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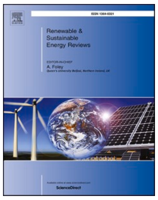

Decarbonizing the ceramics industry: A systematic and critical review of policy options, developments and sociotechnical systems

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ABSTRACT

Ceramics are considered one of the greatest and earliest most useful successes of humankind. However, ceramics can be highly damaging to natural and social systems during their lifecycle, from material extraction to waste handling. For example, each year in the EU, the manufacture of ceramics (e.g., refractories, wall and floor tiles and bricks and roof tile) emit 19 Mt CO2, while globally, bricks manufacturing is responsible for 2.7% of carbon emissions annually. This critical and systematic review seeks to identify alternatives to mitigate the climate effects of ceramics products and processes to make their lifecycle more sustainable. This article reviews 324 studies to answer the following questions: what are the main determinants of energy and carbon emissions emerging from the ceramics industry? What benefits will this industry amass from adopting more low-carbon processes in manufacturing their products, and what barriers will need to be tackled? We employ a socio-technical approach to answer these questions, identify barriers to decarbonise the ceramics industry, and present promising avenues for future research. In doing so, we show that environmental and energy challenges associated with the ceramics industry are not just limited to the manufacturing stage but also relate to the extraction of raw materials, waste disposal, and landfilling.

1. Introduction

Ceramics are considered one of the greatest and earliest most useful successes of humankind. In part because they represent how humans learned to control fire and manipulate clay [1]. Ceramics were among the first objects to be manufactured, and owing to their various applications, their importance in material culture has remained over millennia and persists today [2]. Across the globe, the production of ceramics plays an important role in terms of economic activity, artistic value, and cultural heritage, with their products often linked to regional and historical environments in which they were and are produced [3].

The term "ceramics" comes from the Greek "keramos" word meaning 'burned earth' and is used to describe materials of the pottery industry [4]. Ceramics are defined as non-metallic inorganic solids [5]. However, in a more precise sense, ceramics are a solid obtained by firing inorganic powders [6]. Some key characteristics of the ceramic products include

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Abbreviations: BAT, Best available technology; BEIS, Department for Business, Energy & Industrial Strategy; CCS, Carbon capture and storage; CAGR, Compound annual growth rate; CO_2, Carbon dioxide; CO_2e, Carbon dioxide equivalent; DECC, Department of Energy and Climate Change; EU, European Union; IEA, International Energy Agency; HAP, Hazardous air pollutant; HPHE, Heat pipe heat exchanger; $MtCO_2$, Metric tons of carbon dioxide; O3, Tropospheric ozone; PM, Particulate matter; SPS, Spark plasma sintering; TOE, Tonne of oil equivalent; TOC, Total organic compounds; VOC, Volatile organic compounds; WHR, Waste heat recovery; WTE, Waste to Energy.

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long service life, low density, strong electromagnetic response, corrosion resistance, chemical inertness and nontoxicity, resistance to heat and fire, high strength, and sometimes, electrical resistance or porosity beneficial to particular applications [7–9]. Due to these attributes, ceramics are positioned as a superior material for various applications compared to metals [10]. Moreover, ceramic products require little maintenance and have high resistance to environmental conditions [1].

The production of ceramics and its relation to society has a long history, with the first pieces being reported around 24,000 years ago as ritual items. Later, circa 6400 BC, extensive pottery manufacture became common when civilizations settled near river beds, and the agricultural economy was developed [11]. Bricks, the oldest known artificial building material [7]; used for centuries and still vital today in the construction industry [12], are traced back to 10,000 BC [13], while fired-clay bricks date as early as 4500 BC [8]. In India, for instance, the history of brick-making dates back as far as 5000 years [14], while the antique city of Ur, now in modern Iraq, was home to the first civilization that adopted clay bricks as its main building material, 4000 years ago [15]. The Romans, 2000 years ago, expanded the technique of brick making to other parts of Europe, while glazed ceramic plates decorated the Egyptian pyramids in 2600 BC [5]. Porcelain, another type of ceramic, was originated in China during the T'ang dynasty (618–907 AD); nevertheless, high-quality porcelain products were not developed until the Yuan dynasty (1279–1368 AD) [1]. Surprisingly, the first documented drilling for natural gas took place in China in 1013 AD, to drill for gas and use it in porcelain manufacturing [16]. Despite ceramics' earlier developments, the principles of their fabrication process remained somewhat the same. That is, a clay paste comprising fine-grained earthen materials is shaped into objects of virtually any form [2].

The ubiquity of ceramics has allowed them to be present in most aspects of our society as promising materials for aerospace and high-temperature structural applications [10,17], ballistic armours and automotive brakes [9], information storage and optical devices [18], lamp envelopes and transparent armours [19] and bone void fillers and coating materials for dental and orthopedic applications [20]. Ceramics also facilitate water purification, such as industrial wastewater, oil-water separation, and hazardous waste treatment [21,22]. Within the sustainability dimension, ceramics have been used as high-temperature CO_2 adsorbents [23,24], as an alternative to batteries for electricity storage [25], thermal energy storage in solar power plants [26], energy harvesting applications [27], as a substitute for Nickel [28] and as a mean to recover the thermal energy from cooling water in power plant turbines [29].

Given the multitude of applications for ceramics, it is less surprising that the global ceramics market had an estimated value of around $229.13 billion in 2018, with projections pointing to a lucrative compound annual growth rate (CAGR) 8.6% from 2019 to 2025 [30]. The high demand for ceramics products is attributed to the constant growth in the construction industry, technological advancements in nanotechnology, 3D printing, and ceramics in health (i.e., oral healthcare through the production of dental crowns, implants, and bridges) [30,31]. This industry also consumes large amounts of energy. For instance, in the UK alone, the ceramics industry demands around 4.7 TWh of delivered energy per year, where gas accounts for 80–82% of the industry's total energy mix [32]. In the EU, the production of refractories, wall and floor tiles, and bricks and roof tile emits around 19 Mt CO_2 [1], while globally, bricks manufacturing is responsible for 2.7% of carbon emissions annually [33].

This systematic review employs a "sociotechnical" lens to investigate a critical issue associated with the future of ceramics: achieving significant decarbonization or even net-zero production. This study asks five key questions:

1 What alternatives exist to abate the climate effects of ceramics production and thus make the full life cycle of ceramics more sustainable?
2 What are the key determinants of energy and carbon emissions from ceramics?
3 What technical innovations have been identified to make ceramics manufacturing low carbon?
4 What benefits will amass from a more carbon-friendly process in ceramics manufacturing?
5 What barriers will need to be tackled to achieve more sustainable process in ceramics manufacturing?

The motivation behind this work is driven due to the lack of research attending to this pressing issue. Although our list of research surpasses the 320 references, this paper is the only study, to the author's knowledge, that approaches the decarbonization of the ceramics industry through a sociotechnical lens, and also one with a systematic review searching protocol. That said, this review utilizes a sociotechnical system [34,35] approach that scrutinises the manufacturing processes and different ceramic uses while providing options for its decarbonization (including electrification, heating and heat recovery, biofuels, waste recovering, and other emerging innovations).

The article proceeds as follows. Section 2 offers a comprehensive background on the process of ceramics making, its categorization, along with this industry's market dynamics. In Section 3, we present the research design. Here, we discuss why we have implemented a critical and systematic review approach and why we studied the ceramics industry through a sociotechnical lens. Section 4 presents the energy use and emissions emerging from the ceramics industry, as well as other environmental issues emanating from this industry. Section 5 presents no less than 15 approaches to decarbonise the ceramics industry and more than thirty complementary technologies and processes to improve energy efficiency during the ceramics making process. Section 6 identifies current barriers to decarbonizing the ceramics industry, while Section 7 presents five potential avenues for future research. Section 8 concludes.

2. Background

In this section, we first present ceramics categorization and use. Later, we describe the process of ceramics making. At the end of this section, our review analyses market trends and dynamics.

2.1. Categorizing ceramics and its sectoral uses

The ceramics industry is often divided into two broad categories. The first entails traditional ceramics such as refractory ceramic goods, bricks and roofing tiles, tableware and other domestic or toilet articles, heavy clay, wall and floor tiles, vitrified clay pipes, and expanded clay aggregates [36]. This group represents the majority of the overall production of the sector, the energy consumed, and the total amount of trade [37]. The bricks and roof tiles and wall and floor tiles subsectors represent the biggest markets and the largest energy consumers from this category. The second category, advanced ceramics, comprises bioceramics, electrical and electronic ceramics, and ceramic coatings. Advanced ceramics are unique because of their physical and chemical properties and their manufacturing process from chemically prepared powders, making them more expensive than traditional ceramics [38]. In terms of economics, advanced ceramics represent a smaller market, reaching an estimated value of $8.49 billion in 2021 [39]. Meanwhile, this subsector has disproportionately large carbon equivalent emissions due to the high firing temperatures employed [32]. However, there is no precise information on the emissions emerging from this subsector [5].

Our review builds on these different categories to differentiate eight core sectors of the industry shown in Table 1.

Table 1
Eight sectors of the ceramic industry. Source: authors. Compiled from [5,32,40–57].

Sector	Key characteristics
Bricks and roof tiles	Bricks are arguably one of the most commonly used materials in construction. Bricks have many properties, including high water vapour permeability, mechanical resistivity, resistance to moisture fluctuations, slag corrosion and thermal shock, compressive strength and thermal and resistive properties for different climate and weather types. The annual production of fired bricks worldwide is estimated to be about 1.39 trillion units.
Wall and floor tiles	Ceramic tiles are thin slabs made from clays and other inorganic materials. The ceramic tile industry is the largest component of the traditional ceramic sector. In fact, in 2015 alone, a total of 12,673 million m^2 of ceramic tiles were produced globally. This sector consumes 75% of the total energy consumed by the traditional ceramics sector and represents a market of around 14 billion tiles. These materials entail floors, furniture for bathrooms and kitchens, covering roofs, walls and showers. They are traditionally used in these applications due to their technical characteristics and their aesthetic qualities. Some notable features of ceramic tiles from a sustainability perspective include resistance to fire, ultraviolet radiation and water and release of volatile toxic substances or organic compounds when exposed to high temperatures. The manufacturing process of tiles consists of five steps: the raw material and body preparation, shaping, drying, firing and final product shipping.
Table- and ornamentalware (household ceramics)	This subsector entails tableware, artificial and fancy goods made of earthenware, porcelain, and fine stoneware. The most typical products are dishes, bowls, cups, vases, plates, and jugs.
Vitrified clay pipes	Fittings and vitrified clay pipes are used for sewers and drains and tanks to contain acid. For this process, chamotte and clay are employed as raw materials for the manufacturing process of clay pipes.
Expanded clay	Expanded clay aggregates are characterized by a uniform pore structure of fine, closed cells and a densely sintered firm external skin. These materials are often used as loose or cement-bound material for the construction industry (e.g., blocks and other prefabricated lightweight concrete components, loose fillings, and lightweight concrete).
Sanitaryware	Sanitaryware encapsulates all-ceramic goods used for sanitary purposes, including bidets, drinking fountains, washbasins, lavatory bowls, and cisterns. These products are often made of earthenware or vitreous china (semi-porcelain). The mix of raw materials applicable in a typical batch preparation of sanitaryware includes kaolin and clay 40–50%, quartz 20–30%, feldspar 20–30% and between 0 and 3% calcium carbonate.
Refractory products	Refractory products are ceramic materials capable of resisting temperatures above 1500 °C. Several refractory products are employed for different industrial applications, including iron, steel, glass, ceramic, lime, house heating systems, petrochemicals industries, power plants, and incinerators. Refractory products are considered essential to high-temperature processes and can withstand all types of stresses (thermal, chemical, mechanical) such as corrosion, creeping deformation and thermal shocks. They consist of chamotte (calcined raw plastic clay), natural rocks (i.e. dolomite, bauxite, quartzite and magnesite), clay and synthetic materials (i.e. spinels, sintered corundum and silicon carbide). Refractory products are divided into different categories based on the method of manufacture (sintered and fused), method of implementation (shaped and unshaped), chemical composition (special, basic and acid), and porosity content (dense and porous).
Abrasive ceramics	These materials are employed in different mechanical processes to change, shape, finish and texture industrial and artisanal processes. These products consist of natural ceramic, which is often mixed with other abrasive powders such as silicon carbide and quartz.
Technical ceramics	Technical ceramics are not only based on clays but also synthetic raw materials. Technical ceramics are based on the following materials: carbides, oxides, nitrides and borides of Al, Mg, Mn, Ni, Si, Ti, W, Zr and other metal ions. This may include: MgO (periclase or dead burned magnesia), Al2O3 (alumina), TiN (titanium nitride), SiC (silicon carbide), and WB2 (tungsten boride).

2.2. *The process of ceramics making*

The process of manufacturing ceramic products is largely uniform [32,58]. In general, raw materials are cast and mixed, extruded, or pressed into shape. During the manufacturing process, water is regularly employed for thorough mixing and shaping. The water used in this process is evaporated in dryers. Later, the products are either manually placed in the kiln (particularly for periodically operated kilns) or placed in carriages where materials are transferred through continuously operated kilns [5]. Table 2, displays the ceramics manufacturing stages, while Fig. 1 illustrates this process.

The first stage of production consists of a mixture of powdered base material, binders and stabilizers. The mixture is “turned” into shapes and then fired (sintered) in kilns at temperatures ranging from 800 °C to 2500 °C (see Tables 3 and 4 for specific temperature requirements including technical ceramics materials) for days or even weeks [61]. Some variations will depend on the type of ceramic. For instance, a multiple-stage firing process is often used for wall and floor tiles, sanitaryware, household ceramics, and technical ceramics.

2.3. *The ceramics market*

The most important ceramic subsector is the wall and floor tiles (See Figs. 2 and 3). Worldwide, ceramic tile production was approximately 13,500 million square metres [59], with China leading the market with over 45.7% of the world’s total. In China alone, the annual production of ceramic tiles has exceeded 10 billion m^2 [63]. The other key players are South America and the European Union (EU), producing 11% and 9%, respectively [64]. In Europe, the ceramics industry employs 338,000 people, produces about 1304 million m^2 of tiles, encompasses around 2000 companies, and contributed to a business turnover of 30 billion

Table 2
Stages of the manufacturing process for traditional ceramics. Source: authors. Compiled from [5,50,58–60].

Stage	Process
Raw materials preparation	Ceramics preparation takes place as dry or wet milling. In wet milling, the most popular preparation method of raw materials, thermal energy consumption occurs in three stages: spray drying, drying, and firing, accounting for more than 50% of overall thermal energy consumption.
Forming (shaping) of the piece	Forming methods are divided into three large groups (i) forming by isostatic or uniaxial semi-dry pressing of a granulate material with low moisture content. (ii) plastic forming by extrusion, wheel throwing, and plastic pressing. (iii) forming by pressure casting of suspensions or air slip casting.
Drying	The water is removed to proceed with the glazing and/or firing stages. The most popular drying method in the ceramics industry is convection. In this process, heated air is circulated around the ceramics, and sometimes the heat can be recovered from the kiln’s cooling zone.
Glazing	This stage is only carried out for glazed products.
Heating	Depending on the raw material composition, unfired products are heated from ambient temperature to 800 °C. During this stage, outgassing of the ceramic body takes place to avoid bubbles, pinholing, bloating, glaze porosity, and colour differences at higher temperatures.
Firing	The firing stage typically varies between 850 °C and 1350 °C, depending on the main physio-chemical transformations. During this stage, ceramic materials reduce their porosity.
Cooling	This process starts when the heat input ends. During this stage, product temperature is reduced from peak to near ambient temperature.
Sorting and packaging	Before packaging, products are closely inspected to separate them according to trade categories, detect defects and/or discard the products.

