., 2023; Zamani et al., 2023). Therefore, an effort is needed to better define the target where to direct the search for new formulations for ceramic tiles (Conte et al., 2024b).

Eco-design can benefit from different approaches to the technological modelling of ceramic formulations, which can move top-down or bottom-up. In the first case, it starts from the general, analyzing the macroscopic characteristics (technological behaviour of the bodies) to arrive at defining batch formulation and processing conditions. This top-down approach has been implemented with the statistical design of experiments (Lassinantti Gualtieri et al., 2011; Menezes et al., 2008; Zanatta et al., 2021; Alves et al., 2023). These powerful tools can remarkably improve the empirical approach in batch design, but they are not widespread in the industrial field because they suffer from some limitations still to be solved. First, it is difficult to adequately represent the complexity of industrial batches, especially in the case of porcelain stoneware, where formulations with many raw materials are often used (typically from 6 to 10). Second, the useful life of formulations has decreased dramatically in some areas, forcing the search for less demanding batch design practices. There is also some mistrust about the robustness of the conclusions, linked to the fact that the results depend greatly on the choices needed to simplify the design of experiments. These can lead to trivial results or results substantially influenced by process conditions, not always optimal, fixed *a priori*.

Another possible approach to technological modelling starts from the particular, considering the microstructural variations that occur during the production cycle of tiles. This bottom-up path aims to relate the phase transformations of the individual components with the technological behaviour of the ceramic body to define batch formulation and optimal processing conditions. It is a path recently undertaken for porcelain stoneware (De Noni Junior et al., 2023; Zamani et al., 2023; Conte et al., 2024b) and that needs to complete a theoretical formalization and then to develop predictive models applicable to the industrial reality. Although it is at a much lower readiness level than the design of experiments, the microstructural approach has a much greater ability to understand the mechanisms that regulate the behaviour of the tile bodies and therefore to address the technological solutions to increase the circularity.

One issue that often hinders the circular economy is the overload of administrative obligations and legal responsibilities that waste recycling entails. A seemingly simple step, such as replacing a natural raw material with a residue, in many countries means moving to a regime of increased environmental impact controls. All this is quite manageable, as long as a compositional affinity exists between ceramic body and waste (see section 3.4). When waste from other supply chains is introduced into the ceramic body, it is necessary to have knowledge that is usually not necessary in the production of tiles. The possible occurrence of hazardous elements, in particular, obliges to control their degree of stabilization in the finished body and thus to know the firing behaviour of components that usually occur in trace amounts into waste-free batches (Garcia-Valles et al., 2007; Karayannis et al., 2017; Ardit et al., 2022).

Strategically, it is important to focus efforts on recycling waste materials which are a significant socio-economic problem, such as those available in huge quantities and which cannot be recycled otherwise (Zacco et al., 2014; Liu et al., 2021; Swain et al., 2022). The analysis of waste streams helps to identify certain types of waste as abundant and challenging for recycling, which can be used in the production of ceramics (Hemali and De Alwis, 2022; Boschi et al., 2023; Caro et al., 2024). This challenge can be addressed by extending body formulations well beyond the current perimeter and developing technologies capable of producing new products based on waste materials. The success of this route is a radical change in the logic of the market, which should be directed towards new types of products that feed a massive flow of waste recycling, as envisaged in section 3.5, also with Green Public Procurement policies (Timellini et al., 2007; Monfort, 2012; Andreola et al., 2016).

A comparative analysis of various strategies to enhance circularity in ceramic tile production was conducted, and the main results are summarized in Table 1. As previously illustrated, the specific actions exhibit different Technology Readiness Levels (TRL) and varying degrees of diffusion within the ceramic tile industry. Overall, the strategies that are more widely adopted and technologically advanced pertain to zero-waste production and resource efficiency. Their impact on circularity is significant (*e.g.*, addressing the issue of process residues); however, the amount of recyclable waste through operational or management tools largely depends on the effectiveness of other strategies. Therefore, improving actions that facilitate the incorporation of waste from other sectors is crucial, especially since recycling performance has substantial potential for growth. It is important to note that TRL varies significantly based on the type and origin of waste materials. Enhancing circularity must occur throughout the entire supply chain and life cycle, where actions downstream of ceramic tile production face low TRL, while those upstream experience limited diffusion, despite the availability of existing technologies.

