THE CERAMIC TILE INDUSTRY IN THE CHALLENGE OF SUSTAINABILITY THROUGH RESOURCE EFFICIENCY

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ABSTRACT

The purpose of this contribution is to draw a critical picture of the situation of the ceramic tile industry, which must face the challenge of converting to a low carbon economy, from the point of view of the management of raw materials and the circular economy, discussing criticalities and providing scenarios for product innovation. The actions put in place to improve sustainability of ceramic tiles (pollution prevention, environmental labels, best available technologies, industrial technology roadmap, standard on sustainability) are briefly reviewed to highlight how resource efficiency is involved. The pitfalls along the path to a low-carbon economy are outlined through the life cycle studies in the literature, which both provide hotspot diagnosis and propose corrective actions. The role of resource efficiency in sustainability practices is critically discussed with regard to the supply chain, waste valorization, technological value of raw materials, critical raw materials and hazardous substances, and the circularity of the ceramic tile industry.

1. INTRODUCTION

The purpose of this contribution is to draw a critical picture of the situation of the ceramic tile industry, which must face the challenge of converting to a low carbon economy, from the point of view of the management of raw materials and the circular economy, discussing criticalities and providing scenarios for product innovation.

Sustainability was originally defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [1]. Since then, the concept has shifted in meaning and a current definition is the capacity to endure in a relatively ongoing way across various interconnected domains: environmental, economic, and social. It implies that the exploitation of resources, the direction of investments, the orientation of technological development, and institutional policies are all balanced to meet human needs [2].

In the last two decades, sustainability has been increasingly valued by the ceramic tile industry. The situation that, at the end of the last century, saw environmental issues did not affect the competitiveness of the ceramic tile sector [3] and ceramic districts being a peak of non-sustainability, due to huge consumption of non-renewable resources [4-5], has been changing profoundly. Since then, a wide range of actions have been put in place to improve sustainability, including pollution prevention and reduction as well as environmental labels and declarations [6-7]. The adoption of these practices has proven to provide benefits in terms of environmental impact [8-13] allowing, where there has been a systemic approach to sustainability, levels of excellence to be reached [14]. Nowadays, there is an awareness that environmental problems now affect the production of ceramic tiles [15] and attention to environmental impact is a fundamental key [14].

However, there are critical voices regarding an unbalanced assessment of the impact of ceramic tile production, implicit in political directives on the environment, which sees an excessive weight of the LCA, without adequately considering the social and economic sustainability of certain choices, and the advantages from the long lifespan of ceramic products. This is the position of the European ceramic industry, which clearly recalls "durability of products is a major driver of sustainability" [16]. This has paved the way for advanced life cycle assessment approaches, which seek to include a variety of aspects in the evaluation procedures [17-19].

This review will first look at the role of raw materials in the sustainability strategy for the ceramic sector, analyzing strengths and weaknesses in light of the intensification of directives on the environment. Critical points in the ceramic tile supply chain will be then discussed together with corrective measures to fulfil the low-carbon economy target. Finally, the actions aimed at improving resource efficiency in sustainability practices will be illustrated.

2. RAW MATERIALS IN THE SUSTAINABILITY STRATEGY

The ceramic tile industry has to conform to a global strategy for sustainability since the European Union has declared its commitment to the goal of sustainable development. The framework for both economic and environmental objectives is ecological modernization [20,21]. The policies for the protection of the environment have followed one another continuously over the last three decades, producing a complex picture (Fig. 1).

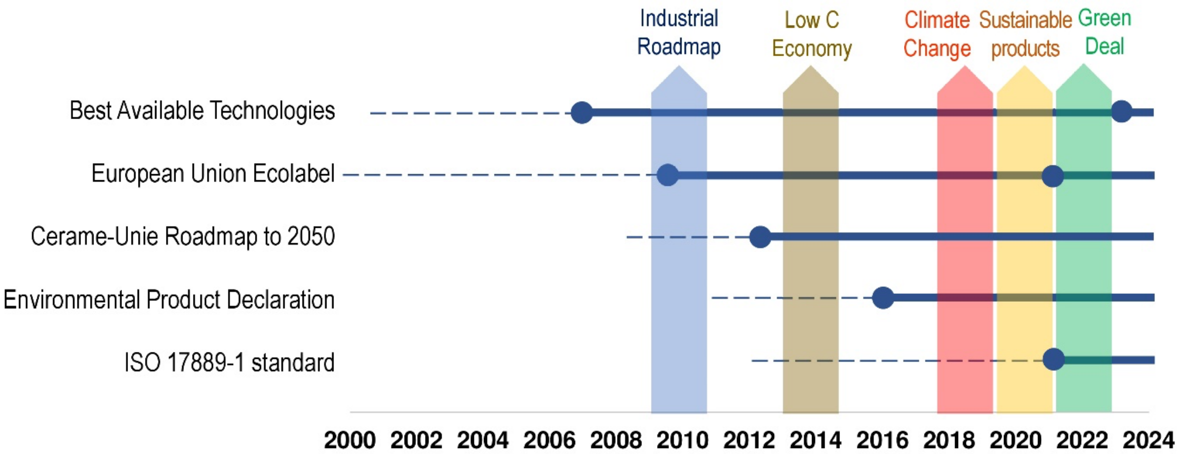

***Figure 1**. Timescale of strategic actions taken to improve the sustainability of ceramic tile production, with gestation time* (---) *before publication of the document* (●). *Vertical arrows indicate the main EU policies to protect the environment.*

For ceramic tiles, concrete actions were implemented, which resulted in a series of measures in cascade (Fig. 1). They are divided into two pillars: pollution prevention and reduction, and environmental labels and declarations. These actions are briefly reviewed to highlight the aspects that most concern raw materials.

2.1. POLLUTION PREVENTION AND REDUCTION ACTIONS

Best Available Technologies (BAT) are aimed at avoiding, or if not possible, reducing emissions in the air, water, soil, as well as the production of waste. They consist of technical plant engineering, management, and control solutions, which concern plant design, construction, maintenance, operation and closure [22-23]. Such solutions are illustrated in the BAT reference document (BRef) that was issued for the ceramic sector in 2007 [24]. The BAT do not directly involve the selection of raw materials, but the efficiency in their processing, especially in terms of environmental impact. The criteria in some way related to raw materials are listed in Table 1: they essentially concern emissions to air and water [25-26] as well as the generation and management of waste.

Since the requirement to adopt certain types of BAT must in any case guarantee their application in economically and technically suitable conditions, taking into account the costs and advantages, the BRef is going to be updated according to the innovations and technological progress achieved. The BATs for the ceramic sector are currently under review and this process is expected to come to a decision in 2023 [27]. At present, a list of criteria that are going to be monitored has been provided (Table 1).

There is a notable expansion of the list of hazardous components, both for gaseous compounds and for wastewater, when the criteria of BAT under review [27] are compared to the current criteria [24].

The main implication is about the growing concern for environmental impact that leads to an apparent conflict between reducing emissions and promoting waste recycling. In fact, post-consumer and pre-consumer waste is likely to be one of the main vehicles for introducing substances of concern into the ceramic body [28]. This issue will be discussed in section 4.5.

Criteria	**BRef 2007**	**BRef 2021** substances included in the review
Dust and odour	Particulate matter (from dusty operations, drying and firing)	Particulate matter *(through plant)* Odour
Gaseous compounds	Fluorine *from kiln* Chlorine *from kiln* Sulfur *from kiln* Nitrogen *from kiln and cogeneration*	Fluorine *(through plant)* Chlorine *(through plant)* Sulfur *(through plant)* Nitrogen *(through plant)*
		CO *(through plant)* Carbon dioxide *(through plant)*
	Heavy metals *(no list)*	As, B, Cd, Co, Cr, Cr (VI), Cu, Hg, Mn, Ni, Pb, Sb, Se, Sn, Te, Tl, V, Zn *(through plant)*
	VOC *(no list)*	Acetaldehyde, ammonia, benzene, formaldehyde, naphthalene, PAHs PCDD/Fs, phenols, styrene, TVOC *(through plant)*
Wastewater	AOX	AOX, COD, HOI, naphthalene, TOC, TSS
	Cd, Pb, Zn	Al, B, Ba, Cd, Cl, Co, Cr, Cu, F, Ni, Pb, SO4, Zn
Waste	Sludge *(recommended reuse 0.4-1.5% in the body)*	Sludge *(specific amount generated and sent to disposal and/or recovery)*
	Solid process losses *(recommended reuse in the body)* Broken ware *(recommended reduction)*	Used/broken ware/materials *(specific amount generated and sent to disposal and/or recovery)*
		Flue-gas cleaning waste (*(specific amount generated and sent to disposal and/or recovery)*

AOX: Halogenated Organic Compounds; COD: Chemical Oxygen Demand; HOI: Hydrocarbon Oil Index; PAHs: Polycyclic Aromatic Hydrocarbons; PCDD/Fs: Polychlorinated Dibenzo-p-Dioxins and Polychorinated Dibenzofurans; TOC: Total Organic Carbon; TSS: Total Suspended Solids; TVOC: Total Volatile Organic Compounds; VOC: Volatile Organic Compounds.

Table 1*. Criteria linked to raw materials of the Best Available Technologies for ceramic tiles.*

Industrial Technology Roadmaps, among EU policy initiatives, are designed to create greater synergies between research, innovation, and industry, for a more rapid diffusion of new industrial technologies. The mission is to provide a practical, independent, and objective analysis of the pathways to achieve a low-carbon economy in Europe, starting with energy-intensive industries. The Roadmap 2050 project is an initiative of the European Climate Foundation based on the goal of reducing greenhouse gas emissions by at least 80% compared to 1990 levels by 2050, and the next steps required by 2030 to stay on track towards complete decarbonization by 2050 [29].

A Roadmap to 2050 was proposed by Ceram-UNIE [30] with the aim of paving the way for a decarbonization of the ceramic industry. It illustrates current and future technologies that are expected to reach the 2050 target and a timeline of the effects of new technological solutions expected to reduce CO_2 emissions.