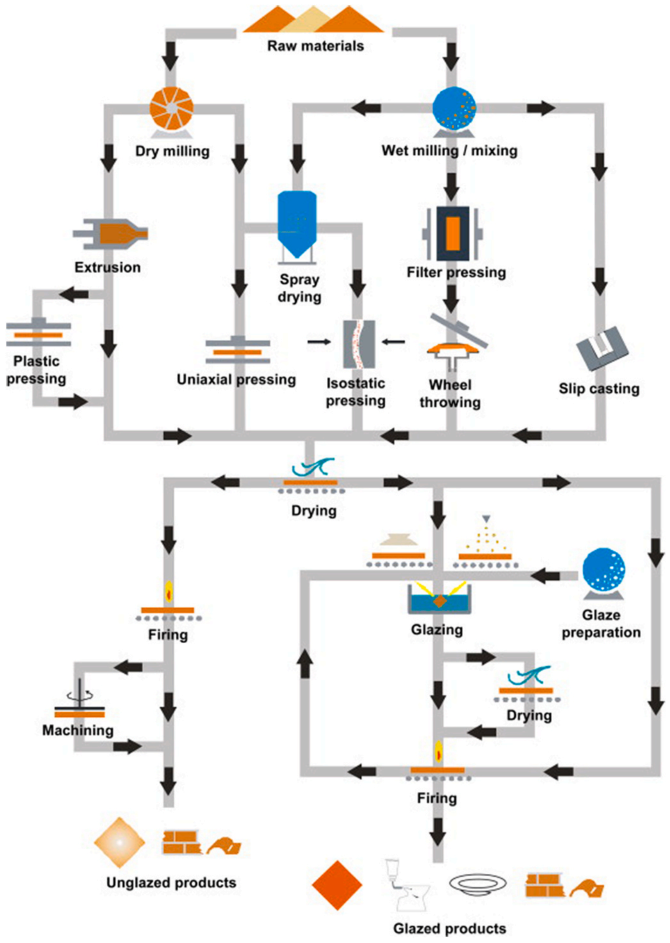


Fig. 1. Stages of the manufacturing process of traditional ceramics. Source [50].

Table 3
Specific required temperatures for the ceramics sectors. Source: authors. Compiled from [5,62].

Sector	Temperature requirements
Bricks and roof tiles	Bricks and roof tiles are heated at temperatures varying between 800 and 1300 °C.
Vitrified clay pipes	Temperatures range from 1150 to 1250 °C, while the firing time lasts between 30 and 80 h.
Refractory products	These materials are fired at temperatures ranging between 1250 and 1850 °C.
Expanded clay aggregates	These materials are subjected to a firing process of temperatures ranging between 1100 and 1300 °C.
Floor and wall tiles	The temperature required for floor and wall tiles varies between 1050 and 1300 °C.
Sanitaryware	Normally the required temperatures for vitreous china ranges between 1200 and 1210 °C and is about 1220 °C for fireclay.

euros in 2018 [55,65]. Spain and Italy are the biggest ceramic tile producers, representing about 70% of the EU's total production [59]. In South America, the most prominent manufacturer is Brazil, where the ceramic industry represents circa 1.0% of the GDP with about 5000 active companies [66].

Table 4
Sintering temperatures for technical ceramic materials. Source: authors, compiled from [5].

Technical ceramic material	Sintering temperature
Aluminium oxide	Between 1600 and 1800 °C
Alumina porcelain	Approximately 1250 °C
Cordierite	Between 1250 and 1350 °C
Quartz porcelain	Approximately 1300 °C
Recrystallised silicon carbide	Between 2300 and 2500 °C
Silicon nitride	Approximately 1700 °C
Sintered silicon carbide	Approximately 1900 °C
Steatite	Approximately 1300 °C

Bricks are another key material within the ceramic industry, with a demand historically rising [44]. China is the world's lead manufacturer, producing approximately 1 trillion bricks; South Asia is the second-largest brick manufacturing region, making around 310 billion bricks annually [67]. India plays a vital role in the bricks sector too, with more than 100,000 brick kilns, it is capable of manufacturing 240 billion bricks yearly, generating an annual turnover of more than US$ 3 billion in 2016 [68]. Bricks manufacturing in India is likely to increase, with research forecasting that by 2050, the country will manufacture 2.3 trillion bricks per year [69]. Pakistan is the third-largest brick producer, manufacturing around 59 billion bricks with approximately 12,000 brick kilns [70].

The sanitaryware sector has an important economic role as well. The global market of this sector is estimated to reach $59.17 billion by 2022, with a CAGR of around 7.8% during the period entailing 2018–2022 [71]. Again, the world's largest manufacturer is China, with approximately 30% of the total global production. Within the EU, more than 2.6 million sanitaryware pieces were produced, and these registered a turnover of € 296 million in 2017 [53]. Regarding ceramics tableware, China dominates the market with an export value of around $375 million or 21% of the world export value [72]. Meanwhile, the EU-15 is the most important manufacturer of refractories, with a total production of 4.6 million tonnes, corresponding to €3300 million and employing over 18,000 people [5].

3. Research design and conceptual approach

To investigate the decarbonization of ceramics, we utilized a systematic searching protocol with a critical review approach and the guiding conceptual view of sociotechnical systems [34,35].

3.1. Critical and systematic review approach

We classify our review as systematic and critical because a "critical review" seeks to demonstrate that a research team has broadly scoured the literature and critically assessed its quality [73]. It goes beyond just reviewing the literature to interpreting it and making evaluative statements on the possible research gaps and quality of evidence [35]. To do so, it presents, analyses, and synthesizes a variety of material from various sources. A critical review offers the possibility to "take stock" and assess value across multiple bodies of evidence associated with a particular topic or research question. It offers both a "launch pad" for conceptual novelty and an empirical testing ground to judge the strength of evidence.

Assuming that a weakness of critical reviews is that they do not always prove the systematic nature of more rigorous approaches to

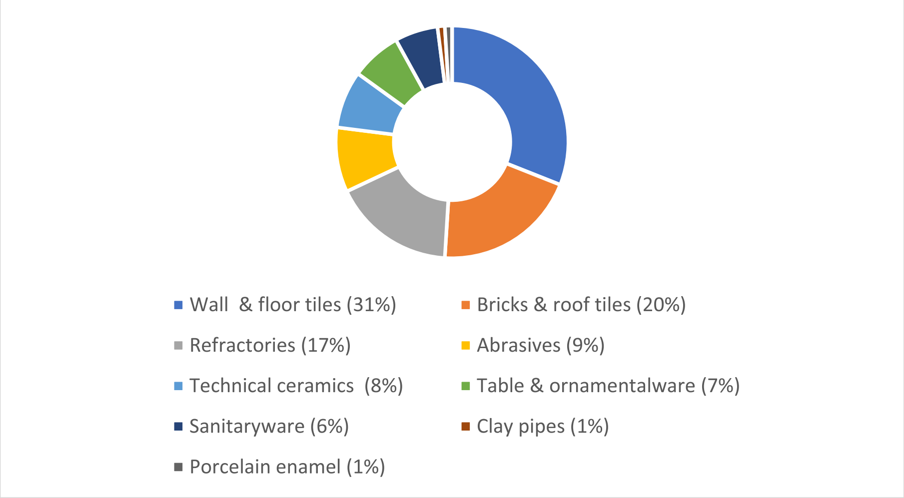


Fig. 2. Production value of the ceramics industry in the EU. Source: authors. Compiled from [55].

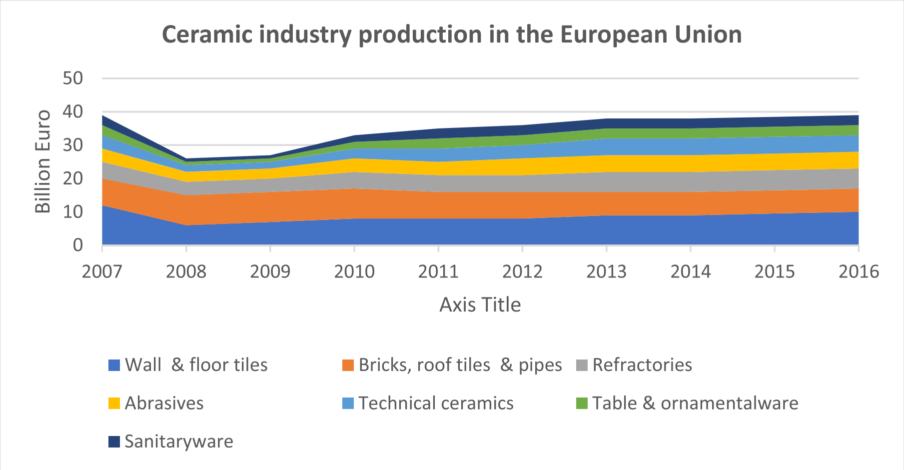


Fig. 3. Ceramic industry production in the European Union (in billion Euros). Source: authors. Compiled from [55].

reviewing, we also made our review "systematic" [74,75]. Specifically, this technique provides the following benefits.

- It avoids opportunistic evidence,
- A focused investigation,
- Allows replicability through documented study inclusion,
- It discriminates between sound and unsound studies, therefore, assessment of methodological quality and,
- It increases transparency, which decreases subjectivity and bias in results.

Furthermore, systematic reviews minimize unintentional bias (excessive self-citations or those of friends and colleagues, e.g., "citation clubs") and encourage diversity. For these reasons, a number of studies have called for greater use of systematic reviews in the domains of environment and energy, climate change and energy social science [76–78].

3.2. Searching protocol and analytical parameters

To guide our critical and systematic review, we used three distinct classes of search terms, as shown in Fig. 4. We executed each permutation of these search terms across 12 separate databases or repositories, resulting in 2592 search strings. We decided to employ this approach since we did not want to leave space to miss any important articles. In turn, we decided to systematically search in what we considered the most important databases to include all relevant studies. Entering these searches with these strings allowed us to capture the most pertinent state-of-the-art research related to our topic. In this space, we also acknowledge that although we did not include Web of Science and Scopus as part of our databases, we encourage researchers to include them in future research since these are also prominent databases with quality-controlled journals.

Table 5 presents our results. While our general searches delivered more than 2.7 million possibly relevant documents, this number dropped to a final sample of 673 pertinent studies. After screening them for

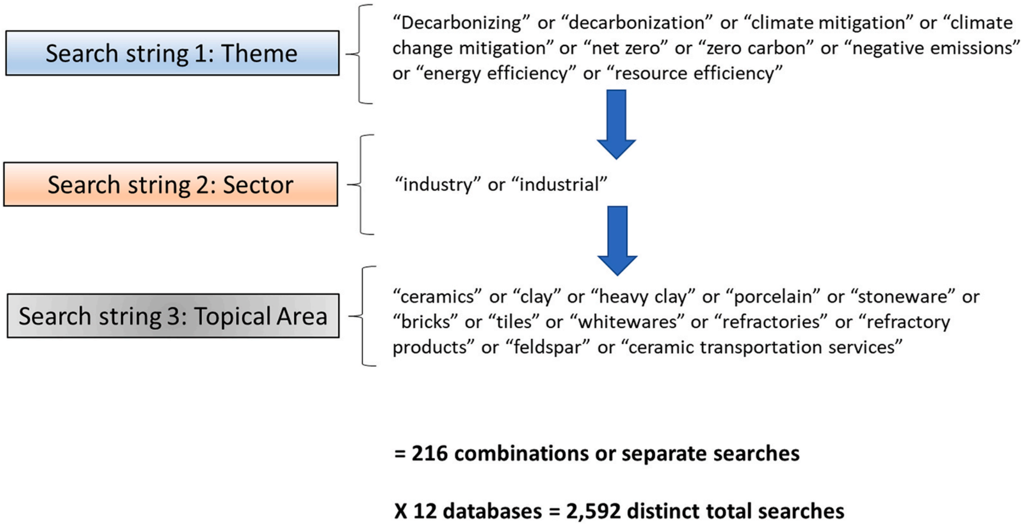


Fig. 4. Summary of critical and systematic review search terms and parameters. Source: authors.

Table 5
Summary of critical and systematic review search results and final documents. Source: authors.

Database	Main topical area of database	Initial search results	Deemed relevant after screening titles, keywords and abstracts	Deemed relevant after scanning full study	Number of duplications	Total
ScienceDirect	General science, energy studies, geography, business studies	40,266	281	178	–	178
JSTOR	Social science	7483	14	8	0	8
Project Muse	Social science	4872	21	3	0	3
Hein Online	Law and legal studies	20,471	32	9	0	9
PubMed	Medicine and life sciences	15	7	7	3	4
SpringerLink	General science, business and area studies	30,161	44	28	1	27
Taylor & Francis Online	General science	3662	28	20	1	19
Wiley Blackwell (Wiley Online Library)	General science, area studies	7553	31	16	0	16
Sage Journals	General science, area studies	986	17	8	0	8
National Academies Publications (nap.edu)	General science	1,090,798	12	4	0	4
Targeted internet searches	White papers, reports, grey literature (e.g., International Energy Agency, International Renewable Energy Agency, World Bank, UN agencies, and the online OECD library)	1,572,771	98	69	18	51
Google scholar	General science	225, 448	88	74	34	40
Total		2,779,038	673	424	57	367

relevance (they had to address the topic of climate change mitigation and/or decarbonization), originality (we adjusted the results to eliminate duplicates), and recency (documents had to be published from 2000 onward), this number fell to 367 studies. We reference most of these studies throughout the review.

3.3. The analytical frame of sociotechnical systems

To help guide and structure our results from this body of 367 documents, we employed the conceptual approach or analytical frame of sociotechnical systems [79,80]. As Fig. 5 displays, this conceptual approach considers the ceramics industry as far more than just a collection of physical products or objects such as bricks, tiles or whitewares. Rather, this approach views the entire set of social and technical systems involved in making, distributing, and using ceramics. Therefore, this approach includes not only the instruments used to manufacture ceramics and how products are shipped to stores, but also entails issues pertaining to local regulations and ceramics waste. Fig. 5 organizes the ceramics industry sociotechnical system to include resource extraction, policy frameworks, the intersection of social organizations, capabilities of local infrastructure systems, legislation, progress on science and technological developments, environmental impact and markets. The sociotechnical system for ceramics therefore incorporates dimensions such as, but not limited to, the construction industry, social wellbeing, health and medicine, energy efficiency and innovation.

Though not all documents in our model employed this frame of a sociotechnical system, we use it throughout the following sections to structure our results and conclusions.