All pathways present potential advantages and disadvantages from technological, environmental, economic, and social perspectives. Clear trade-offs emerge: while economic and social benefits generally have a side effect in terms of technological drawbacks during the implementation of specific actions. This analysis has deemed every action that enhances circularity as beneficial from an environmental standpoint, with a weight assigned proportionally to the amount of recyclable waste involved.

Actions that are technologically ready (TRL 9) and demonstrate a net benefit—considering technological, environmental, economic, and social aspects—are recommended for implementation in the production of ceramic tiles. In some instances, these recommendations suggest improvements expected to arise from technological solutions currently under development. Certain actions may be better suited for niche applications or may require support in terms of standards and acceptance, such as Green Public Procurement (GPP). Additionally, the impact on circularity may not be directly related to the ceramic tile supply chain but rather to other industrial sectors. For example, problematic residues

Table 1
Comparative analysis of the various strategies and actions to enhance circularity in ceramic tile production.

Strategy	Action	TRL	Advantages/Disadvantages				Diffusion in the industry	Impact on circularity	Waste in the ceramic batch	Recommendation
			Techn.	Envir.	Econ.	Social				
Zero-waste production (process residues)	Direct recycling	9	/	+	++	/	widespread	significant	up to ~13 %	TBI
	Direct recycling + adjustment	9	–	+	++	/	widespread			
	Recycling after treatments	9	− −	+	+	/	partial			
	Problematic recycling	2–6	− − −	++	–	/	none	limited	<1 %	to other sectors
Entire supply chain and life cycle	Upstream: full exploitation	7–9	/	++	++	++	limited	significant	other sectors	to other sectors
	Downstream: CDW	4–5	− −	+	−|+	+++	none	limited	<2 %	to other sectors
	Downstream: CTDW	3–4	–	+	−|+	+++	none	significant	up to ~5 %	under development
	Unsold and fired scraps	9	− −	+	+		limited	significant	up to ~5 %	TBI
Incorporation of waste from other sectors	Substitution of raw materials	5–9	–	++	−|+	++	widespread	high	up to ~20 %	TBI (improved)
	Model for batch design	3–4	+	++	+	+	none	very high	up to ~40 %	under development
	Design product architectures	5–9	− −	++	−|+	+	limited	significant	up to ~30 %	TBI (improved)
	Waste-based products	3–7	− − −	+++	−|+	+++	none	very high	up to 100 %	GPP
	Low firing formulations	4–5	− − −	−|+	+	/	none	significant	up to ~5 %	niche products
Operational, management and resource efficiency	Waste management tactics	9	/	+	+	/	widespread	significant	depending on the other strategies	TBI
	Lean practices	9	/	+	+	/	widespread	significant		TBI
	Life Cycle Assessment tools	7–9	/	+++	−|+	+	limited	high		TBI
	Digital Twin and AI	6–7	+	++	−|+	+	none	high		under development
	Industrial symbiosis	4–6	/	+++	−|+	++	none	high		under development

Advantages (+), disadvantages (−) or no significant effect (/) in ceramic tile production from technological, environmental, economic and social viewpoints. TBI: To Be Implemented. CDW: Construction and Demolition Waste. CTDW: Ceramic Tile Demolition Waste. GPP: Green Public Procurement. AI: Artificial Intelligence.

from ceramic tile manufacturing, bulk CDW or various types of mining waste are often more effectively valorised in other sectors.

5. Conclusions

The status of actions (possible or already underway) to improve circularity in ceramic tile production is illustrated for the first time analysing the entire supply chain (from raw material extraction to end-of-life management of tiles). The present contribution, which integrates results from scientific literature with what has been put into practice by the ceramic industry, provides an up-to-date picture that goes beyond the current state of knowledge. The tactics of the ceramic industry were critically investigated, with distinct ways to enhance circularity through waste recycling being identified. Across these tactics of action, there are general strategies, which have been examined with particular emphasis on systemic approaches at various levels.