Although the role of raw materials may appear secondary to challenging purposes – such as the conversion to renewable energy sources and the improvement of heat treatments – resource efficiency is entailed in three enabling technologies (Fig. 2). Although already available today, at least on a pilot scale, these technologies require substantial development to allow for major improvement in energy and resource efficiency.

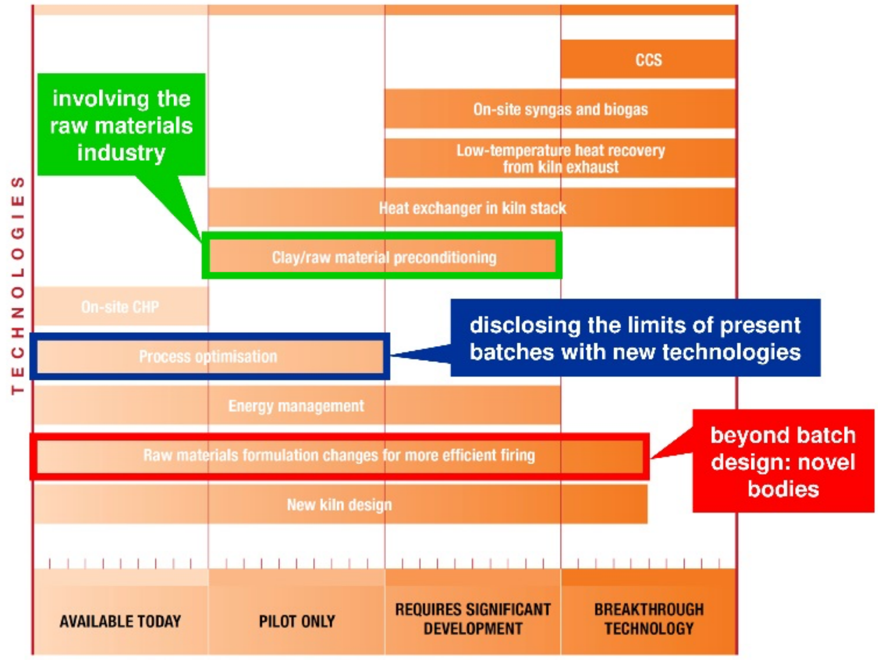

Figure 2. *Key-enabling technologies concerning raw materials claimed in the Roadmap for the ceramic industry to 2050 [30].*

<u>Process optimization</u>: although the ceramic process is now highly standardized [14,18], it is necessary to consider the advent of new technologies and the modification of the bodies in a circular economy key. It will therefore be necessary to establish what the limits of the current batches are and therefore how to adapt the use of raw materials to new granulation, forming and firing processes.

<u>Raw material preconditioning</u>: advantages can be gained from a more efficient processing of ceramic batches, which entails a better structuration of the supply chain to promote a deeper involvement of the mining industry in some fundamental stage of the ceramic process, e.g., particle size preconditioning.

<u>Raw material formulation changes for more efficient firing</u>: this challenge cannot be faced, in a context of substantial uniformity of body formulations, through incremental improvements. A disruptive innovation is also necessary, with a drastic rethinking of raw materials, which allows firing temperatures to be significantly lowered and thermal cycles to be made less energy intensive. This issue will be discussed in section 4.6.

2.2. ENVIRONMENTAL LABELS AND DECLARATIONS

Environmental labels and declarations are environmental management tools that aim to minimize the way in which production processes negatively affect the environment (i.e., cause adverse changes to air, water, or land) and comply with applicable laws, regulations, and other environmentally oriented requirements.

The ISO 14020 standard establishes the guiding principles for the development and use of environmental labels and declarations, distinguishing three types of environmental labels. Hereafter, the role of raw materials is discussed for types I and III.

Type I (ISO 14024): voluntary ecological labels based on a system that considers the entire life cycle of the product, which are awarded to products that meet a set of pre-determined requirements. Take for example the EU Ecolabel, which is a label of environmental excellence that is assigned to products and services that meet high environmental standards throughout their life cycle, focusing in particular on the extraction of raw materials, production, and waste management [6,31].

The Ecolabel for hard covering products was first set up in 2009 [31-32] and licensed to several ceramic tile manufacturers [33]. It contains criteria that involve raw materials: management of mineral extraction, selection of materials, production process, as well as generation and management of waste (Table 2). The Ecolabel criteria have recently been revised, so introducing significant changes that also affect raw materials [33]. While the requirements for extraction and waste management are essentially procedural and have remained substantially the same, the minimum recycling threshold for process waste has been changed: from 85% to 90% (since all licensed Ecolabels have higher values).

For the selection of raw materials, the absence of risk phrases (and asbestos) is no longer required, having been replaced by the ban on substances of very high concern (SVHC) with the derogation for TiO_2 and crystalline silica. The specific constraint on the content of Cd, Pb, and Sb in glazes was confirmed for lead and cadmium but extended to inks for digital decoration. These are only apparently formal changes, because the SVHC list includes many substances, and because inks containing cadmium-based pigments have now come into use in inkjet printing. This issue will be discussed in more detail in section 4.5.

Criteria	Ecolabel 2010 Decision 2009/607/EC	Ecolabel 2021 Donatello et al. 2021
Mineral extraction management	Extraction activity project and environmental recovery requirements: environmental impact assessment; valid authorization for the extraction activity; rehabilitation management plan; map of the quarry; declarations of conformity with environmental Regulation (alien species) and Directives (habitats; birds).	
Raw materials	Absence of risk phrases in raw materials No asbestos	Restricted substances in raw materials and additives: no SVHC (with derogation for titania and crystalline silica)
	Limitation of substances in glazes Pb 0.5% Cd 1.0 % Sb 0.25%	Glazes and inks: maximum amount Pb: 0.10% Cd: 0.10%
Production	Emissions to air: dust, HF, and SO_x (see Table 3)	Emissions of dust, HF, and SO_x (see Table 3)
	Emissions to water, limit_ - suspended solids: 40 mg/L - Cd: 0.015 mg/L - Pb: 0.15 mg/L - Cr (VI): 0.15 mg/L	Wastewater management, limit: - suspended solids: 40 mg/L - Cd: 0.015 mg/L - Pb: 0.15 mg/L
Waste	Waste management procedures for: a) separating and using recyclable materials from the waste stream; b) recycling materials for other uses; c) handling and disposing of hazardous waste.	
	Waste recovery (at least 85% of process waste must be reused)	Reuse of process waste (minimum 90%, maximum points for 100%)

***Table 2**. Criteria linked to raw materials for EU Ecolabel award for ceramic tiles.*

Another example of a voluntary certification is LEED (Leadership in Energy and Environmental Design), a program that covers the entire life cycle, from design to construction, of a building. LEED certification has essentially one requirement that can be exploited by ceramic tiles in the light of resource efficiency: the recycled content. It is calculated as the sum of the post-consumer recycled content plus half of the pre-consumer recycled content, based on cost [34].

Type III (ISO 14025): the Environmental Product Declaration (EPD) contains objective and quantifiable information on the environmental impact associated with the life cycle of a product. It is based on LCA data and enables comparison between products fulfilling the same function. In particular, the EPD for ceramic tiles, first issued in 2016, is assigned upon assessment of the environmental impact and the resources consumed (materials, water, or energy). It takes into consideration all phases ranging from the extraction of raw materials to those of transport, manufacture and disposal of waste and end-of-life products [35-37]. However, the role of RMs is not evidenced, as the LCA accounts for the extraction and transport of raw materials and the manufacture of the tiles all together. Nevertheless, some analyses indicate raw materials extraction and transport among the hotspots [35-36]. In any case, all reviews on EPD agree with the fact that tile manufacturing is the stage with the highest environmental impact [35-36,38-39]. Although it is concluded that the industry indisputably follows the guidelines of sustainability [38] some methodological questions seem to be still open [36,39].

2.3. SUSTAINABILITY ASSESSMENT OF CERAMIC TILE PRODUCTION

A standard on the sustainability of ceramic tiles (ISO 17889-1) was recently issued [40]. It outlines the requirements for sustainable tiles, including environmental, economic, and social criteria. Its main objectives are: a) promoting the development and use of sustainable ceramic tiles; b) guiding the stakeholders towards the environmental responsibility through the entire supply chain; c) increasing the value of sustainable tiles.

This standard encompasses several factors related with raw materials, which consist of a mandatory limit and a rating increasing from a minimum (mandatory limit) to a top score:

- *Indigenous raw materials*, if the distance mine to factory is below 800 km (by truck) or below 3200 km (by rail or water); no minimum threshold, top score for $\geq$90%.
- *Waste management*, with a distinction in post-consumer, pre-consumer, reclaimed waste (i.e., ceramic process residues) and wastewater; the minimum threshold is $\geq$3% and top score for $\geq$30% (related to the sum of raw materials + grinding water; pre-consumer and reclaimed waste is counted for half).
- *Emissions* to atmosphere, with limits only for dust and fluorine compounds, which are definitely high, when compared to the current ecological labels and the 2007 BAT for the ceramic sector (Table 3). As a matter of fact, the top score substantially corresponds to the emissions threshold fixed by law in Spain.

This standard appears to be set with the aim of a corporate defense of the ceramic tile sector rather than a stimulus to improve the environmental and social performance of individual producers. In fact, a non-virtuous message is conveyed, that all ceramic tile production is sustainable, some more and some less, once a series of formal requirements have been met. It is not required to meet at least the limits of the 2007 BRefs and the top score is attributed to much lower performances than those usually achieved with the current BAT.

Limit of release (mg/kg)	**Fluorine** (as HF)	**Chlorine** (as HCl)	**Sulphur** (as SO_2)	**Dust** kiln	Ware drier	Spray drier
Legal threshold: Italy (1) Legal threshold: Spain (1)	5 10	30 -	1500 600	15 90	30 90	150 150
BREF, 2007 (2) [24]	30	-	2500 (3) 10.000 (4)	20	-	150
EU Ecolabel, 2010 (1) [32]	10	-	1500 (3) 5000(4)	10	250	
EU Ecolabel, 2010 (1) *licensed data* [33]	*mean* *3.5*	-	*mean* 1150	-	*mean* *65*	
EU Ecolabel 2021 [33] mandatory maximum points awarded	20 6	-	1300 750	50 10	50 10	
ISO 17889-1, 2021 [40] mandatory maximum points awarded	100 10	-	-	--	- 500 - 250	- -

(1) converted from mg/m^2 using 20 kg/m^2 as specific weight of tiles.
(2) converted from mg/Sm^3 using 3 Sm^3/kg as specific flue gas consumption.
(3) for bodies with SO_3 < 0,25% by weight.
(4) for bodies with SO_3 > 0,25% by weight.