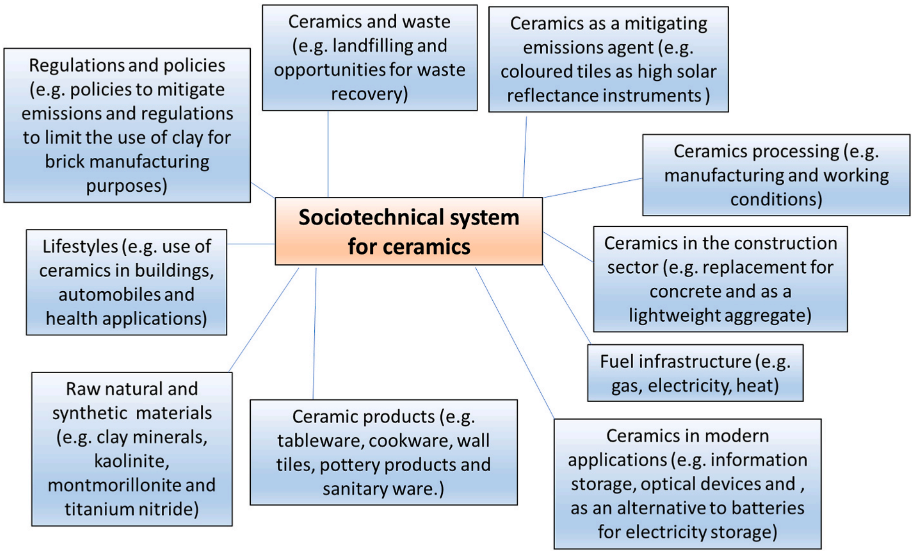


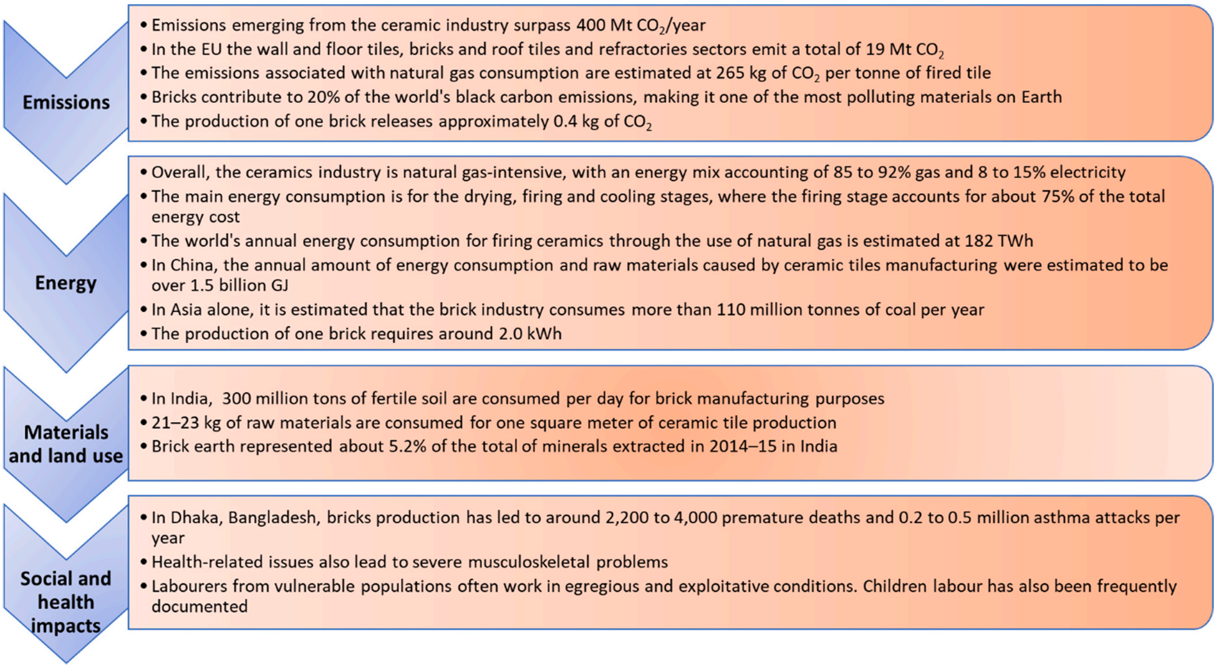
Fig. 5. Framing ceramics as a sociotechnical system. Source: authors.

4. Energy use, carbon emissions and environmental concerns associated with ceramics

This section focuses on the emissions and energy use profiles for ceramics, as well as other environmental concerns related to water, raw materials, and waste. Fig. 6 and Table 6 attempt to summarise these key concerns.

4.1. Estimations of energy use and greenhouse gas emissions

All ceramic sectors are considered energy-intensive because the energy consumed in producing them represents about 30% of the total production cost [38,60,81]. The IEA estimates that, worldwide, emissions emerging from the ceramic industry surpass 400 Mt CO_2/year from calcination of carbonates and energy end-use [82]. In the EU, the wall and floor tiles, bricks and roof tiles, and refractories sectors emit a total of 19 Mt CO_2 [1]. Of these emissions, 66% are due to fuel combustion,



Emissions

- Emissions emerging from the ceramic industry surpass 400 Mt CO_2/year
- In the EU the wall and floor tiles, bricks and roof tiles and refractories sectors emit a total of 19 Mt CO_2
- The emissions associated with natural gas consumption are estimated at 265 kg of CO_2 per tonne of fired tile
- Bricks contribute to 20% of the world's black carbon emissions, making it one of the most polluting materials on Earth
- The production of one brick releases approximately 0.4 kg of CO_2

Energy

- Overall, the ceramics industry is natural gas-intensive, with an energy mix accounting of 85 to 92% gas and 8 to 15% electricity
- The main energy consumption is for the drying, firing and cooling stages, where the firing stage accounts for about 75% of the total energy cost
- The world's annual energy consumption for firing ceramics through the use of natural gas is estimated at 182 TWh
- In China, the annual amount of energy consumption and raw materials caused by ceramic tiles manufacturing were estimated to be over 1.5 billion GJ
- In Asia alone, it is estimated that the brick industry consumes more than 110 million tonnes of coal per year
- The production of one brick requires around 2.0 kWh

Materials and land use

- In India, 300 million tons of fertile soil are consumed per day for brick manufacturing purposes
- 21–23 kg of raw materials are consumed for one square meter of ceramic tile production
- Brick earth represented about 5.2% of the total of minerals extracted in 2014–15 in India

Social and health impacts

- In Dhaka, Bangladesh, bricks production has led to around 2,200 to 4,000 premature deaths and 0.2 to 0.5 million asthma attacks per year
- Health-related issues also lead to severe musculoskeletal problems
- Labourers from vulnerable populations often work in egregious and exploitative conditions. Children labour has also been frequently documented

Fig. 6. Extracts of key information from the ceramics industry. Source: authors.

Table 6
Extracts of key information of the ceramics industry regarding emissions and energy use. Source: authors.

Sector	Emissions	Energy use
Ceramics (from an overall perspective)	Worldwide: 400 Mt CO_2/year European Union: 19 Mt CO_2/year	The world's annual energy end-use for firing ceramics through natural gas is estimated at 182 TWh.
Wall and floor tiles	Manufacturing one fire tile emits 265 kg CO_2/t	Ceramic floor tiles require between 940 and 1670 kWh per ton of product. Manufacturing one kg of the final product of ceramic floor and wall tile requires approximately 1.5 kWh.
Bricks and roof tiles	The production of one brick releases approximately 0.4 kg of CO_2	Bricks and roof tiles consume, on average, 380 and 1250 kWh per ton of product Every brick of 3 kg weight consumes between 110 and 700 g of coal

while electricity and process emissions represent 18% and 16% of total emissions, respectively [1].

Emissions from the ceramics industry depend on two factors, the chemical transformation from raw materials employed during the manufacturing process and fossil fuels used [58]. Direct process CO_2 emissions can also emerge from the combustion of the organic matter present in the raw materials or organic admixtures in the manufacturing process [50]. There are also indirect CO_2 emissions, which stem from electricity and raw material preparations [58]. In addition to CO_2 emissions, chlorine, fluorine, sulphur, and nitrogen oxides emissions are released in the manufacturing processes. However, emissions from the ceramic industry have been mitigated in the past years. For instance, fluorine emissions have been reduced by more than 80% in the last decades [83]. Similarly, in industrialized countries, thermal and CO_2 emissions have decreased due to the use of natural gas and by adopting novel technologies (e.g., cogeneration systems, single firing, and roller kilns) [84].

Overall, the ceramics industry is natural gas-intensive, with an energy mix accounting of 85–92% gas and 8–15% electricity [1,85]. The intensive use of gas is well illustrated in Turkey, where this industry accounted for over 12% of the total natural gas consumption in the manufacturing sector [37]. Brazil is yet another relevant example. There, in 2014, the ceramics industry represented around 5.8% of all energy consumed in the Brazilian industrial sector, which accounts for 5.7 Mt, with most of is the energy produced from renewable sources and natural gas [66]. Gas is fundamentally used to reach high-firing temperatures ranging between 800 °C and 1850 °C. However, refractory and technical ceramics manufacturers employ electric arcs for higher firing temperatures to reach 2750 °C [86]. During the manufacturing process, the main energy end-use is for the drying, firing and cooling stages. The firing stage accounts for about 75% of the total energy cost [47] and more than 50% of all required energy during the manufacturing process [38]. One study indicates that the world's annual energy end-use for firing ceramics through the use of natural gas is estimated at 182 TWh [87], with the firing process generating around 265 kg CO_2/t of fired tile [88]. Another study suggests that more than 80% of GHG emissions occur in the firing and drying stages [89].

During the manufacturing process of ceramics, plants demand significant amounts of heat for drying and to remove the water from the material. In most cases, manufacturers rely on fossil fuels to evaporate the water [90]. For instance, the energy end-use for dry grinding is approximately 60 kWh, accounting for up to 20% of the total thermal energy end-use during the manufacturing process of dry clay types [5]. Therefore, this process is complex and expensive and demands strict control of process variables to guarantee the quality of the final product [91]. Although drying systems have evolved with the deployment of novel technologies, energy end-use at this stage certainly remains high [92].

The energy intensity of the ceramics industry is well illustrated in its energy end-use and carbon footprint. Manrique et al. indicate that clay and ceramic floor tiles require 940 kWh per ton, while ceramics for electrical use require between 5000 and 5830 kWh per ton and bricks and roof tiles consume, on average, 380 and 1250 kWh per ton of product [64]. Quinteiro and team indicated that the carbon footprint of an earthenware ceramic piece weighing 0.417 kg was 1.22 kg CO_2e, and 90% of the total GHG emissions resulted from energy end-use [93].

Most studies do not take a holistic approach that covers all of the ceramics industry or its applications. Instead, many studies in the literature focus on a narrower range of either the tiles sector or the bricks sector.

For example, *wall and floor tiles* are among the most popular materials in building construction applications. However, these materials cause damaging environmental impacts through their lifecycles due to the high consumption of resources, including energy and water, and the issues associated with noise and waste [3]. CO_2 emissions from ceramic tiles are divided into two categories, combustion and process emissions. The first relates to the emissions resulting from the exothermic combustion reaction between the fuel and the oxidizer. The latter is associated with the emissions emerging from the decomposition of the carbonates present in the raw materials in the firing stage [85]. During the tiles manufacturing process, thermal energy is required during three phases: drying the freshly formed tile bodies, tile firing, and ceramic slurries [94]. Fig. 7, below, breaks down thermal energy end-use in the manufacturing process.

Producing ceramic tiles require large quantities of natural gas. The emissions associated with natural gas consumption are estimated at 265 kg of CO_2 per tonne [47]. These emissions represent around 90% of all CO_2 emissions during the tile manufacturing process. In contrast, the emissions from the decomposition in the firing of the magnesium carbonates and/or calcium in tile bodies are estimated at about 10% [88]. Other studies have indicated that it will require 1670 kWh of energy to produce one tonne of ceramic tiles. The same research suggests that €1.5 billion are spent each year in Italy only for natural gas requirements in the ceramic sector [96]. Similarly, Ros-Dosdá et al. estimate that around 30–40 kWh of energy and 21–23 kg of raw materials are consumed for

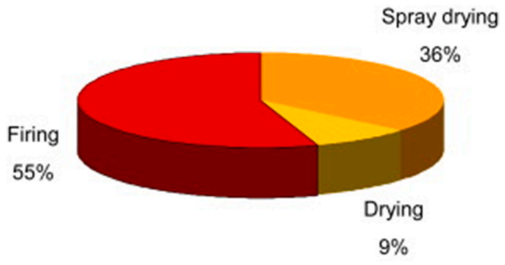


Fig. 7. Breakdown of thermal energy end-use for the ceramic tile manufacturing process. Source [95].

one square meter of ceramic tile production [97]. Other studies have revealed that to get one kg of the final product of ceramic floor and wall tile, approximately 1.58 kWh of energy is needed. This, in turn, corresponds to about 1.90 kWh of primary energy [49]. On a similar vein, Confindustria Ceramica states that the Italian refractory materials and ceramic tile sectors are characterized by a yearly consumption of methane gas equal to 1.5 billion m^3 to meet an electricity demand of 1800 GWh/y [98]. In China, the annual amount of energy end-use and raw materials caused by ceramic tiles manufacturing were estimated to be over 1.5 billion GJ and 0.2 billion tons, respectively. Meanwhile, the carbon emissions in China emerging from this sector were estimated at 0.15 billion tons [99].

Other studies have explored the lifecycle assessment of ceramic tiles. The researchers, in this case, considered all stages, from mining raw materials and transport to tiles management as construction and demolition waste at the end of their lifecycle. Their results indicate larger environmental impacts emerge from the tile manufacturing process, followed by clay atomisation and product transportation and distribution [100,101]. An explanation for this may be found in a thermodynamic analysis that demonstrates that kiln efficiency is low because only 5–20% of the energy input is used to fire the tiles. The rest is lost through the cooling stacks (30–35%), flue gas stacks (20–25%), the kiln walls and vault (10–15%), and through the fired tiles (5–10%) [95,102]. Similarly, Ferrer et al. show that single-deck roller kilns worldwide showed low energy performance where over 61% of the total energy input in the kiln was lost through the gas exhaust stacks [59].

Similarly, *conventional bricks* are often produced from non-renewable or cementing materials at high firing temperatures [103]. Bricks are an important source of GHG emissions and air pollution globally [104]. Worldwide, 1.5 trillion or 3,750,000,000 m^3 bricks are produced every year by 300,000 formal brick kilns [105]. From these, close to 1.3 trillion bricks (or 87%) are manufactured in developing countries [106]. China manufactures around 700–800 billion bricks per year, while Pakistan, India, Bangladesh and Vietnam manufacture over 260 billion bricks per year, catering to approximately 75% of the global demand for fired bricks [107]. In Bangladesh alone, 22.7 billion bricks are produced per year. The majority are made with coal and firewood heated kilns, which emit 9.8 Mt of GHG emissions annually [108]. In Asia alone, research estimated that the brick industry consumes more than 110 Mt of coal per year [109]. In this context, one study calculates that the radiative forcing generated by the black carbon and GHG emitted by brick kilns in South Asia is equivalent to the radiative forcing of the whole U.S. passenger car fleet [110].

The manufacturing process entails firing the bricks to achieve strength. This process consumes about 24 Mt of coal a year [111], contributing to 20% of the world's black carbon emissions, making it one of the most polluting materials on Earth [112]. It is worth noting that energy end-use varies among different kilns. However, research indicates that between 11 and 70 tons of coal are needed to fire 100,000 bricks. In other words, every brick of 3 kg weight consumes between 110 and 700 g of coal [113]. Such differences extend to the embodied energy of bricks varying from 611 kWh per tonne to 1641 kWh per tonne [114]. For instance, in the UK, manufacturing bricks emit, on average, 234 kg CO2e/tonne with a typical energy end-use reported at 706 kWh/ton of brick [115]. In contrast, on average, the production of one brick requires around 2.0 kWh of energy and releases approximately 0.4 kg of CO_2 [116,117]. Contaminants are not limited to CO_2 only but also include, nitrogen dioxide (NO_2), nitrogen oxide (NO), total organic compounds (TOC) (including ethane, methane, fluorides, volatile organic compounds [VOCs], particulate matter (PM), carbon monoxide (CO), sulphur dioxide (SO_2), metals, tropospheric ozone (O_3), as well as hazardous air pollutants (HAPs) [104,118]. Such contaminants are linked to countless cases of severe health problems in humans and animals, as well as damage to agriculture, land cover, vegetation and biodiversity [119,120].