Five possible pathways to improve circularity in ceramic tile manufacturing were evaluated:

Full recycling of in-house residues is a well-established practice in the ceramic tile industry, particularly in Italy, where technological solutions alternative to landfilling have been developed. This can prevent a huge amount of waste (globally estimated ~45 million tons per year) but the situation is not well-known worldwide. The implementation of the best available technologies and practices is necessary to achieve the goal of zero-waste manufacturing of ceramic tiles.

Actions upstream of tile production entail the supply of ceramic raw materials from a full exploitation perspective. This pathway aims at transforming all residues from mining (and frit production) into secondary raw materials for building and construction, and further applications. Examples of sustainable practices in the mining industry demonstrate that is possible to reduce the environmental impact, conserve natural resources, and provide economic benefits at the same time.

Actions downstream must face the fact that ceramic tiles, at the end of their life cycle, are usually included in construction and demolition waste. Recycling of CDW is challenging, unless properly sorted, because of worse technical performance compared to natural aggregates. Ceramic tile waste can be successfully recycled, in the same production cycle and in others (*e.g.,* cement, concrete). In the absence of selective demolition or deinstallation of buildings, enabling technologies are needed for the effective separation of ceramic materials from the rubble, which would provide fractions with higher added value.

Recycling waste from other industrial sectors is a well-known option, but the absence of unified standards for waste-derived raw materials creates uncertainty and slows adoption. Several factors constrain the recommended percentage of residues: chemical compatibility between waste and ceramic body; limited technological readiness and a lack of scalable solutions for processing diverse waste categories, the fluctuating availability, incompatible composition and preprocessing costs of waste materials, uncertainties surrounding long-term economic benefits, inconsistent market incentives, and the lack of sufficient financial support for recycling initiatives. Moreover, the need to comply with standard prescriptions and market demand makes it improbable to introduce more than a few percent of waste from other industrial sectors in current ceramic productions.

These limitations are pushing the search for alternatives to increase the quantities of recycled waste materials. One promising avenue is to combine residues and raw materials to create new **waste-based ceramic products**. The necessary condition is to engineer the batch design according to the characteristics of waste and raw materials. As a consequence, these new ceramic materials generally do not meet the technical and aesthetic requirements of the market. Social acceptance also plays a role, as end-users and manufacturers may hesitate to embrace recycled content due to perceived quality or safety concerns. To bridge existing gaps, future studies should focus on developing standardized testing methods for evaluating the performance and safety of recycled ceramic products. Specific policies are encouraged to find applications for products able to enhance substantially the circularity of ceramic production (*e.g.,* Green Public Procurement).

Transversally to pathways, general strategies should be put into practice by the ceramic industry to improve recycling actions within the circular economy:

A systemic approach aims to adopt **resource efficiency criteria and operational tools** based on the Life Cycle Thinking approach to measure and monitor the environmental, economic and social performances of ceramic tile production employing waste as secondary raw materials. The use of these tools can effectively contribute to demonstrating and quantifying reductions in the environmental, economic, and social impacts arising from the substitution of virgin raw materials with selected wastes, the use of raw materials sourced from local mines and transported via more sustainable systems, as well as from nearshoring or reshoring strategies. These tools are therefore highly recommended for implementation by ceramic industry players to reliably assess the sustainability of their manufacturing processes, thus avoiding burden shifting among different life cycle phases or across various environmental issues.

Automation and digitalization of the ceramic process make it possible to perform these reliable assessments dynamically, thus continuously monitoring and potentially intervening towards reductions in the associated impacts. These life cycle-based tools can also be used under an eco-design perspective to account for sustainability in the very first steps of the development of ceramic products.

The need to manage the growing complexity of the supply chain makes it necessary to find a balance between circular economy (waste recycling in particular) and sustainability. Various methodologies have been recently proposed and applied to the supply chain of ceramic tiles, which provide different approaches that can be used for improving circularity and waste recycling. Particularly, the promotion of the above-mentioned life cycle tools by the different actors involved in the ceramic supply chain would promote a mutual exchange of environmental, economic and social information that could significantly increase the quality of the inventory data needed to perform the assessments, thus the reliability of the obtained results.