Table 3*. Limits of emissions to air of pollutants linked to raw materials.*

If we consider that the Directive on industrial emissions is currently under revision by the European Commission [41], and a discussion is ongoing on the hypothesis of lowering the limits (particularly for dust, halogens, and sulfur), there is a real risk that this standard will be outdated for European tile manufacturers already immediately after its issue.

3. THE LOW-CARBON ECONOMY TARGET

In a rapidly changing global situation under the pressure of climate change – with its environmental, economic, and social implications – the actions to strengthen the sustainability of ceramic production, described in the previous section, are not sufficient, although necessary. Further challenges are announced, and all are in some way linked to the transition to a low-carbon economy. The ceramic tile industry is facing such radical changes that they seem like real technological revolutions:

Energy supply: it has already been highlighted that the achievement of the CO_2 emission targets for 2050 by the ceramic sector is linked to the availability of renewable energy sources and green hydrogen [42]; this involves a drastic revision of energy production and of the distribution grid [43].

Circular economy: it is a concept, now found in the political strategies of many countries and of the European Union, which implies keeping the materials value throughout the life cycle of the products. Therefore, it requires a systemic approach, with a profound rethinking of the way in which products and services are designed precisely to promote many circular actions that go well beyond mere recycling [44].

Building design and rehabilitation: it is a process that has just begun with the current *Renovation Wave* and is not limited to the objectives related to the Near Zero Energy Buildings [45]. It will entail not only the ongoing revision of the requirements of building materials (e.g., directive on energy performance) but also a different rationale in the design approach (e.g., buildings that will have to be dismantled and no longer demolished) with great emphasis on social paradigms and sustainability.

3.1. LCA DIAGNOSIS OF HOTSPOTS IN CERAMIC TILE PRODUCTION

A pressing question exists on how sustainable the ceramic tile production is, in light of the above-mentioned challenges. Several studies have been carried out to answer this question, in particular through various life cycle assessment approaches (LCA, LCSA, LCC) and different extension of the investigation (cradle-to-gate, gate-to-gate, cradle-to-grave). The outcome is a varied account of environmental, social, and economic issues in evaluating the technological development and management of the ceramic tile industry [5, 18, 35-36, 46-59]. This depends on some differences in terms of type of ceramic products, year of investigation, geographical area, and methodological procedure. Overall, the results draw a picture where the life cycle studies converge to the diagnosis of the main sources of environmental impact (Table 4).

LCA study >	57	56	18	55	54	53	35	52	51	50	49	48	47	46	5
CRADLE															
mining activities													■		
raw materials transport	■		■	■	■		■	■	■			■	■		
additives production				■					■			■			
GATE															
body preparation	■	■				■				■				■	■
pressing	■							■							
drying		■					■	■		■					
glazing and decoration				■		■									■
firing	■	■		■	■		■	■	■	■	■	■			■
finishing and packaging						■									
GATE															
product distribution			■	■		■				■					
tiling installation						■									
end-of-life															
GRAVE															

Table 4. *Ceramic tile life cycle from cradle to grave: stages having the main environmental impact (hotspot in gray color) according to LCA studies.*

Interestingly, all the main stages are indicated by at least one LCA study as a hotspot for environmental impact. Nevertheless, most gate-to-gate assessment investigations agree with the major role played by energy consumption, in particular during body preparation and firing. In the case of a cradle-to-grave assessment, the impact of logistics becomes the main hotspot, entailing both the transport of raw materials to the tile manufacturing site and product distribution.

3.2. LIFE CYCLE ASSESSMENT: PROPOSALS OF CORRECTIVE ACTIONS

The LCA studies mentioned in the previous section also recommended various solutions in order to strengthen the sustainability of ceramic tile production. Two mainstreams are indicated about raw materials: actions leading to an improved resource efficiency (going beyond the supply chain management) and towards the conversion to a circular economy (going beyond waste valorization and recycling). These suggestions converge in the following issues:

a) Reducing the amount of raw materials consumed in the bodies (e.g., thinner tiles) and glazes [36,46,51,55,56,57];

b) Increasing the efficiency of thermal processes, improving the technology of kiln and drier, adopting heat recovery and fast firing cycles, and lowering the maximum temperatures [5,36,46,48,56,58];

c) Improving logistics of raw materials and finished products, e.g., reducing the distance from mine to plant [18,35,48,54,55];

d) Reducing the amount of process waste, and recycling waste from both tile production and external sources [36,51,55,59];

e) Implementing the Best Available Techniques [35,48,50,59];

f) Developing new batch formulations for glazes and bodies, maximizing the recourse to raw materials with a lower environmental impact and CO_2 footprint [36,58];

g) Reducing the water footprint by switching body preparation to the dry route [56,58];

h) Avoiding hazardous substances and controlling upstream the production of chemicals [5,48,55];

i) Turning to renewable energy sources [36].

Some actions correspond to the technologies claimed by the ceramic tile industry in the Roadmap to 2050 [30]: process optimization (points a and e); formulation changes for more efficient firing (f); new kiln design and heat recovery (b); energy management and on-site syngas and biogas (i). The other recommendations from researchers (c, d, g, h) seem not to be strategic from the industrialist's point of view to meet the CO_2 emissions target. Overall, the above-mentioned LCA studies appear to be asymmetric: while the analysis of hotspots was broad and detailed, the various remediations proposed do not seem to be supported by an adequate database.

4. RESOURCE EFFICIENCY IN SUSTAINABILITY PRACTICES

This section intends to delve more deeply into the obstacles and bottlenecks in the implementation of the corrective actions that have been proposed in the previous section, focusing on six main playgrounds: foundations of the circular economy; supply chain; waste management and valorization; strategic value of some resources; potential impact of critical raw materials and hazardous substances; the challenges of product innovation.

4.1. CIRCULARITY OF THE CERAMIC TILE INDUSTRY

Since the linear flow model of the modern economic system (extract-produce-use-dump material and energy) is becoming unsustainable, the alternative flow model of Circular Economy, based on a cyclical approach, is gaining popularity. In fact, the policies aimed at the Green Deal have recently made the Circular Economy one of the main drivers of sustainability. The circularity of industrial production no longer seems an option, but rather a mandatory step. It is of great appeal to policy-makers, scholars and practitioners because it is viewed as a tool to allow an operationalization for businesses that goes beyond the concept of sustainable development, which has been often considered too vague. However, the Circular Economy concept entails a wide set of strategies, all aimed at keeping the value of materials, which are not limited to an industrial symbiosis for waste management. In addition, it requires a paradigm shift in product design, which must include end-of-life material management aspects [44,61,62].

Ceramic tile production has an essentially linear supply chain, in which there is little chance of setting up the various strategies envisaged by the circular economy (Fig. 3). As a matter of fact, ceramic tiles at the end-of-life cannot be recovered for incineration or remanufactured; although they might in principle be repaired, restored, or reused, these are not meaningful solutions at the large scale.

Circular economy ↑ increasing circularity (rule of thumb) ↓ Linear economy	Strategies	Purpose	declined for ceramic tiles
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product	*totally unwanted*
	R1 Rethink	Make product use more intensive (e.g., by sharing product)	*not applicable*
	R2 Reduce	Increase efficiency in product manufacture and use by consuming fewer natural resources and materials	**pursued to a limited extent**
	R3 Reuse	Reuse by another consumer of discarded product which is still in good conditions and fulfil its original function	*feasible but not a meaningful solution*
Extend lifespan of product and its parts	R4 Repair	Repair and maintenance of defective product, so it can be used in its original function	*feasible but not a meaningful solution*
	R5 Refurbish	Restore an old product and bring it up to date	*feasible but not a meaningful solution*
	R6 Remanufacture	Use parts of discarded product in a new one with the same function	*feasible as recycling in mortar, concrete, etc.*
	R7 Repurpose	Use discarded product or its parts for a new product with a different function	*not applicable*
Useful application of materials	R8 Recycle	Process materials to obtain the same or lower quality	**extensively pursued**
	R9 Recover	Incineration of material with energy recovery	*not applicable*

Figure 3. *Strategies to be followed towards a Circular Economy (R10 framework) set out for the ceramic tile sector [modified after 62].*

From this standpoint, only two strategies seem feasible for the ceramic industry: recycling of waste (systematically implementable) and reducing the consumption of raw materials (achievable through some actions, such as reducing the thickness of the tile). In any case, thin tiles are only suitable for certain applications, and the thickness of the tiles is usually designed to achieve the minimum unit weight conforming to standard requirements. Therefore, limited gains can be expected from this action. The efforts therefore seem to converge mainly in waste recycling. However, recycling of ceramic tiles – to close the cannibalistic loop – is not viable because tiles are part, together with the other building materials, of societal stocks that at the end-of-life turn into demolition waste. In addition, the lifespan is very long, as the duration of a ceramic covering is generally from 20 to over 50 years. After such a long time interval, the end-of-life products that are going to be recycled are completely different from those manufactured today (which may imply additional difficulties, e.g., high PbO levels in the glaze).

This circumstance undoubtedly represents a critical issue that prevents the life cycle of the ceramic tile from being circular, as, for example, occurs in large part with bottle glass (Fig. 4). Although the ceramic tile industry can extensively recycle its process residues, this result is not considered a breakthrough from the Circular Economy viewpoint. This because the reclaimed waste has a lower strategic "weight" than post-consumer waste.

Figure 4*. Circularity of the life cycle of ceramic tiles versus bottle glass.*

However, an important, often underestimated, aspect is the cyclical nature implicit in the circular economy, which implies that products undergo repeated life cycles. Ceramic coverings guarantee a great advantage as their outstanding durability leads to a much lower number of cycles than other materials.