An important factor influencing energy end-use in brick production is the kiln type, of which there are two: intermittent and continuous. The first is fired in batches. In this process, the fire is allowed to die out, and it is acceptable to let the bricks cool after the firing process. In continuous kilns, the fire is continuously burning, and bricks are heated, fired, and cooled at the same time in different parts of the kiln. Due to their heat recovery characteristics, continuous kilns are more energy-efficient [121]. Others indicate that to improve the efficiency during the brick-manufacturing process is necessary to improve fuel feeding practices, provide periodic maintenance of the kiln walls, reduce leakages, deliver proper fuel preparation, enhance supervision of the firing operation, adequate drying of the bricks as well as reducing the mass of each unit by increasing its perforations [122].

Although natural clay—a key material for producing bricks—is abundant in many countries, an increasing and continued demand for clay bricks are triggering its shortage in many parts of the world. In India, for instance, 300 Mt of fertile soil are consumed per day for brick manufacturing purposes [123]. In addition, brick manufacturing is having other environmental impacts such as affecting organic soils for agricultural purposes and demanding large volumes of water [124–127]. For instance, brick earth represented about 5.2% of total minerals extracted in 2014–15 in India [128]. This situation has led some countries, like China, to limit the use of clay for brick manufacturing purposes and instead, they encourage the substitution of clay with industrial waste products such as fly ash for bricks production [129].

There are associated health costs as well since this sector has high death rates. For instance, in Dhaka, Bangladesh, bricks production has led to around 2200 to 4000 premature deaths and 0.2 to 0.5 million asthma attacks per year [130]. Health impacts from brick-making chiefly originate from breathing in smoke and hours of physically demanding work outdoors, in tandem with extreme weather causing heatstroke and other illnesses such as respiratory infections and pneumonia [131,132]. Other health-related issues are associated with the posture that kiln workers adopt for prolonged periods, which commonly lead to severe musculoskeletal problems [133]. Issues with brick manufacturing are not limited to health but expand to social issues. Labourers from the most vulnerable populations often work in egregious and exploitative conditions, considered by some as modern-day slavery with child labour frequently documented [133–137].

4.2. *Water use in the ceramics industry*

Water is a key material in ceramic manufacturing; however, the amount used varies among sectors and processes [58]. On average, water consumption per square metre of manufactured tiles is about 20 L [85], where milling consumes approximately 60% of the water employed [94]. However, it requires more water to manufacture a roof tile since one unit requires 10.496 L, consisting of 10.48 L blue water and 0.016 L greywater [138]. Process wastewater is generated primarily when clay materials are suspended and flushed out in running water during the production process. Process wastewater mostly contains inorganic materials, mineral components (insoluble particulate matter), small quantities of numerous organic materials and heavy metals [5]. The water containing salts and inorganic solid suspension particles is not only contaminated, but it is also not easily treatable for reuse since salt concentrations increase after every cycle [139]. In turn, water degrades progressively after each production cycle. Fig. 8, displays the water assessment for a traditional sanitaryware factory.

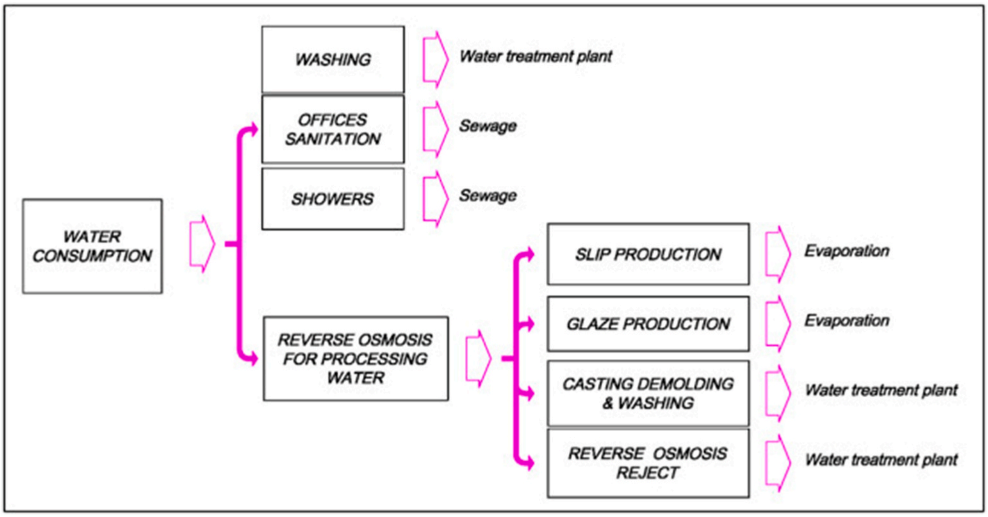


Fig. 8. Water assessment for a typical sanitaryware factory. Source [139].

4.3. Extraction of raw materials

Other issues emerge from the extraction of raw materials. For instance, Lithium's physical and chemical properties turned it into a key material for the manufacturing industries (e.g., ceramics, metallurgy and lubricants) and renewable energy technologies [140,141]. From these applications, lithium-ion batteries account for the primary global end-use, followed by ceramics. However, before 2015, as Fig. 9 illustrates, ceramics and glass were the primary industries utilising Lithium ore [142]. This situation has led to an increment in Lithium prices and estimated shortages [143]. Ziemann and colleagues suggest recycling lithium-containing products (e.g., ceramics, aluminium products, and alloy) to mitigate this situation. For instance, they claim that ceramics can be crushed and refined as a packed bed in road construction [144]. However, others reject this idea since they state that Lithium used in ceramic glazing is not recoverable, as the glazing often wears out over time, and broken ceramics are not disposed of in a way that enables cost-effective Lithium recovery [141].

Other studies highlight how the intense ceramics production of Spain and Italy has led to severe repercussions on demand for raw materials.

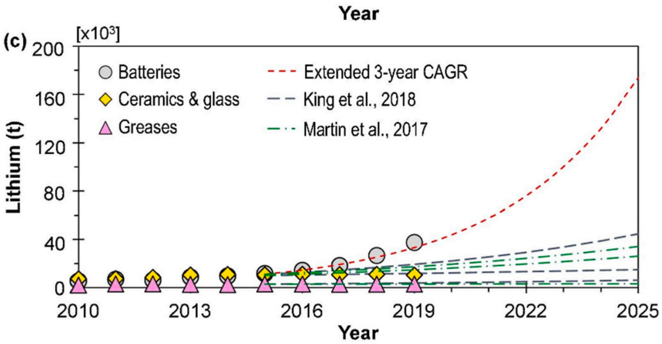


Fig. 9. Global lithium consumption from 2010 to 2019. Source [142].

Particularly sodic feldspar (mostly from Turkey) and high plasticity clays (mostly from Ukraine). The authors warn that alleviating the supply risk is urgently needed since reserves for sodic feldspars and highly plastic ball clay are limited with no viable economic alternatives [145]. Regarding feldspathic raw materials, more than 575 Mt have been globally mined since 1971, largely to produce ceramic and glass materials. Currently, the production of feldspathic materials is close to 29 Mt per year [146]. Dondi warns that regardless feldspars are the main constituents of the Earth's crust, the increasing demand ought to raise concerns given the market flux of the ceramic industry [146].

Cobalt is another material whose availability has been affected by the ceramics industry. Particularly in China, with research indicating that cobalt demand will surpass its overall domestic reserve base by 2022 [147]. Others have focused on how refractory production is vastly dependant on high-quality raw materials. Researchers have identified that many of these resources are becoming increasingly scarce, with prices rising and only a small fraction of them recycled in refractories [54,148]. This situation has led Hertwich et al. to argue that the availability of some construction materials (e.g., bricks and tiles) are at risk in some regions even when accounting for secondary materials [149].

How this situation will be handled in the future remains daunting. Particularly, for the case of lithium, since the demand for this material will continue to increase due to its many applications, especially for mobile phone batteries and electric vehicle batteries [143]. In addition, others warn about resource nationalism and monopolistic behaviors since Argentina, Bolivia, and Chile control more than 40% of the world's resources [150,151]. Therefore, it would be problematic for countries like the USA and China to highly depend on these countries for political reasons [143]. In these circumstances, Tabelin et al. suggest three means to remediate this issue. First, they call to assess further the potential of unconventional lithium resources such as desalination brines, geothermal brines, seawater, and solid waste streams from coal and salt mines. Second, they suggest exploring efficient emerging purification technologies such as layered ion-exchange membranes, double hydroxides, Li-ion sieves, solvent extraction, selective electrochemical-based and precipitation methods capable of extracting Li^+ in solutions even at high salinity and low concentrations. Third, they suggest recovering lithium from alternative recycling techniques [142].

4.4. Ceramics waste and recycling

Ceramic waste can be categorized into two groups, non-hazardous and hazardous waste [50]. Typically, around 30% of the materials used in the ceramic industry are dumped in landfills [152]. For instance, porcelain tiles generate large quantities of waste that require special landfill treatment, generating substantial environmental and financial costs [153].

In the EU, 20% of used refractories are recycled for refractory purposes, 27% are reused in non-refractory applications, 35% are dissolved during use, and the remaining 18% are considered unusable waste [1]. It may be surprising that large amounts of ceramic waste go into landfills when they possess rich mineralogical variability [154]. Moreover, ceramics are cost-effective sources of Si and Al compounds, and both can be used as inexpensive raw materials for synthesizing high-value catalysts for biodiesel production [155,156].

Ceramic waste is generated not only through manufacturing but also by the construction sector. Regarding the latter, significant amounts of ceramic waste are generated yearly from demolition practices. Often, ceramics are disposed of in landfills, leading to severe environmental issues due to the occupation of large spaces of land and dust pollution [157]. Ceramic waste from the construction sector comes from discarded roof tiles and bricks, stonewares, tiles and vaults. Ibrahim and Maslehuddin estimate that around 50% of demolition and construction waste are ceramics [158].

5. Options for decarbonizing the ceramics industry

Continuing with our sociotechnical approach, this section describes 19 different technological innovations and managerial practices that could help to decarbonise the ceramics industry, with an overview displayed in Fig. 10. Later, in Subsection 5.5, we present 32 emerging technologies that can help transition the ceramic industry towards a low-carbon future.

As already summarized in detail in Section 4, energy costs are a major concern for the ceramics industry, representing around 30% of production costs [1]. For several decades, the industry has strived to improve its efficiency. For instance, since 1990, the European Ceramic Tile Industry has adopted novel technologies and implemented energy-saving actions to mitigate CO_2 emissions and reduce energy end-use [51]. The approaches implemented at ceramic facilities are improving energy management, fuel switching, raw materials formulations for more efficient firing, and process optimization [94]. We discuss these options throughout this section.

5.1. Options for extraction of raw materials and alternatives to replace ceramics

As discussed in the following sections, most measures to reduce energy use and emissions in the ceramic industry are related to the drying and firing processes. However, another sustainable pathway is raw materials optimization. This approach delivers energy savings through two means: new materials and waste recovery. Regarding the first, ceramic fibres and low thermal mass materials have reduced energy end-use by using novel ceramic formulas that require less heat during the firing process. Such an approach has led to up to 20% in energy savings. Meanwhile, material or waste recovery enables energy savings during the raw material preparation stage [62,159].

For instance, Mendoza et al. identified that granite slabs could almost replace feldspar and sand inputs and substitute for a percentage of clay mineral requirements. They conclude that granite slabs could lead to large energy and water savings in ceramic production with similar or superior technical properties to traditional products [160]. Schabbach et al. noted that using large amounts of post-treated bottom ash could be tailored to fully replace feldspar and quartz sand, leading to a number of environmental benefits. These benefits include minimising the storage of bottom ash and reducing natural resources consumption, avoiding the pre-washing process, and reducing the temperature for firing ceramics [161]. Lao and colleagues explored the effects of feldspar and sintering temperature on the *in-situ* synthesis of SiC whiskers. Their results revealed that cleanliness and safety related to the *in-situ* method delivers energy savings between 1240 and 1300 kWh when producing one ton of

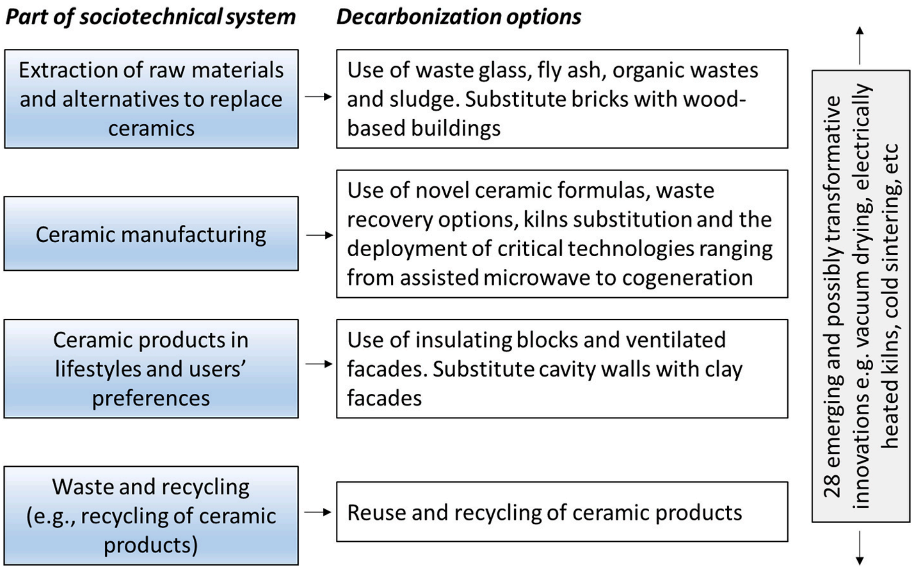


Fig. 10. Sociotechnical options for decarbonizing the ceramics system. Source: authors.

SiC-containing vitreous ceramics [162]. Others have noted that the utilisation of boron wastes for ceramics production operates as a fluxing agent that does not increase the thermal expansion coefficient of ceramic products. Therefore, using this material can expedite the vitrification process, produce ceramics at lower temperatures, reduce environmental impacts, and promote a zero-waste economy by reducing raw material costs [163]. Also, by using boron derivative waste, Koroglu and Ayas synthesized monticellite based ceramic powder at 800 °C for 4h reducing energy end-use during the heat-treatment stage [20].

Kim and team explored the use of LCD waste glass as a feldspar substitute for porcelain sanitaryware. Their results show that LCD waste glass (WG) allows the sanitaryware sector to save raw materials while achieving energy savings [164]. Similarly, through an innovative approach, Liu and Li combined LCD WG with calcium fluoride and wastewater to manufacture glass-ceramics. Their results indicate that this mixture could operate as a replacement for quartz sand [165]. Others have used WG as a ceramic flux to decrease the temperature during ceramic firing. The study reports that WG reduced by 100 °C the firing temperature for producing porcelain, cut the time of sanitaryware firing, and expedited the densification process [166]. Bohn et al. showed that ceramic paver manufactured with WG contributes to eliminating WG and results in a more energy-efficient ceramic firing process due to the fluxing enhancement of waste glass [167]. Andreola et al. reported that scrap glass reduces the kiln temperature from 1250° to 1000 °C for ceramics manufacturing [168]. WG has also been used as a substitute for feldspar fluxes to produce glass-ceramic stoneware. The studies report that WG utilisation reduces firing temperatures and provides more energy-efficient manufacturing processes [169,170].

Others have investigated the use of fly ash as a low-cost material for ceramics production. The studies have revealed that fly ash can be incorporated into ceramics pastes with little treatment. Furthermore, the use of fly ash as a partial clay replacement reduces the consumption of natural resources [171,172]. Kizinievič et al. studied the application of centrifugation waste of mineral wool melt in ceramic products. Their study revealed that this approach lowers drying and firing shrinkage and increases compressive strength and water absorption. They conclude that centrifugation waste of mineral wool can be employed to produce various ceramic products [173]. Sludge can also be used as a replacement for clay to manufacture high-quality ceramic products [174]. Another innovative approach was explored by Handoko et al. when they employed Automotive Shredder Residue to manufacture titanium-based ceramics. Their study shows that this material leads to environmental benefits related to landfills reduction, and manufacturers can be less dependent on conventional raw materials [175].