Another strategy consists of the **development of processes and management solutions** to maximize waste recycling. New processes can be implemented to overcome technological bottlenecks, for example in wet milling, due to rheological constraints of slips, by switching from the wet route to the dry route in body preparation. Other actions concern making more efficient waste management within the single plant of tilemaking or plants of the same production group or at the level of the ceramic district. Furthermore, there are recycling tactics to manage the distribution of waste within the thickness of ceramic tile and thus create appropriate product architectures.

A third strategy sees ceramics as a major receiver of waste, as the firing process can ensure an adequate level of inertization also for hazardous elements. This paves the way for the eco-design of new formulations of "green" ceramic tiles, even with a high content of residues. It should be strategically important to focus on waste materials which are a significant socio-economic problem, such as those available in huge quantities and which cannot be recycled otherwise. This challenge ought to extend body formulations well beyond the current perimeter and develop technologies capable of making new products based on waste materials. However, to have full control over waste recycling, a deep understanding of how it affects the technological behaviour of ceramic tiles is essential. Therefore, both investment in research and a radical change in the logic of the market are required, which should be directed towards new types of products that feed a massive flow of waste recycling. Additionally, interdisciplinary approaches that combine materials science, environmental engineering, and economics can offer a more holistic understanding of how circularity can be effectively achieved in the ceramic industry.

To summarize, this review advances current literature by systematically consolidating the challenges, strategies, and opportunities associated with incorporating waste materials into ceramic tile production, with a clear focus on circular economy principles. It provides a multidimensional perspective that bridges technical feasibility with regulatory, economic, and societal considerations, offering a practical knowledge base for diverse stakeholders. For policy-makers, the findings highlight the need to establish standardized guidelines for waste-derived raw materials and to support innovation through targeted funding and incentives. Industry players are encouraged to adopt waste auditing practices, collaborate with external waste generators, and gradually integrate recycled inputs while monitoring performance benchmarks. Researchers can build on this foundation by exploring underutilized waste streams, improving material compatibility, and assessing long-term durability of recycled ceramics. Together, these coordinated actions can accelerate the shift toward more sustainable and resilient ceramic manufacturing systems.

CRediT authorship contribution statement

Sonia Javed: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Sonia Conte:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Chiara Molinari:** Visualization, Validation, Investigation, Formal analysis. **Roberto Rosa:** Writing – original draft, Visualization, Investigation, Formal analysis, Conceptualization. **Anna Maria Ferrari:** Writing – original draft, Methodology, Funding acquisition, Conceptualization. **Michele Dondi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Formal analysis, Data curation, Conceptualization. **Chiara Zanelli:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, 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.

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Appendix A. Supplementary data

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Data availability

Data will be made available on request.

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SUPPLEMENTARY MATERIAL: Table S1. Recent research on waste recycling in ceramic tiles.