A path that could substantially enhance the circularity of tilemaking sees the ceramic industry take on the responsibility of using the tiles at the end of their life. There are several solutions that have already been more or less extensively tested, which suggest the feasibility of ceramic waste recycling especially in concrete [63,64], mortar [65], asphalt [66], Portland cement [67], and road pavement substrate [68]. This hypothesis could enable ceramic manufacturers to diversify through the development of geopolymer binders or alkali-bonded ceramic composites [69,70].

4.2. LOGISTICS OF THE CERAMIC SUPPLY CHAIN

The logistics of raw materials is an aspect at the center of attention in the evaluation of environmental and economic sustainability, and it stood out in most LCA studies on ceramic tile manufacturing [18,51,54]. However, in many cases the impact of transport was considered in a simplistic way, while the supply chain of the ceramic districts is complex and is continuously being optimized from an economic point of view [71]. This should imply that environmental and social side effects are also somewhat minimized. Anyway, it must be underlined that the weight of logistics on the environmental impact is not limited to the delivery of raw materials, but also concerns the mobilization of finished products and waste [50,53-55].

Costs, energy consumption and local traffic overload are diversified for transport by truck, water, or rail, which obviously have a different social and environmental impact. This issue is managed in the LCA but according to different databases, while the ISO 17889-1 standard, for example, estimates an impact of road transport four times higher than that by rail or sea [40]. An accurate and detailed analysis on the impact of different logistic networks, however, is lacking for the ceramic supply chain.

Considerations on the provenance of resources used in the tile production are frequently limited to a shortcutting contrast: "local" versus "long distance" raw materials. Unfortunately, the concept of "local" or "indigenous" raw materials is fuzzy and arbitrary: for instance, LEED rewards transport distances below 160 km, while the ISO 17889-1 standard classifies as "indigenous" all raw materials with a distance from the mining site to the ceramic factory below 800 km. Unfortunately, since the mileage of transport by sea or rail is counted a quarter, this leads to the contradictory classification of "local" raw materials even those embarked in a port more than 3000 km away from the ceramic factory. In addition, local and long-distance raw materials are not the same, from the technological viewpoint, as it will be discussed in the section 4.5. There is therefore a tangible risk of roughly contrasting "indigenous" and "long-distance" resources, which can lead to an underestimation, among other things, of the impact on local traffic or the benefits of well-structured and organized hubs.

4.3. WASTE VALORIZATION

Waste management and valorization is a focal point on which many circularity strategies converge, and which has generated a remarkable set of expectations of success. This has inspired a considerable number of technological studies [72-76]. Nevertheless, most of these studies are focused on the particular (recycling issues of a certain waste) rather than on an overall view of the problem (industrial symbiosis and transition from a linear to a circular supply chain, at least partially).

At present, the question whether secondary raw materials can replace natural resources to a significant extent or not is still unanswered. Recently, the waste recycling procedures in tilemaking have been critically reviewed from the technological and environmental points of view [72,77]. Several hindrances to waste recycling, of varying severity, have emerged along the manufacturing chain, which effectively limit the Technology Readiness Level (TRL) to the point that currently few residues are actually utilized in the production of tiles (Fig. 5). Some obstacles are critical, in the sense that viable solutions for the ceramic industry have not yet been found, for a variety of reasons. In fact, the effective sustainability of waste recycling, including economic and social aspects, is known for the few documented success stories [72,74,77]. Indirectly, it can be inferred in cases of unsuccessful recycling, at least where apparently no obstacles existed of a technological and/or environmental nature. At all events, waste recycling is not always advantageous in terms of environmental impact, as it has been demonstrated from a life cycle perspective in some cases [78].

A critical element emerges from the technological characterization of a vast variety of waste in the literature [72,77]. They are overwhelmingly candidates to act as fillers or fluxes in the production of ceramic tiles, while there are very few waste materials that provide plasticity and therefore could replace clays. This implies, in a global view, that there are not enough residues to replace clayey materials, which constitute more than half of the ingredients of ceramic tile batches.

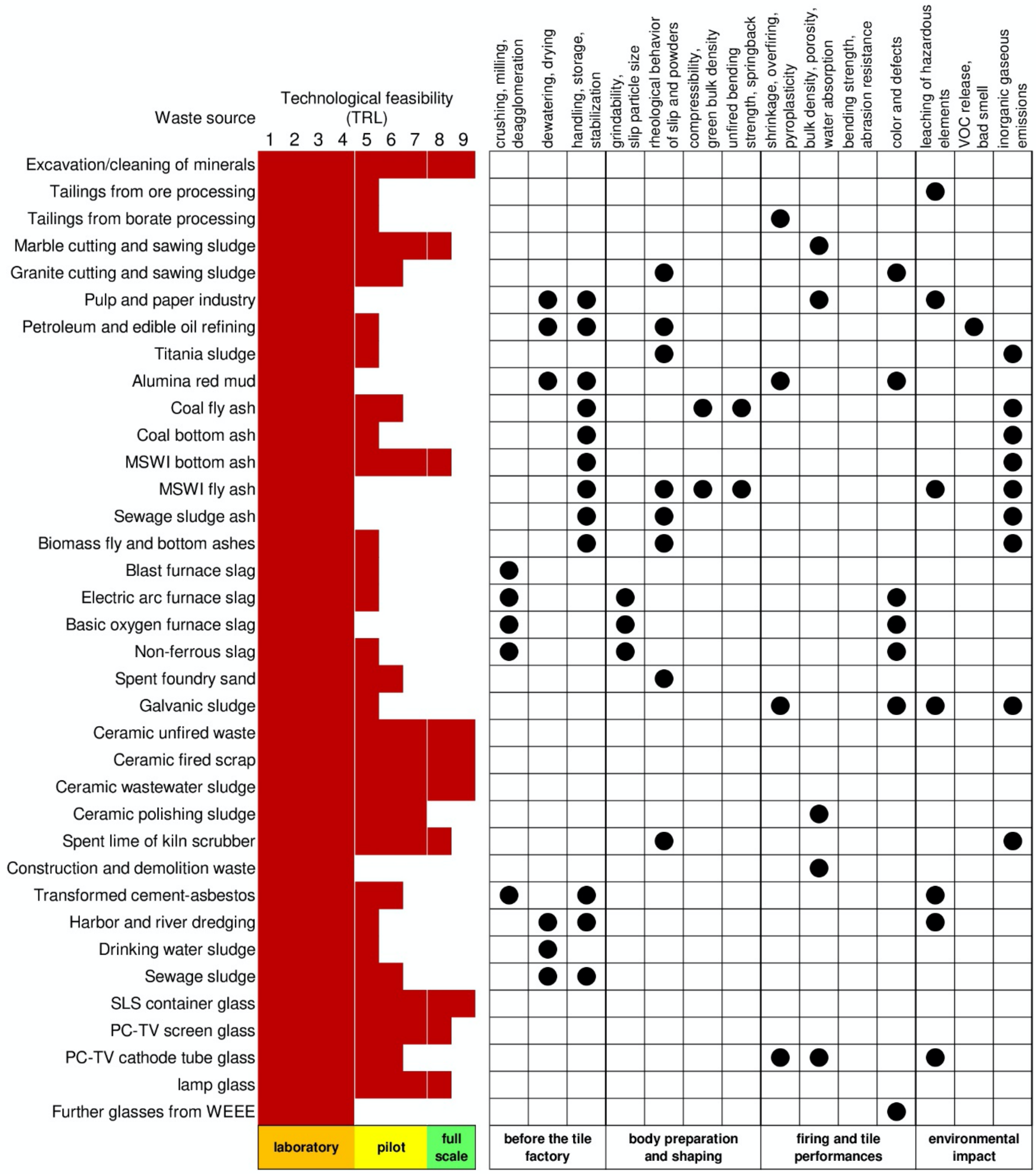

Figure 5*. Technological development of recycling for different types of waste (left) with critical obstacles met in ceramic tile production (right) [modified after 77].*

There is the need to go from the particular to the general: the recycling of waste is not necessarily more sustainable, if we consider the entire supply chain, nor actually feasible when the availability of waste must match the demand for raw materials. It is advisable to move from looking for "direct" solutions to "advanced" solutions; for example, from replacing a batch ingredient with waste, to developing new types of raw materials and products more prone to contain waste [79]. It is difficult to believe, however, that such green products could compete on the same level as tiles manufactured with mineral commodities, so a preferential path should be established (in the wake of Green Public Procurement and the Minimum Environmental Criteria for building materials).

A crucial aspect, so far eluded by the discussion on the actual feasibility of a circular economy based on waste recycling to replace natural raw materials, is a balance at the scale of the supply chain. Assuming that batches containing a high content of waste and suitable production technologies are developed, as has already been demonstrated [72-77 and literature therein], the question is whether there is actually the possibility of having suitable residues, in sufficient quantity and quality, to support the demand for raw materials of a ceramic district. A preliminary answer came from a study conducted on the Italian ceramic district and on the waste management of the Emilia-Romagna region (Fig. 6). It revealed that:

- only a modest fraction of the amount of municipal and industrial waste is compatible, from a compositional and technological point of view, with ceramic tile production;
- most of the compatible special waste is actually produced during ceramic production and almost entirely disposed of in the same production cycle;
- compatible residues not related to ceramic production, such as those deriving from the separate collection of municipal waste, are already recycled (cullet glass) or under development (MSWI bottom ash);
- cases of industrial symbiosis (use in tilemaking of waste from other manufacturing sectors) are very few and at present limited to mining residues and scraps from other ceramic productions (sanitaryware);
- the overall quantity of waste from both urban and industrial sources produced at the regional level is lower – by at least one order of magnitude – than the raw material needs of the ceramic tile district;
- to ensure the delivery of the necessary quantity of waste, an adequate supply chain must be set up, including long-distance routes.