Others have documented that the ceramic industry is well suited for using organic waste [176,177]. For instance, Delaqua et al. explored the application of Salvinia auriculata Aublet microphyte biomass in red ceramics. Their study indicates that biomass presents a suitable composition to be used in ceramic materials. Using this approach can lead to energy savings of up to 5% in the manufacturing process [154]. Finally, Simon and colleagues explored the effects of inerting zinc ions from a pine sawdust biomass containing heavy metals in applications in burnt ceramic matrices. Their study indicates that this mix results in an appropriate ceramic material used in construction [178].

5.1.1. *Alternative materials and options for more sustainable tiles*

The main raw materials for the ceramic tile sector are feldspar, quartz and clay. However, the flexibility of the tile manufacturing process allows for several types of wastes to be incorporated in the production of ceramic wall and floor tiles [179]. For instance, LIFE CLAYGLASS documented that manufacturing ceramic tiles using recycled glass (e.g. from end-of-use vehicles and electrical waste from electronic equipment) as a flux material delivers environmental benefits. The study demonstrated that by adding 10% of glass into the mixture, the firing temperatures reduced by about 100 °C, production costs fell by 3–7.5%, and CO_2 emissions decreased by 13–19% [180]. Similarly, Rambaldi et al. has recently shown that combining scrap packaging glass in the production of ceramic tiles reduces the firing temperatures by 200 °C while maintaining high technical performances [181]. The inclusion of glass in the manufacturing of ceramic tiles was also explored by the Indonesian National Council on Climate Change. The report concludes that the utilisation of WG reduces the energy associated with raw material preparation and acquisition while providing large energy efficiency benefits in the manufacturing process [182].

Other researchers have documented that applying ceramic powder waste saves raw materials and reduces the temperatures in the production of wall and floor tiles. The researchers showed that utilising this waste lowers the energy required during the firing process by 100 °C [179]. To reduce energy end-use and mitigate pollutant emissions emerging from ceramic tile production, sugarcane bagasse ash can be employed for ceramic floor tile production [183]. The same outcome is achieved by using furnace slag [184]. Reusing brick and roof tile wastes is another alternative to produce eco-friendly porcelain stoneware tiles. The application of these materials helps reduce landfilling, saves raw materials, and mitigates the negative environmental impacts related to GHGs emitted by machines used in the mining industry [52].

5.1.2. *Alternative materials and options for more sustainable bricks*

Typically, bricks are manufactured using non-renewable resources, including soil, which is fired at high temperatures. Since the construction of buildings continues to increase [185], the demand for bricks has augmented, causing a significant use of raw materials [186]. Due to the scarce availability of suitable soil, there is a pressing need for alternative materials to manufacture bricks through an energy-efficient process [187]. Therefore, finding sustainable options for brick production is an effective solution to help overcome the scarcity of natural resources and reduce the degradation of forests and crops while helping to manage waste and mitigate emissions [188]. The production of more sustainable bricks also leads to social benefits due to reductions in PM2.5 emissions. For instance, the conversion to cleaner brick kiln technologies in Greater Dhaka could save between 800 and 1200 lives each year [189].

One material that has been amply explored to develop more sustainable bricks is WG. Kazmi and team indicate that incorporating up to 25% of WG sludge increased by 2% the brick's bulk density while decreasing porosity. The study concludes that bricks made with this material can be used in masonry construction while addressing landfill issues associated with WG [190]. Phonphuak et al. documented that bricks with 10% WG in their mixture could be fired at 900 °C [191]. Similarly, Demir showed that incorporating 10% WG reduced the firing temperature to 950 °C and increased the brick's strength [192]. Another study notes that replacing clay with 25% WG reduced the firing temperature to 850 °C, and bricks showed a 37% improvement in compressive strength [193]. Others have reported that incorporating WG to produce bricks improves structural and durability properties while reducing manufacturing costs and saving raw materials [194,195].

Others have explored the application of marble waste in the production of burnt clay bricks. The utilisation of this material saves natural clay resources and mitigates environmental concerns related to waste and GHG emissions, paving the way towards more sustainable construction practices. For instance, Migliore et al. show that bricks incorporating 50% waste from marble quarries reduce up to 50% of GHG emissions compared to a 100% virgin brick (2.6 and 5.2 kg CO_2 eq./t, respectively) [196]. Others have noted that bricks mixed with waste marble sludge have improved their thermal conductivity [197]. Munir and team concluded that up to 15% of waste marble sludge results in the manufacture of more energy efficient burnt clay bricks. Therefore, offering environmental and health alternatives related to landfilling [188]. Another study shows that incorporating ceramic sludge into brick manufacturing improves clay bricks' durability, thermal performance, and strength [186]. Dos Reis explored the introduction of sludge resulting from construction and demolition waste into the preparation of fired bricks. Their results show that up to 70% of construction and demolition waste produced fired bricks with enhanced mechanical and physical properties [103]. Weng and colleagues documented that incorporating 20% sludge (from an industrial wastewater treatment plant) into the mixture to manufacture bricks not only improves their strength but decreases the firing temperatures [198]. Similarly, Limami and colleagues used wastewater sludge as a material additive to produce unfired lightweight earth bricks. Their results indicate over 30% gains in thermal properties while still reducing the energy demand during the manufacturing process [199].

The paper industry is a major contributor to global waste generation. However, waste from the paper industry could contribute to the production of more sustainable bricks. For instance, Kizinievič et al. reported that paper sludge additive reduces brick's thermal conductivity and density. Nevertheless, they also warn that it impairs brick mechanical properties [200]. Other studies have reported that paper sludge can be introduced in bricks production as natural additives, such as lightweight aggregates [200,201]. Another approach is taken by Mohajerani et al. They explored the effects of introducing cigarette butts into fired clay bricks. Their results indicate that introducing 5% by weight of cigarette butts leads to energy savings of up to 5% and could save 58% of energy during the firing process. Moreover, incorporating 1% cigarette butts into bricks manufacturing could recycle 48 Mt of cigarette butts each year [202].

Another material that effectively enhances the properties of burnt clay bricks is fly ash. For instance, research indicates that fly ash increases water absorption and porosity and makes bricks stronger and more durable [128,135,203]. Others have documented that fly ash could operate as a partial or complete replacement of quartz sand in building bricks [204]. In a similar vein, Chou et al. report that using up to 50% of fly ash produced superior bricks in terms of physical consistency, compressive strength, insulation capability, and colour to those produced commercially [205]. In fact, it is estimated that in India, around 20 billion ft^3 (0.566 billion m^3) of topsoil could be saved each year if all 140,000 red brick kilns in the country started using fly ash [206]. Teoh et al. investigated using waste engine oil and coal-fired ash in the production of roofing tiles. Their results indicate that this approach produces tiles at 0.4178 kgCO$_2$/kg and 35.2 kWh/kg, respectively. That is lower with respect to the traditional roofing tiles [207].

Taha et al. revealed that recuperating residual coal from coal mine waste rocks enhanced the quality of fired bricks. This residue increases bricks flexural strength while reducing the open porosity and water absorption. Their results show that integrating this material reduced GHG emissions by around 70% in the production of fired bricks [208]. Javed and colleagues explored another innovative method by incorporating lime-bentonite clay composite to manufacture bricks. The team reduced the cooling load and carbon footprint value by 31.91% compared to traditional burnt brick elements [209]. Goel and Kalamdhad employed water hyacinth as an additive to produce fired bricks. The application of this material leads to reductions in bulk density, firing temperatures and therefore mitigates GHG emissions [210].

Since the energy end-use required for firing a brick ranges between 0.694 and 4.13 kWh depending on the kiln and firing method used [202], others have attempted to reduce energy end-use by incorporating organic wastes in the manufacturing process. For instance, Barbieri investigated introducing agricultural biomass wastes including cherry seeds, grapes, and sawdust as a pore-forming agent and sugar cane ash as silica precursor in bricks. The team concluded that these residues should be incorporated in percentages of no more than 5% to decrease weight and shrinkage and increase porosity in bricks. Otherwise, negative effects such as decreased mechanical strength may occur [211]. Pérez-Villarejo demonstrated that pore-forming agents, olive wood, olive pruning and olive leaves could be added without pre-treatment to improve porosity and reduce production costs in ceramic bricks. This technique minimises clay use and enhances the value of waste since this product is currently disposed of in landfills [176]. Kizinievič et al. revealed that introducing 5–10% of oat husk or barley husk and middling into brick moulding leads to more sustainable manufacturing processes [212]. A similar result is obtained by applying bio-fuel by-product sugarcane bagasse ash as the main material for the production of bricks [213]. Kang et al. in a similar vein, documented that the use of slate tailings as a raw material for synthesis bricks through geopolymerization results in a thicker internal structure and higher compressive strength of the geopolymer brick products [214]. Other studies have noted that adding biosolids to the brick mix results in water and energy savings, mitigation of GHG emissions from stockpiles, and a significant reduction in the use of virgin soils [215,216]. Finally, Velasco documented that applying 11% of kindling from vine shoot reduces the thermal conductivity of fired clay bricks up to 62%. The authors argue that this method leads to energy and fuel savings and represents an option to pave the way towards a low-to-zero-carbon future since it is a biofuel [217].

Innovative research also points to the production of more sustainable bricks with the incorporation of new materials. For instance, Encos has manufactured the so-called 'carbon-negative bricks.' Their approach consists of recuperating vegetable-oil-based binders and aggregates. Encos claim that this technique consumes no water and carbon and generates zero waste [218]. Meanwhile, others include bacteria to grow bio-concrete bricks in a process comparable to coral formation [219]. Similarly, the University of Colorado, Boulder, uses bacteria to absorb CO$_2$ and create calcium carbonate that can be used to produce bricks that can self-repair their own cracks and drastically mitigate GHG emissions [220]. Construction companies are also developing eco--plastic bricks that perform better than concrete walls when used in emergency rooms [221]. Researchers from Washington University converted red bricks into energy storage units named 'supercapacitor' through nanofibers that penetrate inside bricks. Therefore, the polymer coating serves as an ion sponge, storing and conducting electricity [222]. Finally, thermally efficient bricks been three-dimensionally printed from upcycled waste plastic delivered up to 10 times better insulation compared to clay bricks [223].

5.1.3. Sustainable options to replace ceramics in the construction and buildings sectors

Alternatives for more sustainable ceramics are not limited to new materials and waste recovery. Options expand to more sustainable materials as substitutes in the construction industry. For instance, Frenette and colleagues compared building materials such as fibreglass, bricks, and extruded polystyrene with similar insulation levels. Their results documented that wood-based buildings represent the most sustainable option [224]. Other studies corroborate this point and show that wood-based buildings generally have fewer lifecycle emissions than concrete or brick buildings [225–227]. Yu et al. compared a typical brick–concrete building with a bamboo-structure building. Their findings show that the latter requires less energy and emits less CO$_2$ emissions while delivering the same functional requirements [228]. Finally, Nicoletti and colleagues demonstrated that ceramic tiles performed worse in environmental terms than marble tiles due to the raw materials utilized for glaze manufacturing [229].

Rosselló-Batle et al. [230], compared terrazzo[1] to stoneware, porcelain stoneware, granite and linoleum. They found that porcelain stoneware and stoneware possessed 65% greater embodied energy

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[1] Terrazzo is a material made of marble chippings, granite and glass mixed through a cement binder [324].

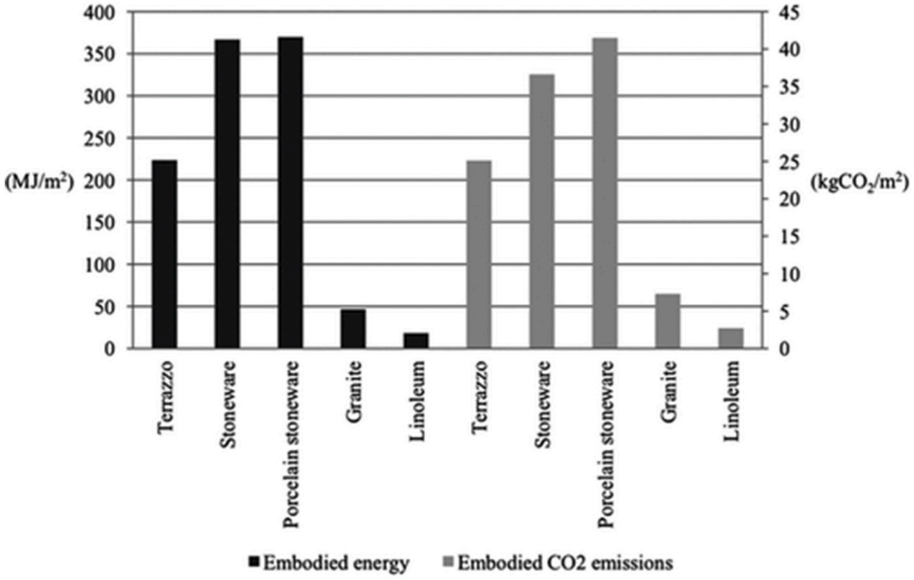

Fig. 11. Embodied energy and CO_2 emission values per square metre of useable surface for the floorings assessed. Source: [230].

values. In contrast, both granite and linoleum had embodied energy values that were 79% and 92% lower, respectively, as Fig. 11 displays. However, ceramic tiles represent a more sustainable option when compared to synthetic carpets, parquet, and natural stone. The authors argue that although ceramic tiles are energy-intensive materials, their long-life and low maintenance requirements make them a more environmental-friendly option. Therefore, their results accentuate the importance of analysing the entire lifecycle of materials [231].

5.2. *Sustainable options for ceramics manufacturing*

Since most measures to reduce emissions in the ceramic industry are related to the drying and firing processes. Below, we present a number of critical technologies and indicate how each could contribute to the decarbonization of the ceramics industry.

5.2.1. *Electrification*

Fossil fuels dominate the energy use in the ceramics industry and according to the Department for Business, Energy and Industrial Strategy (BEIS), migrating to a low-carbon electricity system is a key option for the industry's decarbonization [32]. Indeed, Madeddu et al. suggest that in the EU, 78% of the energy demand is electrifiable with technologies currently available, and 99% electrification can be accomplished with the technologies that are currently under development [232]. In this sense, research indicates that electrifying kilns or using low-carbon electricity could be an alternative to mitigate fuel emissions. Especially for large kilns producing roof tiles, bricks and wall and floor tiles [1]. However, others warn that this still represents a "huge challenge." Therefore, they suggest that the impact of using electric heating for firing ceramic products of large ceramic plants needs to be further investigated [233].

5.2.2. *Biofuels*

The European Ceramic Industry Association indicates that the most effective means to mitigate fuel emissions for high-temperature firing is to substitute natural gas with syngas or biogas from waste or biomass by retrofitting existing kilns [1]. The same study argues that syngas resulting from either biomass or organic waste holds the potential to substitute natural gas and mitigate emissions and reduce costs, especially in the brick and roof tile sectors. Similarly, Chan et al. note that biomethane could be a source to substitute heat. They argue that implementing this approach could cut emissions to a net-zero since biomethane's lifecycle would absorb the CO_2 emissions released during the production process [62]. Garres and team analysed innovative technologies in energy-intensive industries and efficiency gains in existing processes and concluded that the highest potential to deploy biomass is in the cement and ceramic production industries. Nevertheless, they warn that existing optimization of manufacturing processes are not enough to reach the 2050 emissions targets and that market readiness is not expected before 2030 [234]. Others report that biomass is a more suitable option than electrification due to the high-temperatures required in ceramic production. They argue that electrical heating cannot reach these temperatures, but gas flames can. Therefore, the possibility to use gas or biomethane from thermochemical gasification of solid biomass should be further considered when manufacturing ceramics [235,236].