Sr.#	Product Type	Waste type	Firing cycle	Recommended concentration (%)	References
1.	PORCELAIN STONEWARE	Raw wastewater sludge	Electrical furnace, 0-550°C, 5°C/min: 30 min: 550-1200°C, 5°C/min	**40**	(Wen et al., 2023)
2.		Thermally hydrolyzed sludge at 180°C and 082MPa for 60min	550°C to 1200°C at a ramp rate of 5°C/min for 120 min		
3.		Municipal solid waste incineration fly ash	750°C at a ramp rate of 8°C/min,120 min, 850, 900, 950, 1000, 1050, and 1100°C at the rate of 5°C/min, 90 min	**36.7**	(Zou et al., 2022)
4.		Lead-zinc tailings		**9.2**	
5.		Waste glass		**45.9**	
6.		Lead slag and lead-zinc tailings	1050°C	**40**	(Zhang et al., 2023)
7.		Granite waste powder as a secondary flux material	1100, 1150, and 1200°C with a ramp rate of 6°C/min for 45 min in a tubular carbolite furnace	**40**	(Ngayakamo et al., 2022)
8.		Investment in casting sand waste to replace kaolin	1200°C at a ramp rate of 50°C/min	**5**	(Bahtli & Erdem, 2022)
9.		Scheelite and kaolin residue	at a ramp rate of 30 °C/min (1150 °C, 1200 °C, and 1250 °C) 5 min	**2** and **27**	(Almeida et al., 2021)
10.		Filter-press cake waste of a ceramic-tile factory	1210°C for 57 min in an industrial firing regime	**6**	(Ozturk, Z. et al., 2023)
11.		High Recycled Content (85 % Soda-lime scrap glass and unfired scrap tiles) and 15% natural clays	1160, 1025, 1210 for 39 min	**85**	(Rambaldi, 2021)
12.		Waste foundry sand	1050, 1250		(Sgarlata et al., 2023)
13.	VITRIFIED +SEMI VITRIFIED	Silica sand tailings	Chamber furnace 950°C for 1 h	**40**	(Liu et al., 2023)
14.		Glycerine pitch (GP) and used cooking oil (UCO)	190°C for 24 h	**12**	(Teoh et al., 2021)
15.		Galvanic sludge	Industrial tunnel gas kiln for 42-h at 1150°C	**2**	(Castañeda et al., 2023)
16.		Coffee grounds waste	1220°C with a heating rate of 15°C/min and 4 min of soaking time in a lfast-firing kiln	**15**	(Busch & França Holanda, 2022)
17.		Glass waste nanoparticles	1000, 1050, 1100, 1150 and 1200°C for 1-h at a ramp rate of 5°C/min	**20**	(Darweesh, 2021)
18.		Calcined dredged sediment (HDSC)	1100, 1200 (1hr) and a heating rate of 10°C/min	**20**	(Slimanou et al., 2022)
19.		Cupola furnace slag	900 °C,1000 °C, and 1100 °C with a heating rate of 2−5 °C/min	**2**	(Thakur et al., 2022)
20.		Sugarcane Bagasse Ash	900 to 1100°C in a muffle furnace for 1 h under 10 °C/min heating rate and cooling rate	**5**	(Sultana & Ahmed, 2022)
21.		Iron ore tailings (dam) (clay)	1050 °C and 1150 °C in a muffle furnace	**66.6**	(Fontes et al., 2021)

Table S1. Recent research on waste recycling in ceramic tiles (continued).