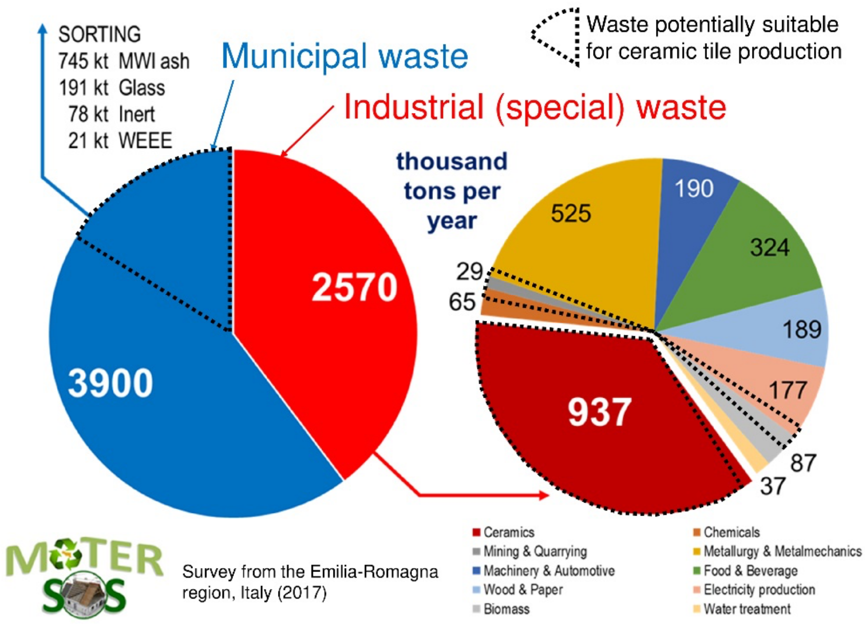

***Figure 6**. Survey of municipal and industrial waste produced in the region of the Italian tile district: amount of waste potentially recyclable in the ceramic production.*

4.4. STRATEGIC VALUE OF RAW MATERIALS

Ceramic raw materials, even pertaining to the same commercial category, have different technological behaviors. Such differences can in some cases be so important as to make the raw material strategic, in the sense that it is difficult to replace, unless ceramic tile quality be downgraded, and product features and performance be deeply revised [71,80,81]. This occurs especially with leading products, more difficult to manufacture due to technical (e.g., large size) and/or aesthetic (e.g., *superwhite* bodies) issues. In other words, these are essential raw materials, without which it is not possible today to ensure the standards of technical performance and above all of economy (productivity, percentage of premium quality).

Therefore, resource efficiency must include some concepts that are not contemplated by the circular economy and by studies on the replacement of natural raw materials with residues. This is a crucial aspect, which can escape an analysis of sustainability made without considering key technological points.

Strategic raw materials often play a double technological role [71]:

- they provide the body with excellent properties (e.g., plasticity, fusibility, rheological behavior of slip) that are not easily achievable with the use of additives;
- act as enablers, that is, they allow the use of other raw materials, of worse technological behavior, as they are characterized by technological properties in themselves inadequate to ensure the usual quality standards, but which are compensated by the superior performance of technological enablers.

It can be estimated that at least one third of the fluxes utilized in Italy and of the white-firing clay materials consumed in Spain are widely used thanks to the technological enablers. They are almost entirely indigenous raw materials. There is therefore a correlation between technological enablers (largely imported) and local raw materials that totally escapes the analysis of sustainability of logistics based solely on the distances between mine and plant and on the means of transport.

Furthermore, a dynamic view of the resource market is needed, as some indigenous raw materials will presumably be subject to a competition that was unexpected until recently. The pressure on the cement industry to reduce its carbon footprint is pushing towards replacing the marl used to make clinker with calcined clay. The most promising candidates appear to be local resources (e.g., kaolinite-rich clays) which would have the chance of being used in sustainable bodies for vitrified tiles.

The simultaneous goal of maximizing resource efficiency and reducing the impact from the transportation of raw materials appears unrealistic. Therefore, the challenge must be better focused: to what extent should we favor resource efficiency at the price of downgrading of ceramic products? This question is intertwined with the discussion made in sections 4.2 and 4.3. The compromise between the efficiency of the supply chain and maintaining the same technical-aesthetic quality of the product seems more viable. This issue has already been raised in the attempt to identify the equilibrium point between circular economy practices and sustainability goals [17]. However, much remains to be done to integrate all the factors at play into a predictive model of sustainability in the medium to long term.

4.5. CRITICAL RAW MATERIALS AND HAZARDOUS SUBSTANCES

The sustainability of ceramic tile production in the long run must also face possible changes in the raw materials availability and cost in the future. This matter encompasses two different challenges:

- to substitute, as far as it feasible, critical raw materials (CRM) and substances of very high concern (SVHC);
- to ensure a sustainable supply of industrials minerals used in tilemaking (particularly strategic raw materials).

Attention must be paid to the concept of CRM, which refers to the identification of the likelihood of a supply disruption of a material and the vulnerability of a system [82]. It is therefore a situation that can change rapidly (indeed the list of CRMs is updated every two years). Thus, CRM is a classification that depends basically on marketing and logistic issues. Hence, it concerns a short-term availability that should not be confused with medium- to long-term availability, which is the requirement sought by ceramic tile manufacturers.

Apparently, the ceramic tile industry is not directly involved in the dispute for CRM [83] and prescriptions about SVHC [84]. In reality, this seems more a delay in becoming aware of the problem than an effective robustness in the ceramic supply chain as a whole. Although the industrial minerals used in bodies do not contain CRM or SVHC, some further components do (ingredients of glazes, inks, waste). An emblematic case is that of decoration: before the advent of inkjet printing, the use of Cobalt and Praseodymium (i.e., two CRM for which rapid growth in the global demand and perhaps future shortage are expected) was limited to yellow, blue or black colored glazes (or bodies of unglazed tiles). Although inkjet technology has made it possible to approximately halve the pigment consumption per unit of product, it works mostly in quadrichromy [85]. This technique consumes yellow ink (containing Pr) as well as cyan and black inks (containing Co) in any graphics that are printed. A detailed survey of CRM flows is therefore needed, and that a contingency plan is necessary, directing research and development efforts towards alternative pigments with low or no Co and Pr content. How much the ceramic supply chain is really exposed to a shortage of CRM has not yet been assessed in detail, lacking an accurate picture of the consumption of CRM and SVHC in the production of ceramic tiles and their various components (glazes, inks, etc.).

The rationale that ceramic tiles are produced from natural resources, which contain hazardous substances in minimal quantities, no longer holds up with modern production. The concern on which and how many SVHC are introduced into the ceramic production cycle or are released, mainly during heat treatments, is growing. The ongoing revision of BAT [27] is moving on this point by extending the range of chemicals under attention (Table 1).

An important aspect, albeit often neglected, is that a waste may introduce some hazardous elements into the body, albeit in small quantities. This brings about more controls on the mobility of hazardous elements: not only release to air (during processing) but also leaching from ceramic products. Fortunately, it is known that ceramics can be an excellent matrix for stabilizing hazardous materials [28] with immobilization efficiency that generally exceeds 99.5% (Cd, Cu, Pb) and in many cases approaches 100% (Ba, Ni, Zn). However, there are risk margins for some hazardous elements, especially those subject to oxidation phenomena (As, Cr, Mo, Sb).

With rare exceptions, the actual size of deposits of ceramic raw materials is not known, as reliable data on reserves are usually not accessible (so estimates of the medium- to long-term availability become uncertain). Apart from those who are inclined to predict the short-term depletion of some resources, there are more optimistic views. On the one hand, we have not run out of any mining commodities yet, and it should be known that any predictions about resource depletion by a certain date have been wrong. On the other hand, there is no doubt that if resources are consumed at an excessive rate, they will eventually be exhausted [86]. Attention must be paid to the terms *reserve* and *resource*, which are poorly understood by many and widely misused. "*A reserve is a known quantity of a resource (established by drilling and sampling). Resource is a broader and more general term than reserve and includes identified material that may be less well characterized, possibly of lower grade and less certain to be economically recoverable"* [86]. It is essential to understand that neither reserves nor resources are the same as "all there is".

Some alarmist forecasts have circulated about the exhaustion of reserves of strategic raw materials, in particular highly plastic ball clays and sodium feldspar. They derive from the mere calculation of reserves (declared at a certain date) divided by annual production, which returns a projection of future activity in the order of 10-15 years (at the present pace) for some mining districts of great importance for the ceramic industry. This prediction is certainly wrong, because "*Resources can be converted to reserves by additional drilling or changes in economic factors, such as price or technology*" [86]. Nonetheless, such data configure a situation whereby, in the absence of important outcomes that come from exploration or changes in technology, production rates could slow down, competition increase dramatically, and prices likely rise.

Another relevant piece of information to consider is the timing of mining activities, which requires long-term planning. In fact, the times for scaling up mining operations are of the order of several years and vary slightly from country to country. For various reasons, demand peaks can hardly be managed by the mining industry, especially in the event of sudden interruptions of branches of the supply chain. Also, in light of these considerations, it is necessary to invest in research and exploration to understand what alternatives exist for the sources of strategic raw materials and therefore what choices to make in advance to prevent serious supply problems.

4.6. PRODUCT INNOVATION

Ceramic tiles currently manufactured with BAT are already close to technically achievable energy efficiency and the margins for improvement through incremental process innovation are limited [87,88]. Even on the resource efficiency side, incremental improvements in logistics and waste management are possible, but it does not seem that they can represent a breakthrough. This is due to the obstacles that stand in the way of widespread use of waste materials (section 4.3) and a significant shortening of the supply chain (sections 4.2 and 4.4). To achieve a radical improvement in resource efficiency, it is therefore likely that a disruptive product innovation must be triggered, obviously accompanied by appropriate process innovations. Thus, it becomes crucial to develop new batches in order to obtain the advantages of energy efficiency, rationalization in the supply of raw materials, and the use of secondary raw materials, with the aim of environmental, social, and economic sustainability.

Ceramic tiles have an overall competitive performance in service compared to that of other materials for hard coverings. Therefore, it is desirable to maintain such competitive advantages, so guaranteeing the current technical and aesthetic characteristics. Many standard requirements refer to the operating surface of tiles and hence ensured in most cases by the glaze (which must be adapted to the characteristics of the new bodies). In order to design new formulations, the way vitrified tiles are obtained by fast firing cycles must be taken into account. Here, porous tiles are not discussed since they already have a less marked energy footprint and a much shorter supply chain than vitrified tiles (porcelain stoneware), as they are produced at lower temperatures with extensive use of indigenous raw materials.