5.2.3. *Heating and heat recovery*

For Manrique et al. the best technology to fire ceramic is a tunnel-kiln-with-wagons and a roller-tunnel-kiln with heat recovery technology incorporated [64]. This same vision is supported by Ibáñez-Flores et al., which revealed that incorporating a system with heat recovery from flue gas could lead to cost savings for the ceramic tiles industry of up to 30% [237]. Others support this claim and document that novel technologies with extensive use of heat recovered from the kiln can consume up to 60% less fuel energy per brick than typical units. The process includes the following steps: 1) preheating bricks in the phases of firing, 2) heat recovery to the dryer, and 3) preheating burner combustion air (instead of using ambient temperature air) [32]. Popov also utilized this approach and increased the production system's energy efficiency by 46–52% [238]. Finally, Mezquita et al. using a theoretical methodology, quantified savings from the energy recovery of the cooling gases in the exhaust chamber to be over 17% [239].

Waste heat recovery (WHR) was another relevant technique that our review identified since this technique reduces GHG emissions and energy costs while improving process energy efficiency [240]. Hussam et al. argue that WHR can deliver up to 100% of possible energy savings during the drying process. Their research documented a yearly energy production of over 115 MWh [47]. Agrafiotis et al. indicate that the recovery of waste heat from the cooling zones of a tunnel can be employed to preheat the combustion air in the kiln. Working from this angle, they reported energy savings of 28%, with investments recovered in two years [49]. For the sanitaryware sector, another study showed that 33% of the energy produced could be saved by recovering the waste heat from the kiln [139]. Oliveira and team report 78% of thermal energy savings and 36% savings in electric energy using a WHR approach [81].

Delpech et al. explored the performance and applications of a heat pipe heat exchanger (HPHE) to recover waste heat. They conclude that this approach can recover over 863 MWh/year of thermal energy from the ceramic kiln. This means that about 110,600 m3 of natural gas can be saved every year while mitigating nearly 164 tons of $CO_{2.}$ [241]. Another study, also using HPHE and recovering waste heat from the cooling zone, achieved reducing natural gas consumption from a drier by 4–5% [96]. Delpech et al. employed a HPHE system to recover waste heat from ceramic kilns. The system recovered the heat from the kiln and transported it to a water flow situated in the condenser. The results suggest that WHR recovery could be of up to 4 kW [38]. Jouhara et al. revealed that the HPHE installed in the plant recovered 876 MWh per year with a return on investments estimated in 16 months and economic savings evaluated at £30,000 per year [47].

Moreover, Peris et al. report that an organic Rankin cycle (ORC) is an efficient approach to recovering heat. Their results show that the recovered thermal power from the clean exhaust gas fluctuated from 128.19 kW to 179.87 kW. Meanwhile, the maximum electrical power production varied from 21 kW to 18.51 kW, with the utmost efficiency of the ORC system, reported at 12.47%. In total, this approach could save about 237 MWh of primary energy and mitigate around 31 tonnes of CO_2 emissions per year [242]. Similarly, another study indicates that an ORC for heat recovery could lead to energy savings of up to 2% [237].

A final technology discussed in terms of heating is microwaves. Employing microwaves has two main advantages. First, only the object is heated instead of the surrounding air; therefore, the chamber remains cool, and the energy to heat the drying chamber is saved [5,47]. The second advantage is that using microwaves for welding and joining ceramics has demonstrated to be less time-consuming than traditional heating technologies [38,229,243,244], with research indicating that this approach can expedite the drying process up to eight times [49]. Others have noted that this process not only reduces processing times but also improves the product's uniformity, purity, microstructure and quality while lowering emissions of harmful gases to the atmosphere [245–247]. In addition, this technique delivers significant reductions in energy end-use, which can be as high as 99% [248]. Other studies have reported that fuels savings range from 7 to 30 times [249] while others have documented reductions in energy end-use of 40% [250] and 50% [62] for what is normally an energy-intensive process.

In our review, we found a tension regarding the maturity of this technology. On one hand, Madeddu et al. suggest that microwave heating is already a mature technology with sufficient capacities for industrial applications to suffice energy demand for space heating, drying, cooling and steam generation [232]. On the other hand, Marsidi and Besier suggest that microwave heating requires a higher temperature than room temperature when exposed to a microwave field. Therefore, they argue that this technique should be a complementary technology only and should still be combined with traditional or electric heating [58]. Given that research indicates that the technology readiness level for microwave heating is 3 [251], we argue that further developments need to occur before its larger diffusion.

5.2.4. *Hydrogen*

Developing low-carbon hydrogen is important to the transition towards a low-carbon future [252]. In fact, low-carbon hydrogen can potentially substitute natural gas for certain industrial high-temperature 'direct firing' services [253,254]. For some, hydrogen even represents a cheaper and more sustainable heating fuel option compared to natural gas [255,256]. Relevant initiatives to use hydrogen in the ceramics industry are already being developed by Iberdrola and Porcelanosa. Specifically, they are working on low or zero-carbon hydrogen from electricity and water electrolysis (i.e., green hydrogen) project to evaluate and develop novel solutions such as high-efficiency heat pumps in dryers and using green hydrogen to achieve the high temperatures required in atomisers and hybrid ovens [257]. While such a project is promising, it is important to note that hydrogen has very different properties from natural gas and hence requires specialized burners for heating applications. Furthermore, onsite storage of hydrogen, which has very low volumetric energy density, can be a challenge. On the same vein, although some hydrogen applications are TRL 9 or above, it depends on the sector, the type of application, the type of fuel cell, etc. to successfully deploy this technology [258]. For these and other reasons, it is unclear whether hydrogen will become widely adopted for heating application in the ceramics and other industries.

5.2.5. *Cogeneration*

The drying systems in ceramic plants often utilize the combined heat and power production of technologies like gas turbines in a process known as cogeneration [259]. Such systems are useful due to the simultaneous demand of heat and electric power required during the ceramic manufacturing process [240,260]. In this way, energy efficiency is improved, emissions are mitigated, and manufacturers minimize fuel consumption while receiving economic benefits [261]. For instance, the use of cogeneration systems in the ceramic tile sector was explored by Caglayan and Caliskan. Their results revealed that cogeneration systems achieved 10–50% energy savings during the drying stage [260]. Gabaldon et al. showed that plants with cogeneration units installed increased their energy efficiency during the spray-dried powder stage by 85 and 90% [51]. Yoru et al. conducted energy and exergy analyses on a 13 MW capacity ceramic plant cogeneration unit with two heat exchangers and three gas turbines. Their study showed that the energy and exergy efficiencies of the cogeneration system were estimated at 82.3% and 34.7%, respectively [262]. Finally, a project conducted by the EU has reported that innovative kiln designs with integrated cogeneration capabilities can mitigate emissions of ceramic plants by up to 20% [263].

5.3. *Ceramic products in lifestyles and preferences*

Ceramics contributes to daily residential energy savings. For instance, insulating blocks and ventilated facades guarantee thermal stability in buildings. The latter can improve the building's energy efficiency by 40% [1]. The same study claims that substituting 1% of cavity walls and clay blocks with clay facades could mitigate 100 Mt of CO_2 by 2050 [1]. The energy efficiency of ceramic products implies low thermal conductivity. This feature allows ceramics to maintain heat inside the buildings [264]. For instance, bricks' high thermal mass can decrease and delay temperature changes within a building. In turn, minimising the risk of overheating in the day and slows the temperature down during the night [265]. Another study reported that bricks not only are a promising material to employ for passive building energy-savings, but also are a mean of storing heat while providing acoustic insulation [266]. Not only can bricks help manage temperature, but they can also represent a more sustainable option compared to other materials. For instance, Utama et al. revealed that the embodied energy of clay bricks is half of that of concrete blocks [267].

Coloured tiles are yet another material that leads to more energy-efficient buildings. Antonaia et al. show that coloured tiles with high solar reflectance on the roof slab mitigate urban heat and decrease building energy requirements for cooling. Their study revealed that the application of this material reduced the primary energy demand by 39% during the summer [268]. Coloured ceramic tiles are also widely used in Brazil not only to reduce the amount of energy absorbed by buildings but also to lower the demand for air conditioning during the warmer months [269]. Similarly, Gonçalves et al. show that ceramic tiles help reflect infrared radiation, thus improving the building's energy efficiency and reducing CO_2 emissions [270]. Pisello and Cotana documented that cool clay tiles can deliver huge energy savings in reducing summer overheating by optimising thermal comfort. The team concludes that cool clay tiles represent a cost-effective solution for passive retrofit in Mediterranean countries [271]. Pisello et al. also demonstrate that cool clay tiles represent an efficient solution to improving historic buildings' energy performance. In their study, the application of novel cool tiles and installing a more efficient energy plant led to energy savings of 69% for cooling and 64% for heating with a payback period of five years [272]. Another study by Pisello and Cotana showed that cool clay tiles are able to save between 11 and 13% of electricity for cooling in an Italian village. Such energy savings translate to the mitigation of 772 tonnes of CO_2eq per year [273]. In a similar vein, another study states that cool ceramic-based tiles can assure a high-quality roof cooling performance by putting together good architectural quality and thermal-energy efficiency [274].

5.4. Ceramics waste and recycling in the construction industry

Due to the high temperatures they undergo during the firing process, and as an inert material, most ceramics can be recycled and/or reused by the ceramic and other industries [275]. For instance, some of the waste emerging from the manufacturing process can be recycled back into the kiln. In contrast, waste that cannot be recycled internally is sent for external recycling (e.g. construction industry) or is disposed of in landfills [61]. To comply with Directive 2008/98/EC to avoid waste generation and reliance on virgin materials from overseas [200], the EU created an internal market to preserve natural stocks of virgin and important materials such as feldspar, clay and limestones and reduce imports of bauxite, zircon and magnesia from overseas [1].

5.4.1. Ceramic wastes and lightweight aggregates

Others have explored the potential options for clay waste. For instance, Ayati and colleagues suggest using clay waste as a raw material for lightweight aggregates [276]. On a similar vein, Boarder et al. have produced lightweight aggregates from London clay generated by Crossrail at a pilot plant scale. The same team estimates that 2.8 Mt of lightweight aggregates could have been made from Crossrail excavated clay. The research concludes that this approach could have manufactured more than 9.0 million cubic metres of low-carbon lightweight structural concrete [277]. Fig. 12 displays the manufacturing process for producing lightweight aggregates from clay. Note that in the figure, the two main stages are sintering and formation.

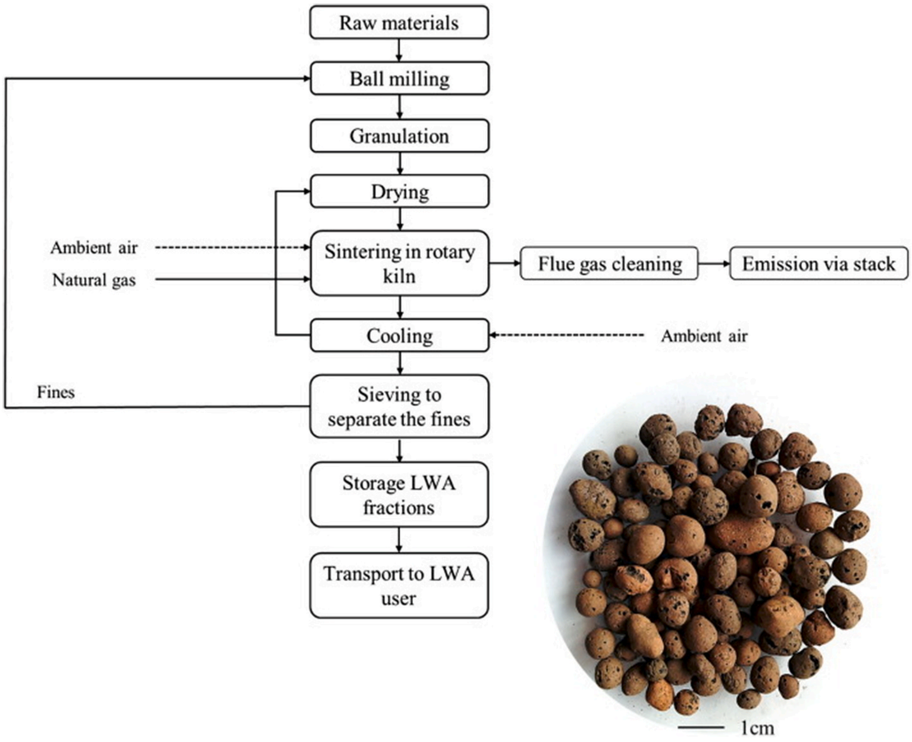

Fig. 12. The manufacturing process for producing lightweight aggregates (LWA) from clay. Source [278].

5.4.2. *Ceramic wastes and mortars*

The use of ceramic waste in mortars is another mean of extracting value from waste. For instance, Higashiyama et al. note that ceramic waste materials can partially substitute river sands. The study finds that ceramic wastes enhance the workability of fresh mortars because of the quantities of water absorbed during the synthesis process [279]. In the same way, fine particles of ceramic waste as an aggregate can improve concrete and mortar's durability and strength. The results showed extraordinary improvements in mortars' long-term durability and performance when exposed to sulphate and chloride attacks [280]. Samadi and colleagues investigated the durability and strength properties of a sustainable mortar mixture employing ceramic waste particles. The results indicate that introducing this waste in the mortar's mixture can reduce fuel consumption, save energy, reduce electricity consumption and mitigate CO_2 emissions [152]. Similarly, Farinha and team conclude that using up to 20% fine sanitaryware ceramic aggregate to manufacture mortar mixes delivers higher mechanical properties and lowers water permeability [281].

5.4.3. *Ceramic wastes and cement*

The applications of ceramics in the construction industry are wide and varied. For instance, Pitarch and colleagues argue that ceramics can be employed to partially replace Portland cement since it is resistant to physical, chemical and biological degradation; it is also durable and hard. The team identified that ceramic tiles, red clay bricks, and sanitary waste could partially replace Portland cement. Similarly, Jacoby noted that porcelain polishing residues improve Portland cement composition leading to technical, economic and environmental advantages [153]. Roy et al. indicate that calcined kaolinitic clays can be employed as a partial substitute of Portland cement during the formulation of blended cement. Others have noted that replacing Portland cement with 30% London clay calcined at 900 °C had no negative effects on long-term or workability on the cement's composition. The same team argues that these temperatures can already be achieved using low-carbon biofuels. Therefore, utilising this approach can significantly reduce carbon emissions associated with the production of Portland cement [282].

The effects of ceramics waste in cement have also been explored by Wong et al. who reports that a low proportion of ceramic particles (20%) can augment the mechanical strength of cement-based materials [283]. The effects of calcined clay in cement have also been widely investigated in terms of emissions reductions [284,285], increasing cement's compressive and flexural strength [286], and durability [287].

Others have investigated the use of ceramics waste for the production of alkali-activated cement. For example, one study documented that the alkali-activation of an aluminosilicate waste obtained from porcelain stoneware and red clay bricks cured at 65 °C for seven days acquired compressive strengths exceeding 20 MPa. Therefore, these wastes can be used to manufacture alkali-activated cement [288]. Fořt et al. explored environmental and functional aspects of alkaline activation of brick powders. Their results show that this mix delivers up to 45% savings in energy end-use and mitigates 72% GHG emissions compared to Portland cement paste [289]. Similarly, Bektas and colleagues show that brick aggregates not only reduced alkali-silica reaction in concrete mixtures but also prevented durability loss [290].