Sr.#	Product Type	Waste type	Firing cycle	Recommended concentration (%)	References
22.	VITRIFIED +SEMI VITRIFIED	Waste mineral wool (MW) and spent catalyst (SC) from cracking of petroleum	1000, 1020, 1040, 1060, and 1018°C, and soaked at the max firing temperature for 8 h	**20**	(Pranckeviciene & Pundiene, 2021)
23.		Aplitic granite waste from dimensional stone production	Laboratory electric chamber oven in an oxidizing environment at 1100, 1200, and 1250°C	**40**	(Vasić et al., 2022)
24.		Post-flotation solidified tailings from copper production	Gradient furnace in the temperature range 800–1250°C	**20, 50**	(Izak et al., 2023)
25.		Municipal solid waste	T room–500°C: 2 h; 500–650°C: 2 h; 650–Tmax: 2 h; Tmax: 900, 950, 1000 and 1050°C over 4 h	**40**	(Jordán et al., 2022)
26.		Granite stone wastes	1000, 1050, 1100, 1150, 1200, and 1250 °C) with an average heating speed of 5°C /min and 1h soaking	**40**	(Rashwan & Abd El-Shakour, 2022)
27.		Waste from cutting volcanic tuff stones	Fast-firing at 1180°C for 50 min within the roller kiln	**5**	(Akpınar & Anlı, 2023)
28.	SEMI POROUS	Spent bleaching earth (SBE), oil palm ash (PA)	1000–1100°C for 2h	**15** (SBE) **5** (PA)	(Srisang & Srisang, 2021)
29.		Drilling cuttings	electric kiln with a 5 °C/min heating rate for 90min at each temperature (750, 850 or 950 ◦C)	**30**	(Maciel et al., 2023)
30.		Crushed scraps of defective fired tiles	Electric laboratory kiln, 1100°C and 1160°C (25°C/min)	**20**	(Castellano et al., 2022)
31.		Marble dust residues		**15**	
32.		Fly ash from thermal power plants.		**20**	
33.		Waste sewage sludge	1350°C for 05 h,	**30, 40, 50**	(Yu et al., 2023)
34.		Hazardous spent methanol synthesis catalyst waste (MSC), red mud (RM) and ferrous slag (FS)	900, 1000, 1050, 1100, and 1150 °C for 1 h	**70** MSC **30** RM	(Mymrin, Alarcon, et al., 2022)
35.		Glass waste (GW) from metal cleaning before the galvanic process	6 h at different temperatures (700, 750, 800, 850, 900, 950, and 1000 °C)	**10**	(Mymrin, Alekseev, et al., 2022)
36.		Phosphate waste rocks	Fired at 1000°C at 3°C/min for 2h	**50**	(Borja et al., 2022)
37.		Marble waste	Fast-fired between 1100°C and 1180°C	**15**	(Carlos R. Ramos et al., 2023)
38.		Rice husk ash (RHA) and ceramic sludge (CS)	850°C	**10** RHA **10** CS	(Subashi De Silva et al., 2022)
39.		Fly ash	1150–1250°C, heating rate of 10°C/min; 45 min	**27.9**	(Wang et al., 2023)
40.		Blast furnace slag		**55.8**	
41.		Desulphurisation gypsum		**7**	
42.		Sewage treatment plant (STP) waste	Fired at 800°C, with a heating rate of 2°C/min, for 120min	**15**	(Areias et al., 2023)
43.		Phosphate rock waste (replacing Portland cement)	400°C and 600°C, for 120min and heating rate of 25°C/min	**25**	(Pires et al., 2022)

Table S1. Recent research on waste recycling in ceramic tiles (continued).

Sr.#	Product Type	Waste type	Firing cycle	Recommended concentration (%)	References
1.	**SEMI POROUS**	Eggshell waste ($CaCO_3$ source)	Heating rate of 5°C/min until 980; for 15 min cooling rate of 5°C/min	**92**	(Vilarinho et al., 2022)
2.		Marble slurry	1200°C for 1 h dwelling time in an electric furnace with heating rate of 8°C/min	**24**	(Solanki et al., 2023)
3.		Colemanite waste calcined at 800◦C	1180°C	**40**	(Cengizler, 2022)
4.		Raw alum sludge (RAS), thermally activated alum sludge (TAAS), pulverized alum sludge ash (PASA)	heat cured at 165 and 195°C for 24, 48 and 72 h	**25-30**	(Teoh et al., 2022)
5.		Tannery waste powder	1000 °C to 1150 °C in a muffle furnace	**10**	(Amin et al., 2018)
6.		Blast furnace slag, ceramic sludge	1100°C for 1 h	**39.9**	(Khater et al., 2022)
7.		Flat glass cutting waste	Fired in a muffle furnace under oxidizing atmosphere at 850 and 950°C for 3 h with a 2°C/min heating hate	**30**	(Rodrigues et al., 2021)
8.		Green liquor dregs		**10**	
9.		Ash from a red ceramic industry	Curing at a temperature of 80°C, in both cases with a curing time of 7, 14 and 28 days	**12.5**	(Ferreira et al., 2022)
10.		Boron waste	Electrical kiln at 950, 1000 and 1030°C, 2h soaking time and slow cooling inside the furnace	**8**	(Christogerou et al., 2021)
11.		Ornamental rock waste	(850, 950 and 1,050°C at a ramp rate of 2°C/min for 120 min	**15**	(Luiz et al., 2020)
12.		Copper slag and munciple solid waste	900, 950, 1000 and 1050°C	**28**	(Jordán et al., 2021)
13.		Waste glass extracted from a WTP	850 °C, 900 °C, 950 °C, 1000 °C, and 1050 °C	**30**	(de Faria Busch et al., 2022)
14.		Electro fused alumina waste.	At a ramp rate of 2°C/min, 750, 850, 950 and 1050°C,	**10**	(Nicolite et al., 2023)
15.		Sorghum bagasse (SB) and molasses (M)	at 103°C for ± 24 h or the weight constant	**M 20**	(Syahfitri et al., 2022)
16.		Ornamental stone wastes	fired at 1050°C	**15**	(Barbosa et al., 2022)
17.		Hazardous toner waste, galvanic glass waste	Heating for an hour at 10°C/min from 1100°C to 1275 °C	**7** TW **23** GW	(Mymrin et al., 2023)