Porcelain stoneware is densified by viscous flow that requires the formation of an abundant liquid phase with adequate viscosity at high temperatures. Its chemical composition resides almost entirely in the SiO_2-Al_2O_3-Na_2O-K_2O system, which ensures a sort of "self-control" mechanism that tends to spontaneously slow down sudden changes in viscosity and therefore opposes permanent deformations during firing [88]. The idea of developing batches containing more local raw materials and more waste, however, implies a reverse design and a shift to other systems with consistent compositional changes (e.g., increase in Fe, Ca, and Mg contents) that also affect the sintering mechanisms. A basic condition is that candidate systems must be sintered effectively at the firing temperature of porcelain stoneware and possibly also have some kind of self-control on densification. By comparing the silica-alumina-alkali ternary systems with the equivalent systems with alkali-earths, it can be observed that the fields of melt formation are similar, although much more extended for Ca than for Na, K and Mg (Fig. 7A). Nonetheless, the fundamental difference between alkaline and alkaline-earth systems is about the liquidus temperatures, which for Ca and Mg are at least 200°C higher than Na or K (Fig. 7B). This constitutes a formidable obstacle to substitute the alkaline aluminosilicate systems, together with the fact that the viscosities of alkaline-earth aluminosilicate systems are lower and presumably inadequate to prevent deformations during firing, if no way to reduce temperatures is found.

A simple transition directly to other systems, maintaining the same performance as porcelain stoneware, is not technologically feasible, as evidenced by experiences in the past with red stoneware batches, more or less rich in Fe, Ca, and Mg. It is therefore necessary to find new targets, for example looking at other parts of the SiO_2-Al_2O_3-Na_2O-K_2O-MgO-CaO systems and/or trying to compensate for the increase in firing temperatures due to the presence of alkali-earths by replacing Al_2O_3 with Fe_2O_3 (Fig. 7C). However, various unresolved issues arise:

- poor densification efficiency observed with the strongly peralkaline melts occurring in low temperature eutectics with low Al content [90];
- lack of knowledge on the existence in alkaline-earth systems of buffers able to effectively control the melt viscosity to prevent excessive firing deformations;
- insufficient knowledge of possible abrupt variations in the melt viscosity (expected in case of changes in the Fe^{3+}/Fe^{2+} ratio).

The most promising route seems to be a cross between alkaline aluminosilicate and iron-high alkaline-earth systems. Unfortunately, the behavior of these complex systems is practically unknown, since there are not even phase diagrams, while instead it is urgent to know if it is actually a technologically meaningful solution.

So, on these issues we are far behind, due to the lack of sufficient basic knowledge to steer R&D in one direction or another. In fact, this is the classic example of research that no one finances, neither from the industrial side nor from publicly funded programs. As in ancient maps, in these little-known areas *Hic sunt leones*.

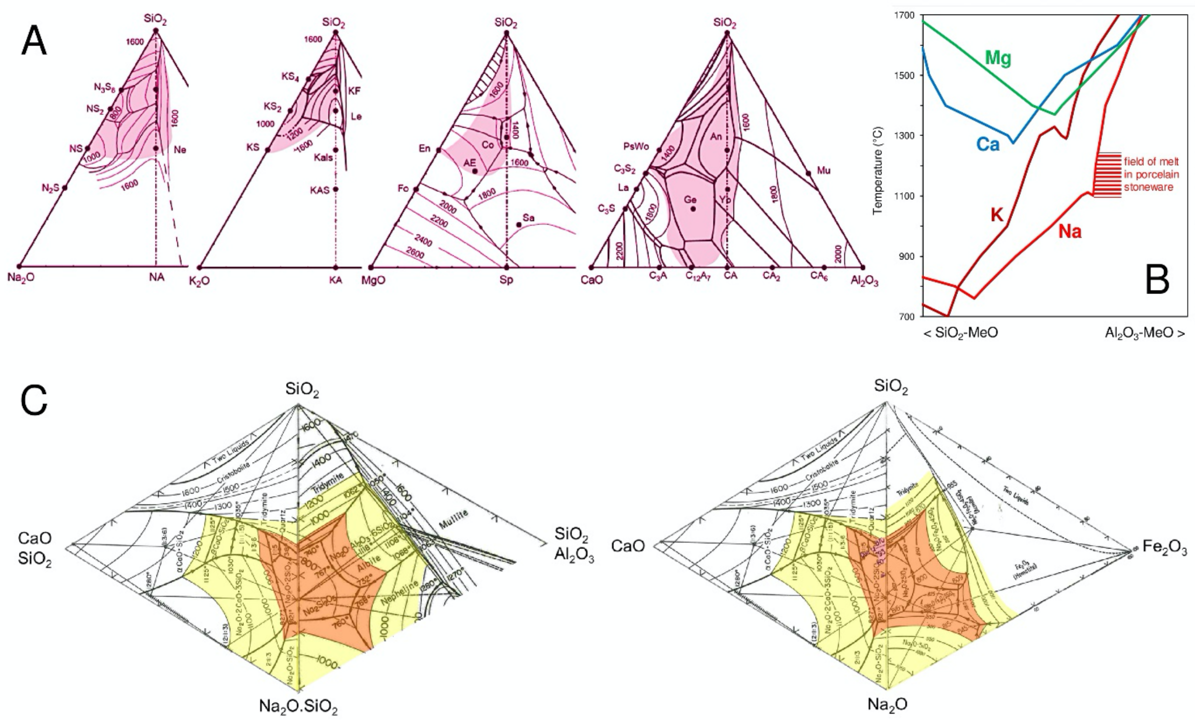

Figure 7. *A) Ternary diagrams SiO_2-Al_2O_3-Na_2O, K_2O, MgO, CaO (from left to right) with fields of melt formation (in color) in usual cooling conditions [modified after 89]. B) In the same systems: liquidus temperatures along the section with silica content of feldspar or cordierite (and typical field of melt composition in porcelain stoneware). C) Fields of compositions with liquidus temperatures below 1200°C (yellow) and below 900°C (orange) in the quaternary diagrams SiO_2-Al_2O_3-Na_2O-CaO (left) and SiO_2-Fe_2O_3-Na_2O-CaO (right).*

5. CONCLUSIONS

The European ceramic tile industry has devoted considerable efforts towards ecological sustainability, especially in Italy, actively taking part in European Union directives and programs. This has led to strict control of atmospheric emissions and the adoption of environmental labels and declarations by many tile manufacturers. Although these measures have been undertaken by major industrial groups, greater efforts must be made to ensure that the entire ceramic tile sector, including the supply chain, conforms to environmental standards.

In the rest of the world, unfortunately, there is no similar commitment by ceramic tile manufacturers to improve sustainability. Although we are witnessing a process of environmental upgrading of products and processes at a global level, parallel to the one driven by the European Union, the constraints are still much less severe than those in Europe, as the recent release of the ISO 17889-1 standard on the sustainability of ceramic tiles emblematically demonstrates.

Under the pressure of climate change, voluntary policies of incremental improvement of the best available technologies, and the adoption of appropriate environmental practices, however necessary, are no longer sufficient. The ceramic sector is therefore called upon to face challenging passages, which will probably require disruptive process and product innovations. A bit like what happened following the energy crisis of the last century, which led to the fast-firing technological revolution and a complete restructuring of ceramic tile factories.

The life cycle studies have highlighted the environmental hotspots on which to intervene through targeted actions, which largely correspond to the provisions of the European ceramic industry in the 'Roadmap to 2050'. Actions that configure an intervention polygon with three main axes: energy efficiency of ceramic plants, rationalization of the supply chain, and transition towards a circular economy. The effectiveness of these countermeasures has yet to be quantified in industrial practice. Uncertainties stem from both inherent technological difficulties and the necessary availability on a large scale in the increasingly short times dictated by policymakers. It is no coincidence that complementary approaches to life cycle assessment are being evaluated, which at the same time also give weight to economic and social aspects.

The ceramic supply chain is currently linear. The flattering results of reuse of processing residues obtained by tile producers do not have a great impact in terms of circular economy. Nevertheless, a curvature up to having a circular supply chain is unrealistic, as there is a huge problem represented by demolition waste, in which the tiles converge at the end of their life. A substantial advance in this direction is possible if the ceramic industry will rethink the tiling systems (new buildings that will be dismantled and no longer demolished) and will take charge of the demolition waste, perhaps envisaging new productions of sustainable materials addressed to green public procurement.

The supply chain of ceramic tiles is much longer and more complex than that considered in most sustainability studies. The trivial dichotomy between local and long-distance raw materials is in some ways misleading because it ignores essential technological aspects (e.g., strategic value of raw materials) as well as the availability of indigenous raw materials in a dynamic scenario and the flows of materials involved. Of course, this does not at all exclude that the path of rationalizing raw material supplies is possible, but it will certainly require a great deal of commitment from the entire supply chain.

Waste valorization seems to be the only circular economy strategy that can be widely implemented in the production of ceramic tiles. Although the actual potential of waste recycling is under exploited, some key points must be carefully considered to avoid overestimation: technological constraints limiting the percentages that can actually be used in current products; effective availability of the necessary quantities of suitable waste; actual sustainability of the waste supply chain. The question of replacing clay raw materials with waste remains totally unanswered, given that residues with properties of plasticity providers are few.

The efforts just described cross the directive on the elimination of substances of very high concern from the production cycle. Furthermore, there is a need to understand the level of exposure of the ceramic supply chain to critical and strategic raw materials, which warmly recommends preparing contingency plans in the event of shortage or strong price increases in the future.

It appears that many of the above risk factors for the survival of the ceramic industry can be circumvented through successful product innovation. This innovation will have to be set on reverse engineering criteria, in order to design products needing less raw materials (thinner tiles) and batches that maximize the use of waste and indigenous raw materials, while also allowing an enhancement of process efficiency. The margins for action to achieve such ambitious goals are limited by the short time left and rather uncertain, due to the lack of basic research to support industrial choices that will soon become urgent. However, this challenging scenario can only represent the stimulus for all the players in the ceramic tile supply chain to join forces in a framework of competitive collaboration and open innovation.