5.4.4. *Ceramic wastes and concrete*

Our review also identified a number of studies indicating how ceramic waste can be used in concrete production. For instance, Nepomuceno et al. evaluate the mechanical performance of concrete produced with recycled ceramic coarse aggregates. Their results reveal that concrete using these wastes presents better mechanical performance when compared to other demolition wastes (e.g., mortar and grout attached) [291]. Suzuki et al. employed about 40% ceramic waste as coarse aggregate to manufacture high-performance concrete. Their study presents a substantial reduction in autogenous shrinkage [292]. Others have focused on the effects of 100% fine aggregates and sanitaryware on the fire resistance of concrete. The study notes that ceramic aggregate concrete brings environmental advantages and delivers better residual strength after exposure to fire [293]. Research also shows that concrete mixes comprising coarse recycled ceramic aggregate have better resistance to abrasion and better long-term concrete durability than control concrete [294]. Medina and colleagues investigated the freeze-thaw resistance of concrete containing 20% and 25% coarse ceramic aggregates obtained from the sanitaryware industry. The team reveals that the scaling rate of the crack development was lower in the recycled concrete than in the standard concrete [295]. Silva and Pereira [296] and Cachim [297] report on the preparation of recycled concrete employing waste brick aggregates. Their results show that although the mixture slightly reduces elastic modulus and compressive strength, the final product is still acceptable for various construction applications. Similarly, others have documented that the use of crushed brick as a concrete aggregate reduces large amounts of construction and demolition waste in tandem with lowering the demand for natural resources [298–300].

This section has shown that ceramic waste can mitigate environmental impacts caused by high energy use, GHG emissions, and landfill deposits produced by the construction and demolition industry. The fact that ceramic waste is locally available helps reduce resource extraction and reduce the environmental impacts of transporting materials long distances. Therefore, we argue that the application of materials incorporating such wastes must be considered in construction applications.

5.5. *Emerging technologies and processes for mitigating the environmental impacts of the ceramic industry*

As discussed, reductions in energy end-use in the ceramics industry have been achieved through improving the kiln's design, more efficient firing techniques, process optimization and other approaches. Table 7 presents 32 emerging technologies that mitigate emissions from the ceramic industry production processes.

The literature also indicates that for the economy segments that are not easily electrified, CCS could be another technology to help mitigate emissions [305] as Fig. 13 illustrates. However, our evidence suggests that this approach could be erroneous. We argue that individual ceramic sites are not considered big enough to justify having dedicated CCS infrastructure. More, if we consider the high costs that emanate from transportation, development and operation of storage sites that CCS entails. Like the glass industry [306], ceramic manufacturers are often located in isolated or rural areas, so carbon capture emissions systems do not seem like a feasible investment option. Another study supports the notion that carbon capture technologies may not be appropriate for commercial application in the ceramic industry [58].

6. Barriers and risks facing the decarbonization of the ceramics industry

Although we have noted many options for the decarbonization of the ceramics industry, decarbonization is not a given. Instead, some barriers prevent their achievement and we review these in the following sections, along with risks. By barriers, we meant any factor impeding

Table 7
32 emerging technologies for making ceramic manufacturing more sustainable. Source: Authors compiled from [5,49,50,62,72,83,249,301–304].

Level of sociotechnical system	Technology	Benefits	Energy and/or emissions reductions
Ceramics manufacturing	Vacuum drying	This technique implements reduced atmospheric pressure to decrease the energy end-use needed for the drying process.	NA
	Microwave-assisted drying and firing	By using microwave heating, energy is delivered more efficiently to dry and fire products. Therefore, reducing energy end-use for the drying process (For a more detailed explanation, see section 5.2.3)	This technique delivers significant reductions in energy end-use, which can be as high as 99%
	Hybrid Kiln	Instead of employing a desulpherised kiln and dryer, exhaust gases are supplemented through a gas-driven heat pump to enhance thermal energy. This approach enables manufacturers to select either electric heating employing CHP as an option and/or primary fuel.	This technology can deliver up to 65% in energy savings
	Reduction of water content in the shaped product	Most of the energy consumed in the dryers is used to evaporate the water contained in the ceramic products. Therefore, reducing water content will require less water to vaporise and less energy to dry formed products during the drying stage.	NA
	Heat pipe heat exchanger	Heat pipe heat exchanger applied to a ceramic kiln employing exhaust gases to preheat water delivered energy recovery rates of about 15%.	Energy savings could reach up to 65%
	Preheat water added for forming heavy clays	Applying hot water instead of cold during the forming stage reduces the drying heating requirements.	This technique can lead to emission reductions of about 3%.
	Controlled dehumidification	The water that is condensed within the chamber releases heat that is supplied in the drying process. This system is entirely closed, and therefore, highly energy-efficient.	The energy savings this technique delivers can be as high as 80%
	Controlled drying air recirculation	In this approach, the inlet and outlet air temperatures remain steady, while the drying agent recirculation coefficient augments. This results not only in reducing the share of new air, but also optimises the air flow.	This technology can lead to energy savings of 25%
	Heat recovery facilities in dryers	Heat recovery enables the drying air to be replaced with hotter gases from other manufacturing processes. Such gases can come from cogeneration engines or the kiln.	This technology can mitigate emissions between 57 and 73% and energy savings ranging between 60 and 80%.
	Cold sintering	This process produces dense ceramic materials below 200 °C, therefore reducing the energy intensity. This technique uses a transitory, often liquid, phase to enable mass transfer to make denser ceramics employing uniaxial pressure. This transitory phase often evaporates in the cold sintering process, delivering densification by solution precipitation.	NA
	'Hybridedroger voor keramiek' (hybrid dryer)	What differentiates this technique from regular drying (drying chambers or tunnel dryers) is that two drying phases are applied in two drying chambers instead of only one. First, aerothermal drying is implemented using significant quantities of air. This is followed by semi-steam drying, which dries the product with air, high temperature and humidity.	Heating requirement decreases from 4 to 10 GJ/t to about 3 GJ/t. Delivering energy efficiency improvements of around 25%
	Optimization of the recirculation of drying air	Improving ventilation techniques to control main parameters such as temperature, humidity, and flow rate increases the efficiency of the hot-air dryer.	This technique can deliver energy savings of 25%.
	Pulsed hot air	Periodically interrupting the airflow permits the use of higher drying air temperatures. This technique gives enough time for the moisture to move from the centroid to the surface. Compared with a classic roller dryer, pulsed hot air is 40 min faster.	By using a pulse firing system, the ceramics industry can achieve savings of up to 30% compared with other traditional systems.
	High-efficiency burners	New high efficient burners allow preheating the combustion air with exhaust gases (e.g., self-recuperative and regenerative burners). These burners can substitute old ones in ceramic tunnel and/or roller kilns to reduce fuel consumption. This technique leads to firing efficiency improvement of about 10%; fuel savings ranging from 25 to 30% in self-recuperative burners and around 50–60% in regenerative burners.	This technology can generate energy savings of up to 15% regarding hot air recycling solutions.
	Airless drying	The main advantage of this technique is that the steam delivers higher specific heat and thermal conductivity relative to air. This allows improving heat transfer while reducing the risk of explosion by avoiding secondary contamination.	This technology leads to savings in thermal energy of 20–50% and significant reductions in the drying time.
	Integral thermal process	This technique optimises the firing process of tiles, and it involves supplying the exact amount of heat during each firing stage. The improved control leads to significant reductions in the firing time compared to fast roller kilns.	NA
	Fast-firing	Applying fast-fire cycles instead of utilising conventional kilns leads to reductions in the firing temperature of up to 50 °C.	This technique leads to reducing CO_2 emissions by 25%.
	Inertizing	This method applies to tiles production. After the pressing stage, there is no drying, instead, a fast stage of drying–firing	Applying this process leads to energy savings of up to 40%.

(*continued on next page*)

Table 7 (*continued*)

Level of sociotechnical system	Technology	Benefits	Energy and/or emissions reductions
		to a maximum temperature of about 900 °C is employed instead. This process lasts between 10 and 15 min depending on the thickness of the tile.	
	Hot air recycling as combustion air in the kiln	The hot air from the cooling zone of a kiln could be utilized as preheated combustion air in the combustion chamber. This technique triggers a reaction where the thermal shock produced by high-temperature airflow reduces the mixture of hot air and air at ambient temperature. Fuels savings range from 15 to 30%.	This technique deliver fuels savings ranging from 15 to 30%.
	Optimization of the kiln charge	Optimising the firing surface area in roller kilns and the working charge in tunnel kilns improves the kiln's efficiency. This practice leads to lowering the energy end-use per unit of the processed product since less energy is required to raise the kiln's car temperature.	NA
	Extended tunnel kilns	Extending the tunnel kiln by 30–50% allow bricks to dry without employing cool air. Thus, making the tunnel kiln more energy efficient. This approach also enables that the drying process is decoupled from the firing kiln, leading to significant energy savings.	Applying this approach can lead to energy savings of up to 30%
	Kiln cars and furniture with low thermal mass	The use of low thermal mass in kiln cars helps in reducing the thermal energy requirement for the heating of supporting refractories. This technique reduces running costs, repairs, and maintenance.	This technique leads to fuel savings of up to 70%.
	Vertical Shift Brick Kiln	With this technique, green bricks are loaded on the top platform and move slowly towards the central firing zone. This allows the fresh air coming from below to cool the fired bricks prior to unloading. The kiln operates as a counter-current heat exchanger, with heat transfer occurring between the upward moving air (continuous flow) and downward moving bricks (intermittent movement). Because of its fairly short firing period of about 24 h, the green brick ought to be suitable to resist fast heating and cooling to deliver high quality bricks.	NA
	Replacing conventional Hot Face Kyanite refractories with Ultralite ones	Replacing Hot Face Kyanite refractories with a density of 1100 kg/m^3 with Ultralite™ can reduce the weight and heat absorption of the kiln car furniture.	This measure can lead to energy savings of 36,865 m^3 N G./year and reductions of CO_2 of 77 tCO2eq/year.
	Optimization of combustion efficiency	Installing an O_2 sensor at the furnace exhaust for combustion air provides continuous feedback of percentages of O_2. Having this information can help regulate combustion airflow to maintain an ideal combustion condition automatically.	Energy saving can reach up to 19,782 m^3 NG yearly and could mitigate 41.344 CO_2 emissions each year.
	Pressure Casting (plasterless)	This technique supplies casting benches with casting slips under pressure. The resin or mould-plastic is employed as a filter instead of waiting for the water to be absorbed. The water in the casting slip is removed through the plastic/resin mould porosity, reducing the casting time. With this approach, energy savings are guaranteed due to the elimination of mould drying before reuse.	NA
Options for extractions of raw materials and alternatives to replace ceramics	Optimization of raw materials	Locally provided raw materials mitigate emissions from long-distance transportation. Ceramic fibres and low thermal mass materials use new formulas that require less heating during the firing process,. Utilising broken ware lead to energy savings and contribute to resource efficiency.	This approach could lead to up to 20% of energy savings
	Incorporating new materials to improve the ceramics' design	New material compositions, for example, incorporating pore-forming agents (such as carbon nanotubes) and through the incorporation of residues to produce thermal energy can lead to energy savings in the drying stage and improve material porosity leading to water savings.	This approach leads to up to 20% in energy savings
	Using low carbonate clay for yellow bricks in heavy clay subsector	In this approach, clay could be employed for the production of yellow bricks. The manufacturing process implementing low carbonate clay with colourant mitigates this emission.	This approach can mitigate emissions by up to 10%.
	Recycling sludge from other industries	Utilising such material in the manufacturing of ceramics can lead not only save raw materials but, in other cases, can also lead to reducing firing temperatures and therefore mitigate GHG emissions. For instance, adding 10%wt of paper sludge results in economic savings of 3% and lowers firing temperature to 750 °C.	This formula can lead to energy savings of up to 20%
Ceramics waste and recycling in the construction industry	Reuse of waste from operations	Broken pieces of ceramics or waste emerging from grinding and the decorating and glazing operations could be added as a raw material in the subsequent batches. Implementing this approach reduces landfills occupation, mitigate emissions and save resources.	See Section 5 for specific numbers regarding energy savings and abatement of emissions
	Ceramics waste	Instead of being disposed of in landfills, avoid waste generation and reliance on virgin materials from overseas, ceramics waste can be employed in diverse materials for the construction industry as we have highlighted in Section 5.4	Section 5.4 for specific information regarding energy savings and abatement of emissions

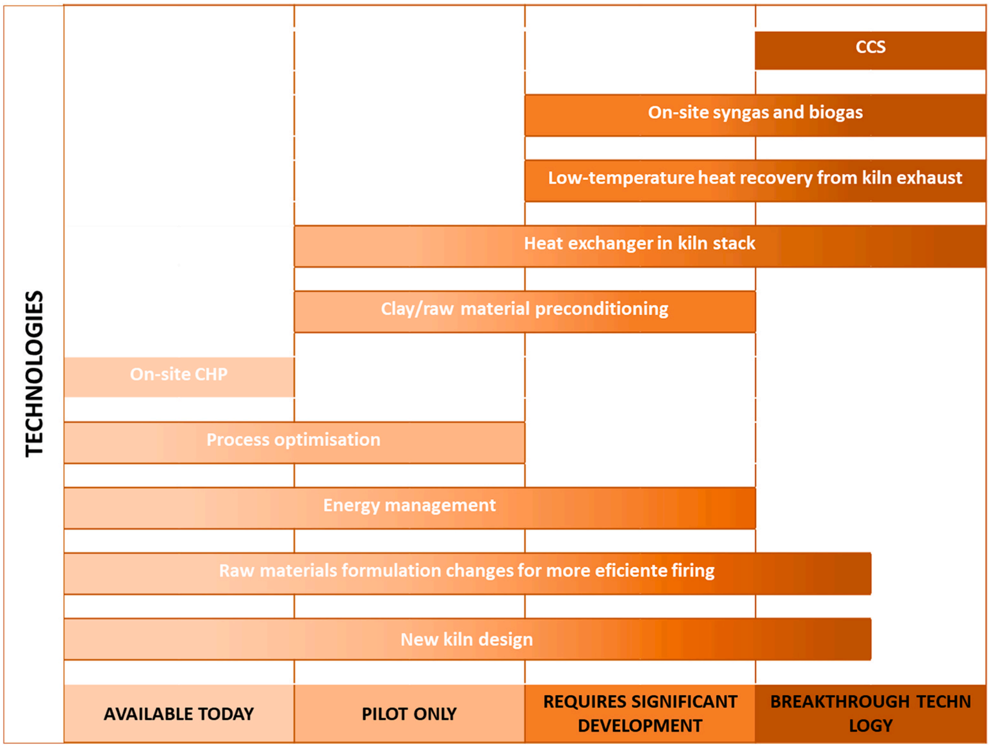

Fig. 13. Roadmap to decarbonise the ceramics industry. Source: authors, compiled from Ref. [1]. Note: CHP = combined heat and power. CCS = carbon capture and storage.

technology adoption, and by risks, we mean any negative outcome to adoption.

6.1. *Manufacturing, managerial and infrastructural concerns*

The ceramic industry has high levels of process emissions that sometimes cannot be completely abated regardless of the utilisation of mitigation techniques such as energy and resource efficiency and electrification [307]. As presented, manufacturing ceramics entails high heating requirements, currently provided with fossil fuels that cannot be easily replaced with existing technologies. For example, in our review, we found a number of studies [1,51,84] suggesting that the objectives for the European ceramic industry are extremely demanding and unreachable with existing policies and technologies. Others have highlighted that installing electric driers and kilns will not be enough to achieve the industrial EU targets on CO_2 emissions [97], which is a common approach documented in the literature (see Section 5.2.1). Regarding electrification, others have argued that electric kilns have not yet been implemented on a continuous and large scale (i.e., in tunnel kilns). Thus, the viability of applying electric kilns in large-scale ceramic manufacturing plants remains debatable. Others note that since this industry is sensitive to fluctuating electricity prices, in tandem with unproven large-deployment of high-temperature heat electrification technologies (e.g. electric kilns), there is an uncertain investment environment to advance the electrification of the industry [254,308,309]. Another study argues that a large-scale continuous electric kiln would operate differently than a kiln heated by gas combustion. The study concludes that further collaboration with manufacturers is needed to produce an appropriate kiln design for widespread application [58].