Nomenclature of ceramic tiles

Ceramic tiles are modular materials for building (flooring and walling, outdoor and indoor) and interior design. They are manufactured in a wide array of formats and sizes, approximately:

- up to 2 square metres (tile),
- from 2 to 6 square metres (slab).

Ceramic tiles and slabs are in most cases composite materials with a thin layer of coating on the support (often called the *body*). The coating is usually constituted by *glaze* on the *engobe* (sometimes substituted by a single layer of *smaltobbio*). The glaze (vitro-crystalline) can be replaced by *frit* (glass). *Unglazed tiles* have almost exclusively a highly vitrified body.

Ceramic tiles are classified according to the standard ISO 13006:2018 "*Ceramic tiles — Definitions, classification, characteristics and marking*". This classification, based on water absorption (WA) and shaping technology, distinguishes five groups for pressed tiles:

BI_a	$WA \leq 0.5\%$	highly vitrified
BI_b	$0.5\% < WA \leq 3\%$	vitrified
BII_a	$3\% < WA \leq 6\%$	semi-vitrified
BII_b	$6\% < WA \leq 10\%$	semi-porous
BIII	$WA > 10\%$	porous

Extruded tiles have the prefix "A" instead of "B".

Informally, these groups are called by reference to the degree of porosity or vitrification of the ceramic body.

Wall tiles have typically a porous support (sometimes semi-porous). *Floor tiles* have usually a highly vitrified body (outdoor, indoor, heavy-duty and interior design applications) to vitrified support (outdoor and indoor) and semi vitrified support (indoor). Ceramic slabs have exclusively a highly vitrified body.

The support of tiles and slabs is produced with various ceramic materials, which allow different physical properties and product performance to be achieved. These bodies are generally classified according to colour and degree of vitrification. Nowadays, the main typologies are:

porcelain stoneware	highly vitrified	light-coloured
red stoneware	vitrified to semi-porous	dark-coloured
monoporosa	porous	dark-coloured or light-coloured
birapida	porous	dark-coloured (sometimes light-coloured)

Every type of ceramic body is designed with characteristic combinations of raw materials with a main technological role:

- *plasticity provider* (ball clay, kaolin, red clay, marly clay, etc.);
- *flux* (feldspars, feldspathoids, quartz-feldspathic materials, etc.);
- *filler* (quartzous materials);
- *pore-forming* (carbonates).

Ceramic tiles and slabs are manufactured with the technological cycle illustrated in Figure 1, which consists of six main stages: *body preparation* (including wet or dry milling and spray-drying or wet granulation); *shaping* (by pressing, extrusion or slab compaction); *fast drying* (by vertical, horizontal or microwave-assisted ovens); *glazing* (by wet and dry applications) and *decoration* (mostly by ink-jet printing); *fast firing* (roller kiln); *finishing line* (grinding, polishing, chamfer, etc). Industrial plants can include all stages (*full cycle*) or have a *partial cycle.* (from shaping to finishing or from glazing to firing).

Distinct semi-finished products are handled at every stage of the manufacturing cycle: *body slip* (aqueous suspension of wet-milled raw materials); *dry powders* (dry-milled raw materials); *granulates* (agglomerated and moist powders obtained by spray-drying or wet granulation); *green tile* (moist compact after shaping); *dry tile* (dry compact after drying and prior glazing); *glaze slip* (aqueous suspension of wet-milled raw materials); *ink* (oil-based pigment suspension, sometimes glycol-water instead of oil); *glazed tiles* (moist compacts after glazing and decoration); *fired tile* (sintered compact prior finishing).

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