REFERENCES

[1] Kuhlman, T., & Farrington, J. (2010). What is sustainability? Sustainability, 2(11), 3436-3448.

[2] Salas-Zapata, W. A., & Ortiz-Muñoz, S. M. (2019). Analysis of meanings of the concept of sustainability. Sustainable Development, 27(1), 153-161.

[3] Russo, M., Börkey, P., Cubel, E., Lévêque, F., Mas, F. (1998). Local sustainability and competitiveness: the case of the ceramic tile industry. European Foundation for the improvement of living and working conditions, Luxembourg, 54 p.

[4] Bastianoni, S., Niccolucci, V., & Picchi, M. (2001). Thermodynamic analysis of ceramics production in Sassuolo (Italy) from a sustainability viewpoint. Journal of Thermal Analysis and Calorimetry, 66(1), 273-280.

[5] Nicoletti, G. M., Notarnicola, B., & Tassielli, G. (2002). Comparative Life Cycle Assessment of flooring materials: ceramic versus marble tiles. Journal of Cleaner Production, 10(3), 283-296.

[6] Palmonari, C., & Timellini, G. (2002). Indústria de Revestimentos Italiana e o Meio Ambiente. Cerâmica Industrial, 7(1), 7-11.

[7] Palmonari, C., & Timellini, G. (2006). The European ceramic tile industry and the new approach to environmental protection. Environmental Issues and Waste Management Technologies in the Ceramic and Nuclear Industries VII, 132, 75-84.

[8] Peng, J., Zhao, Y., Jiao, L., Zheng, W., & Zeng, L. (2012). CO2 emission calculation and reduction options in ceramic tile manufacture-the Foshan case. Energy Procedia, 16, 467-476.

[9] Huang, Y., Luo, J., & Xia, B. (2013). Application of cleaner production as an important sustainable strategy in the ceramic tile plant–a case study in Guangzhou, China. Journal of Cleaner Production, 43, 113-121.

[10] Mezquita, A., Boix, J., Monfort, E., & Mallol, G. (2014). Energy saving in ceramic tile kilns: Cooling gas heat recovery. Applied Thermal Engineering, 65(1-2), 102-110.

[11] Mezquita, A., Monfort, E., Ferrer, S., & Gabaldón-Estevan, D. (2017). How to reduce energy and water consumption in the preparation of raw materials for ceramic tile manufacturing: Dry versus wet route. Journal of Cleaner Production, 168, 1566-1570.

[12] de Souza, W. J. V., Scur, G., & de Castro Hilsdorf, W. (2018). Eco-innovation practices in the brazilian ceramic tile industry: The case of the Santa Gertrudes and Criciúma clusters. Journal of Cleaner Production, 199, 1007-1019.

[13] Branchini, L., Bignozzi, M. C., Ferrari, B., Mazzanti, B., Ottaviano, S., Salvio, M., & Canetti, A. (2021). Cogeneration Supporting the Energy Transition in the Italian Ceramic Tile Industry. Sustainability, 13(7), 4006.

[14] Boschi, G., Masi, G., Bonvicini, G., & Bignozzi, M. C. (2020). Sustainability in Italian Ceramic Tile Production: Evaluation of the Environmental Impact. Applied Sciences, 10(24), 9063.

[15] Gabaldón-Estevan, D., Criado, E., & Monfort, E. (2014). The green factor in European manufacturing: a case study of the Spanish ceramic tile industry. Journal of Cleaner Production, 70, 242-250.

[16] Cerame-Unie (2021). Position on the revision of the Energy Performance of Buildings Directive. Position paper, 3 p.

[17] Garcia-Muiña, F. E., González-Sánchez, R., Ferrari, A. M., Volpi, L., Pini, M., Siligardi, C., & Settembre Blundo, D. (2019). Identifying the equilibrium point between sustainability goals and circular economy practices in an Industry 4.0 manufacturing context using eco-design. Social Sciences, 8(8), 241.

[18] Ferrari, A. M., Volpi, L., Pini, M., Siligardi, C., García-Muiña, F. E., & Settembre Blundo, D. (2019). Building a sustainability benchmarking framework of ceramic tiles based on life cycle sustainability assessment (LCSA). Resources, 8(1), 11.

[19] Medina-Salgado, M. S., García-Muiña, F. E., Cucchi, M., & Settembre Blundo, D. (2021). Adaptive Life Cycle Costing (LCC) Modeling and Applying to Italy Ceramic Tile Manufacturing Sector: Its Implication of Open Innovation. Journal of Open Innovation: Technology, Market, and Complexity, 7(1), 101.

[20] Baker, S. (2007). Sustainable development as symbolic commitment: Declaratory politics and the seductive appeal of ecological modernisation in the European Union. Environmental politics, 16(2), 297-317.

[21] Machin, A. (2019). Changing the story? The discourse of ecological modernisation in the European Union. Environmental Politics, 28(2), 208-227.

[22] Rinaldi, C., Fregni, A., Palmonari, C., & Timellini, G. (2002). Methodology for life cycle assessment of ceramic floor and wall tiles-applications in BAT definition for ceramic tiles industry. Key Engineering Materials, 206, 829-834.

[23] Ibáñez-Forés, V., Bovea, M. D., & Azapagic, A. (2013). Assessing the sustainability of Best Available Techniques (BAT): methodology and application in the ceramic tiles industry. Journal of Cleaner Production, 51, 162-176.

[24] BRef (2007). Reference Document on Best Available Techniques in the Ceramic Manufacturing Industry. European Commission, 260 p.
[25] Breedveld, L., Timellini, G., Casoni, G., Fregni, A., & Busani, G. (2007). Eco-efficiency of fabric filters in the Italian ceramic tile industry. Journal of Cleaner Production, 15(1), 86-93.
[26] Celades, I., Moliner-Salvador, R., Ros-Dosda, T., Monfort, E., & Zaera, V. (2012). Environmental development of the Spanish ceramic tile manufacturing sector over the period 1992–2007. Boletin de la Sociedad Espanola de Ceramica y Vidrio, 51, 111-118.
[27] BRef (2021). Kick-off meeting for the review of the best available techniques (BAT) reference document for the ceramic manufacturing industry. European Commission, 44 p.
[28] Ardit, M., Zanelli, C., Conte, S., Molinari, C., Cruciani, G., & Dondi, M. (2021). Ceramisation of hazardous elements: benefits and pitfalls of the inertisation through silicate ceramics. Journal of Hazardous Materials, 126851, 17 p.
[29] Roadmap 2050 (2010). A practical guide to a prosperous, low-carbon Europe – Technical analysis. European Climate Foundation 100 p.
[30] Cerame-Unie (2012). Paving the way to 2050: the ceramic industry roadmap. The European Ceramic Industry Association, 17 p.
[31] Andrea Blengini, G., & Shields, D. J. (2010). Green labels and sustainability reporting. Management of Environmental Quality: An International Journal, 21, 477-493.
[32] European Commission (2009). Commission decision of 9 July 2009 establishing the ecological criteria for the award of the Community eco-label to hard coverings (2009/607/EC) 21 p.
[33] Donatello S., Garbarino E., Sanfelix J., Fernandez Carretero A. & Wolf O. (2021). EU Ecolabel criteria for hard covering products. Criteria and supporting rationale. EUR 30682 EN, Publications Office of the European Union, Luxembourg.
[34] Amiri, A., Ottelin, J., & Sorvari, J. (2019). Are LEED-certified buildings energy-efficient in practice? Sustainability, 11(6), 1672.
[35] Almeida, M. I., Dias, A. C., Demertzi, M., & Arroja, L. (2016). Environmental profile of ceramic tiles and their potential for improvement. Journal of Cleaner Production, 131, 583-593.
[36] Ros-Dosdá, T., Celades, I., Monfort, E., & Fullana-i-Palmer, P. (2018). Environmental profile of Spanish porcelain stoneware tiles. The International Journal of Life Cycle Assessment, 23(8), 1562-1580.
[37] Liu, Y., Zhang, Y. J., Wang, C., Wen, G., & Ren, S. W. (2020). Technical Specification Development for Ceramic Tile Type III Environmental Declarations. Materials Science Forum, 993, 1481-1486.
[38] Terjek, A., & Dudás, A. (2020). Sustainability and Environmental Awareness in the Ceramic Industry. European Journal of Engineering and Technology Research, 5(8), 970-979.
[39] Liu, Y., Zhang, Y. J., Wang, C., Wen, G., & Ren, S. W. (2020). Technical Specification Development for Ceramic Tile Type III Environmental Declarations. Materials Science Forum, 993, 1481-1486.
[40] ISO 17889-1 (2021). Ceramic tiling systems — Sustainability for ceramic tiles and installation materials — Part 1: Specification for ceramic tiles. International Organization for Standardization, 40 p.
[41] Grebot, B., Tweed, J., Tsamis, A., Scarbrough, T., Lopez, A., Illes, A., Hekman, J., Stephenson, S., Menadue, H., Anderson, N., Winter, B., Waxender, H., Schindler, I., McNeill, A., Pelsy, F., Rouas, V. (2020). Support to the evaluation of the Industrial Emissions Directive (Directive 2010/75/EU). Final Report. Directorate-General for Environment ENV.C - Quality of life, C.4 - Industrial emissions & safety, 216 p.
[42] Ros-Dosdá, T., Fullana-i-Palmer, P., Mezquita, A., Masoni, P., & Monfort, E. (2018). How can the European ceramic tile industry meet the EU's low-carbon targets? A life cycle perspective. Journal of Cleaner Production, 199, 554-564.
[43] Acar, C., & Dincer, I. (2019). Review and evaluation of hydrogen production options for better environment. Journal of cleaner production, 218, 835-849.
[44] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11-32.
[45] Belussi, L., Barozzi, B., Bellazzi, A., Danza, L., Devitofrancesco, A., Fanciulli, C., & Scrosati, C. (2019). A review of performance of zero energy buildings and energy efficiency solutions. Journal of Building Engineering, 25, 100772.
[46] Hocenski, V., Hocenski, Z., & Vasilic, S. (2006, December). Application of results of ceramic tiles life cycle assessment due to energy savings and environment protection. In 2006 IEEE International Conference on Industrial Technology, 2972-2977.
[47] Bovea, M. D., Saura, Ú., Ferrero, J. L., & Giner, J. (2007). Cradle-to-gate study of red clay for use in the ceramic industry. The International Journal of Life Cycle Assessment, 12(6), 439-447.
[48] Tikul, N., & Srichandr, P. (2010). Assessing the environmental impact of ceramic tile production in Thailand. Journal of the Ceramic Society of Japan, 118(1382), 887-894.

[49] Kamalakkannan, S., Peiris, R. L., & Kulatunga, A. K. (2019). Life cycle assessment in ceramic floor tile industry in Sri Lanka. In Proc. of the Int. Conf. on Industrial Engineering and Operations Management, Bangkok, Thailand, March, 5-7.

[50] Ibáñez-Forés, V., Bovea, M. D., & Simó, A. (2011). Life cycle assessment of ceramic tiles. Environmental and statistical analysis. The International Journal of Life Cycle Assessment, 16(9), 916-928.

[51] Pini, M., Ferrari, A. M., Gamberini, R., Neri, P., & Rimini, B. (2014). Life cycle assessment of a large, thin ceramic tile with advantageous technological properties. The International Journal of Life Cycle Assessment, 19(9), 1567-1580.

[52] Tikul, N. (2014). Assessing environmental impact of small and medium ceramic tile manufacturing enterprises in Thailand. Journal of Manufacturing Systems, 33(1), 1-6.

[53] Sangwan, K. S., Choudhary, K., & Batra, C. (2018). Environmental impact assessment of a ceramic tile supply chain–a case study. International Journal of Sustainable Engineering, 11(3), 211-216.

[54] Settembre Blundo, D., Garcia-Muiña, F. E., Pini, M., Volpi, L., Siligardi, C., & Ferrari, A. M. (2018). Lifecycle-oriented design of ceramic tiles in sustainable supply chains (SSCs). Asia Pacific Journal of Innovation and Entrepreneurship, 12, 323-337.

[55] Ye, L., Hong, J., Ma, X., Qi, C., & Yang, D. (2018). Life cycle environmental and economic assessment of ceramic tile production: A case study in China. Journal of Cleaner Production, 189, 432-441.

[56] Wang, Y., Liu, Y., Cui, S., Sun, B., Gong, X., Gao, F., & Wang, Z. (2020). Comparative life cycle assessment of different fuel scenarios and milling technologies for ceramic tile production: A case study in China. Journal of Cleaner Production, 273, 122846.

[57] Türkmen, B. A., Duhbacı, T. B., & Özbilen, Ş. K. (2021). Environmental impact assessment of ceramic tile manufacturing: a case study in Turkey. Clean Technologies and Environmental Policy, 23(4), 1295-1310.

[58] Türkmen, B. A., Özbilen, Ş. K., & Duhbacı, T. B. (2021). Improving the sustainability of ceramic tile production in Turkey. Sustainable Production and Consumption, 27, 2193-2207.

[59] Bribián, I. Z., Capilla, A. V., & Usón, A. A. (2011). Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Building and environment, 46(5), 1133-1140.

[60] Ferrari, A. M., Volpi, L., Settembre Blundo, D., & García-Muiña, F. E. (2021). Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment. Journal of Cleaner Production, 286, 125314.

[61] Korhonen, J., Honkasalo, A., & Seppälä, J. (2018). Circular economy: the concept and its limitations. Ecological Economics, 143, 37-46.

[62] Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. Resources, Conservation and Recycling, 127, 221-232.

[63] Meng, Y., Ling, T. C., & Mo, K. H. (2018). Recycling of wastes for value-added applications in concrete blocks: An overview. Resources, Conservation and Recycling, 138, 298-312.

[64] Pitarch, A. M., Reig, L., Tomás, A. E., & López, F. J. (2019). Effect of tiles, bricks and ceramic sanitary-ware recycled aggregates on structural concrete properties. Waste and Biomass Valorization, 10(6), 1779-1793.

[65] Evangelista, A. C. J., Tam, V. W., & Santos, J. (2019). Recycled ceramic fine aggregate for masonry mortar production. Proceedings of the Institution of Civil Engineers-Construction Materials, 172(5), 225-234.

[66] Silvestre, R., Medel, E., García, A., & Navas, J. (2013). Using ceramic wastes from tile industry as a partial substitute of natural aggregates in hot mix asphalt binder courses. Construction and Building Materials, 45, 115-122.

[67] Pelisser, F., Steiner, L. R., & Bernardin, A. M. (2012). Recycling of porcelain tile polishing residue in Portland cement: hydration efficiency. Environmental science & technology, 46(4), 2368-2374.

[68] Cabalar, A. F., Hassan, D. I., & Abdulnafaa, M. D. (2017). Use of waste ceramic tiles for road pavement subgrade. Road Materials and Pavement Design, 18(4), 882-896.

[69] Medri, V., & Landi, E. (2014). Recycling of porcelain stoneware scraps in alkali bonded ceramic composites. Ceramics International, 40(1), 307-315.

[70] Mahmoodi, O., Siad, H., Lachemi, M., Dadsetan, S., & Sahmaran, M. (2020). Development of ceramic tile waste geopolymer binders based on pre-targeted chemical ratios and ambient curing. Construction and Building Materials, 258, 120297.

[71] Dondi, M., García-Ten, J., Rambaldi, E., Zanelli, C., & Vicent-Cabedo, M. (2021). Resource efficiency versus market trends in the ceramic tile industry: Effect on the supply chain in Italy and Spain. Resources, Conservation and Recycling, 168, 105271, 12 p.

[72] Andreola, F., Barbieri, L., Lancellotti, I., Leonelli, C., & Manfredini, T. (2016). Recycling of industrial wastes in ceramic manufacturing: State of art and glass case studies. Ceramics International, 42(12), 13333-13338.

[73] García-Ten, F. J., Quereda Vázquez, M. F., Gil Albalat, C., Chumillas Villalba, D., Zaera, V., & Segura Mestre, M. C. (2016). Life ceram-zero waste in ceramic tile manufacture. Key Engineering Materials, 663, 23-33.
[74] Rambaldi, E., Valeriani, L., Grandi, L., Beneventi, C., & Bignozzi, M. C. (2018). High-recycling content porcelain stoneware tiles: from industrial production to product certification. Proceedings Qualicer, 10 pp.
[75] Andreola, F., Lancellotti, I., Pozzi, P., & Barbieri, L. (2021). Eco-Compatible Construction Materials Containing Ceramic Sludge and Packaging Glass Cullet. Applied Sciences, 11(8), 3545.
[76] Mugoni, C., Rosa, R., Remigio, V. A., Ferrari, A. M., & Siligardi, C. (2020). Opportune inward waste materials toward a zero waste ceramic slabs production in a circular economy perspective. International Journal of Applied Ceramic Technology, 17(1), 32-41.
[77] Zanelli, C., Conte, S., Molinari, C., Soldati, R., & Dondi, M. (2020). Waste recycling in ceramic tiles: a technological outlook. Resources, Conservation and Recycling, 105289, 30+36 p.
[78] Mugoni, C., Khorassani, Siligardi, C., & Ferrari, A. M. (2015). Life cycle assessment of a sintered tile containing copper slag: is recycling always convenient? La Chimica e l'Industria, XCVII, 18-21.
[79] Novais, R. M., Seabra, M. P., & Labrincha, J. A. (2015). Wood waste incorporation for lightweight porcelain stoneware tiles with tailored thermal conductivity. Journal of Cleaner Production, 90, 66-72.
[80] Dondi, M., Raimondo, M., & Zanelli, C. (2014). Clays and bodies for ceramic tiles: Reappraisal and technological classification. Applied Clay Science, 96, 91-109.
[81] Dondi, M. (2018). Feldspathic fluxes for ceramics: Sources, production trends and technological value. Resources, Conservation and Recycling, 133, 191-205.
[82] Schrijvers, D., Hool, A., Blengini, G. A., Chen, W. Q., Dewulf, J., Eggert, R., ... & Wäger, P. A. (2020). A review of methods and data to determine raw material criticality. Resources, Conservation and Recycling, 155, 104617.
[83] Blengini, G.A., Latunussa, C.E.L., Eynard, U., Torres de Matos, C., Wittmer, D., Georgitzikis, K., Pavel, C., Carrara, S., Mancini, L., Unguru, M., Blagoeva, D., Mathieux, F., Pennington, D. (2020). Study on the EU's list of Critical Raw Materials. European Commission, 157 p., https://rmis.jrc.ec.europa.eu/uploads/CRM_2020_Report_Final.pdf
[84] ECHA (2021). Candidate List of substances of very high concern for Authorisation, European Chemicals Agency, https://echa.europa.eu/candidate-list-table
[85] Molinari, C., Conte, S., Zanelli, C., Ardit, M., Cruciani, G., & Dondi, M. (2020). Ceramic pigments and dyes beyond the inkjet revolution: From technological requirements to constraints in colorant design. Ceramics International, 46(14), 21839-21872.
[86] Meinert, L. D., Robinson, G. R., & Nassar, N. T. (2016). Mineral resources: Reserves, peak production and the future. Resources, 5(1), 14.
[87] Monfort, E., Mezquita, A., Granel, R., Vaquer, E., Escrig, A., Miralles, A., & Zaera, V. (2010). Analysis of energy consumption and carbon dioxide emissions in ceramic tile manufacture. Boletin De La Sociedad Espanola De Ceramica Y Vidrio, 49(4), 303-310.
[88] Gabaldón-Estevan, D., Mezquita, A., Ferrer, S., & Monfort, E. (2016). Unwanted effects of European Union environmental policy to promote a post-carbon industry. The case of energy in the European ceramic tile sector. Journal of cleaner production, 117, 41-49.
[89] Mysen, B. O., & Richet, P. (2018). Silicate glasses and melts. Elsevier, 723 p.
[90] Conte, S., Zanelli, C., Ardit, M., Cruciani, G., & Dondi, M. (2020). Phase evolution during reactive sintering by viscous flow: Disclosing the inner workings in porcelain stoneware firing. Journal of the European Ceramic Society, 40(4), 1738-1752.