Geographical location and the fact that many manufacturing sites are widely dispersed also influence technologies' deployment [83]. For instance, near-term hydrogen areas adoption is most likely to occur in industrial clusters where hydrogen production, distribution, and use are economically feasible [256]. In addition, these locations often have a rather limited installed grid capacity. Therefore, problems around infrastructure capacity when employing electrification options such as electric drying and firing or assisted microwave for drying and firing may occur [1,58]. In these circumstances, we argue that for local and/or small ceramic producers, when the commercial technology is developed and supplied, resistance or even rejection of new technologies may occur due to the economic, business process and technical barriers that new technology adoption involves.

Regarding hydrogen utilisation, some technical unknowns remain, including i) lower volumetric energy content than natural gas and a flame with lower radiation heat transfer than natural gas [310]; ii) potential increase of NOx emissions; iii) safety-related considerations, particularly for storage; iv) costs; v) manufacturing infrastructure that may be incompatible with hydrogen [254]. Our review also noted the potential of biofuels; however, there are some barriers to overcome for their successful deployment in ceramics manufacturing. For instance, The Department of Energy and Climate Change (DECC) suggests that biomass cost and supply represent serious issues for the decarbonization of this industry [58]. On top of that, Cavazzuti and colleagues indicate that a full switch to bio-based fuels is not possible without novel kilns that many industries do not have yet [311]. There are also relevant issues regarding distribution barriers and quality requirements, affecting, in consequence, the availability of biofuels that the ceramic industry would require [32].

We also raise concerns that in some cases, imported technologies (e.g. from China or the EU) are not easily adapted to local contexts. For instance, in Bangladesh, bricks are a quarter larger in size compared to the Chinese ones. In addition, the climate conditions in Bangladesh (i.e. more humid and much hotter) are different than in China. Finally, the physical properties of Bangladeshi clay are also different since these have higher moisture content and therefore they require longer drying time. Thus, once Chinese technologies are directly transferred to the Bangladeshi market, without considering these aspects or making customized improvements and modifications, the efficiency in terms of outputs could drop significantly [67].

Our review also identified that although much research is focused on producing ceramics from waste, the commercial activity through this approach remains limited. Zhang et al. note that potential barriers to the utilisation of waste materials include an absence of relevant standards, little research regarding the acceptance of waste materials-based ceramics by the public and industry, and many materials that could be contaminated [44].

6.2. *Lack of information, knowledge, and skills*

Our research identified that other barriers that impede the decarbonization of the ceramics industry are not related to the technology itself but rather with some inherent issues associated with this industry. For instance, Manrique et al. documented the notorious lack of technology and knowledge transfer opportunities in the ceramic industry. Their work, which is based in Colombia, also identified that another major barrier is related to the industry's values [64]. This issue was associated with the notion that ceramic manufacturers often give low priority to more efficient energy practices as well as sustainability awareness.

This review identified that the absence of information, specifically related to the lack of cost-benefit and viability analyses of efficient technologies, impedes the investments to deploy more sustainable measures. One study suggests that companies delay cost-effective actions not because energy-related investments are perceived as less important but because the selection of these projects is often based on an expected rate of return. Such a process tends to be inaccurate and hence, generates uncertainties for investments [312]. DECC, identified that the absence of technical knowledge and capacity to identify novel technologies and measures to mitigate emissions represent another key barrier [233]. We argue that generally, there is a recurrent lack of information about more energy-efficient practices for small and medium ceramic producers.

Our research noted that another barrier is associated with the long lifetime of technologies operating in the ceramics industry. For instance, the lifespan of a kiln can be up to 40 years and accounts for significant capital investment; therefore, it is not economically feasible to replace them regularly. Given the kilns' lifetime, there will only be one or, at most, two replacement cycles between now and 2050 and hence limited opportunities for equipment improvements [1,233]. In a similar vein, Mazzanti and Rizzo note that the wave of green investments in this industry took place during the late 1990s. Thus, companies are not willing to make further investments in such a short period [313].

Another barrier is related to energy security. BEIS identified that unexpected interruptions of energy supply could generate significant damages to continuous kilns, to the point that the factory could shut down for months and augment their production costs per unit. In tandem, BEIS notes that increasing and volatile gas and electricity prices deter investments in more energy-efficient measures [32].

6.3. *Financial and economic disincentives*

Some argue that the dominant barrier to adopting low-carbon process technologies is related to the costs associated with financing technologies [64,314]. Similarly, Venmans documented that the main barrier is associated with the manufacturer's availability of capital and internal budget rules [312]. We also found that unwillingness to invest in energy-efficient measures with payback times above 3–5 years represent another barrier [32]. DECC, in a similar vein, reports a notable absence from government financial schemes along with a lack of grants to incentivise the adoption of energy-efficient technologies [58]. Finally, The UK Committee on Climate Change argues that until sufficient financial support from the government is provided, the ceramic industry will not transition towards a zero-carbon path [254].

Another barrier is the lack of incentives and regulations to promote less polluting technologies for brick operators. Particularly in countries such as Bangladesh and Nepal, where most brick kilns are not regulated and are beyond the reach of governmental institutions [67]. In such countries, where FCK has a return on investment of about 80% (without factoring in environmental and social costs), brick manufacturers have little incentives to transition towards low-carbon technologies without regulatory bodies to push them to do so.

6.4. *Regulations to mitigate emissions*

Since ceramics represent an energy-intensive industry, this review identified a number of regulations that can contribute to its decarbonization. However, these are not always consistent and show great variation across countries. For example, KPMG noted that in China "The 12th Five-Year Development Plan of Guangdong Building Materials Industry" and "The Transformation and Upgrading Action Program of Guangdong Ceramic Tile Industry" are resolutions that encourage more sustainable manufacturing practices. These approaches suggest a resource consumption-driven model and an innovation-driven model to expedite the transition towards a future in low-carbon ceramics [315]. Table 8 displays a number of regulations that contribute to decarbonization and enhance environmental measures within the ceramics industry. The intention of this table is not to present an exhaustive list of policies, but instead, it seeks to highlight how some of the most pressing issues in the ceramic industry (i.e. emissions, resources and extraction of materials) have now been regulated globally. This review also notes that a common challenge with regulation and policy review papers is that it is very difficult to undertake these based on published papers since policy and regulation are rarely thoroughly investigated.

7. Future research

The final finding from this review is associated with the literature gaps that need to be addressed in future research. We divide these into five areas, namely: ceramics sector-specific estimations including bricks and tiles, resource extraction and human rights, user comfort and preferences and ceramic alternatives, coupling to other sociotechnical systems and cross-cutting solutions, and technology substitution.

7.1. *Ceramics sector-specific estimations including bricks and tiles*

We first note a generalized lack of research concerning advanced and emerging energy-efficient technologies for the ceramics industry, including work that differentiates emissions by different types (direct vs.

Table 8
Regulations to decarbonise the ceramic industry. (Source: authors) compiled from [51,67,97,316–318].

Regulation	Impacts on the ceramics industry
Directive 2004/8/EC of the European Parliament and of the Council of February 11, 2004 on the promotion of cogeneration based on a useful heat demand in the internal energy market	This legislative act promotes cogeneration grounded on a beneficial heat demand in the internal energy market.
Directive 2009/29/EC of the European Parliament and of the Council of April 23, 2009 amending Directive 2003/87/EC on the establishing a scheme for greenhouse gas emission allowance trading within the Community and amending Council.	This legislative act seeks to enhance and extend the GHG trading scheme of emissions allowance from the EU.
Directive 2010/75/EU of the European Parliament and of the Council of November 24, 2010 on the on industrial emissions (integrated pollution prevention and control)	This act addresses industrial emissions (integrated pollution prevention and control).
Commission Decision of December 24, 2009 determining, pursuant to Directive 2003/87/EC of the European Parliament and of the Council	This decision presents a list of sectors and subsectors that are considered to be exposed to risks of carbon leakage.
Brick Act (Bangladesh-2013)	This instrument seeks to control brick manufacturing and brick kiln to promote conservation and enhance environmental practices to protect biodiversity. This Act allows two years as a time limit to transition to modern kiln technologies.
Section 52F of the Income Tax Ordinance (Bangladesh)	This instrument has made mandatory for brick manufacturers to submit income tax payment certificates not only for renewing their licenses but also for obtaining environmental clearance certificates
The Bihar Minor Mineral Concession Rules (Bihar, state in eastern India)	This regulation applies to bricks manufacturing. It establishes that the mining area should not expand beyond 5 ha, and depth of clay mining should be less than 3 m. Blasting is forbidden under this instrument. The mining area is required to be at a specific distance away from protected and/or restricted areas such as rivers, flood embankment, forests, railway lines and others. The miner, under this regulation is liable to restore the land once operation is completed.
The fly ash notification (India)	The 1999 rule set a target of 100% fly ash reutilization by 2009 for manufacturing bricks. This legislation was later revised in 2016 and now requires that brick manufacturing plants within a 100 km radius of a thermal power plant need to reuse the fly ash emerging from those plants. If brick manufacturers are not complying with such measures, their permits must be cancelled.
The Transformation and Upgrading Action Program of Guangdong Ceramic Tile Industry (China)	This resolution promotes cleaner production means in the ceramic tile sector. It also seeks to help transitioning this sector from a resource consumption-driven model to innovation-driven model.
Brick and Tile National Emissions Standards for Hazardous Air Pollutants (USA)	Through this mechanism the Environmental Protection Agency requires that structural clay products and brick manufacturers employ emissions control technologies and put into practice standards to control and minimize releases of hazardous air pollutants.

indirect/embodied, or Scope 1, Scope 2, and Scope 3 emissions). We acknowledge that this may be attributed to various aspects, including the many subsectors existing in the ceramic industry; the differing process conditions, particularly firing temperatures, across ceramic applications; the different sizes (large or small) of ceramics manufacturing companies; and the various applications consumers demand in ceramics. While we observed a substantial number of studies that covered emissions reduction of the industrial sector from a holistic perspective, only a few focused solely on ceramics. This gap leads us to recommend that greater attention should be placed on technological developments for the decarbonization of the ceramics industry alone. This could be complemented by tailored policy recommendations and options for specific ceramic sectors.

Moreover, we noted that many of the technologies and techniques presented in this research are conducted at laboratory scale. Therefore, we call for further research to focus on demonstrating technologies at an industrial scale and further investigating energy and carbon-efficient ceramics manufacturing practices. We also echo the call from Zhang et al. [44], to further research the production and utilisation of bricks from waste materials. This research should cover not only economic, technical and environmental aspects but also entail policy and public education, standardization, and the role of governments.

Furthermore, we noted that those studies focusing on carbon and energy savings (see Section 5) are mainly centred on two ceramic subsectors: bricks and wall and floor tiles. For instance, we only found a handful of studies investigating emissions from the sanitaryware sector; and we did not find a single document researching the environmental impacts of vitrified clay pipes. We acknowledge that bricks and ceramic tiles are, arguably, the most relevant subsectors from the ceramics industry. However, this lack of research offers avenues for future research.

A final issue is that few studies offer quantitative emissions reduction potential for set technologies, options, or pathways relevant to the ceramics industry. Many of the technologies discussed in Section 5 are based on single country or single sector/application studies.

7.2. *Resource extraction and human rights*

As a second theme, we call on future research to focus on the effects of regulations on limiting the use of clay for bricks production and related soil and resource conservation. We urgently call to investigate this area further since we did not find a single study addressing this pressing issue. Similarly, we consider that future research should focus on analyzing which regions have suffered the biggest ecological impacts from resource extraction for ceramics production. This type of analysis could be replicated for all materials used for ceramics manufacturing, including lithium. Researchers could evaluate the economic and environmental conditions under which lithium mines could operate [141] and assess the options for substituting this element, given the potential for shortages in the future.

Moreover, we echo the call from Lundgren-Kownacki et al. [133] to investigate, through a multi-dimensional analysis, means to address forced-labour conditions and violations of human rights of brick makers from vulnerable communities. At the same time, such research should also cover means to reduce pollution and improve the workers' health by considering appropriate technical and cultural solutions.

Finally, we consider that more research should be conducted regarding material substitutes for the ceramics industry that are environmentally friendly. For instance, ceramics are the second-largest consumer of lithium but only a handful of studies explore this problem and even less suggest viable solutions to mitigate it.

7.3. *Social preferences and consumer acceptance*

We further suggest that future research should focus on users' comfort and aesthetic expectations for materials. Given that ceramics are a key element in buildings, more research is needed on how these materials can lead to more efficiency and energy savings while maintaining visual and thermal comfort. Similarly, there is little research addressing the intersection of consumers' preferences and construction materials. Working from the premise that there are more sustainable options to ceramics, it would be worth investigating if the materials that are more valued by consumers are also the most sustainable options. Complementing users' preferences, we call for further research centring on the willingness of kiln owners to adopt more energy and carbon-efficient technologies. Coupled with this, the main drivers for process changes should be explored and potential triggers for behaviour change investigated.

7.4. Coupling to other sociotechnical systems

As presented in Section 3, the ceramics industry does not exist in a vacuum, and like other industries, is associated with other sociotechnical systems [319]. As Fig. 14 displays, the interconnections from the ceramic industry to other sociotechnical systems are notable. They range from vital materials in urban infrastructure (e.g., drainage pipes and underground cable sheathings) to critical materials in the construction sector. Looking at the links with the sociotechnical energy system, ceramics also have an important role in terms of energy end-use and their use, particularly in buildings. Ceramics even touch on sociotechnical systems such as electronics, military, aerospace, health, and automobiles. Finally, the ceramics industry touches upon national and local regulations regarding resource extraction, circularity, and recycling schemes. Our review notes that these interconnections can create enthralling dependencies and result in synergies that are rarely examined. We, therefore, call to investigate these interconnections further.

7.5. Cross-cutting solutions and technology substitution

Most of the documents identified in this review were narrowed to one specific option (e.g., electrification and biofuels) for decarbonising the ceramics industry. Nevertheless, we noted that combining technology paths could deliver, in some cases, greater carbon savings. Thus, we encourage the research community to investigate these techniques further. In this sense, although we found a number of studies that suggested a cross-cutting approach, these were limited to a handful. For instance, Huang and colleagues noted that improving the insulation in old kilns and integrating waste heat utilisation practices can decrease total energy end-use by about 22% [317]. Another approach is suggested by Zapata-Solvas et al. they have documented that insulated graphite die for Spark Plasma Sintering (SPS) enables the sintering of all refractory ceramic materials in less than 1 min with heating rates reaching over 2000 °C/min and energy end-use over 100 times lower than SPS [320].

On a similar track, even though we identified a few studies researching the benefits of employing more efficient equipment [234, 321–323], these were limited to focus on the technology alone, without further investigating how to increase potential benefits. For instance, research could explore the economic and environmental benefits of using new ceramic formulas in most developed kilns. Both approaches are currently available and arguably with a technological readiness level high. Fig. 15, therefore, presents a clear insight; practical and extended options to pave the way towards a low-carbon future is achievable for the ceramic industry. For instance, recycling, resource efficiency and materials substitution touches across all levels of the ceramics system. Stakeholders, investors, manufacturers and policymakers can picture a

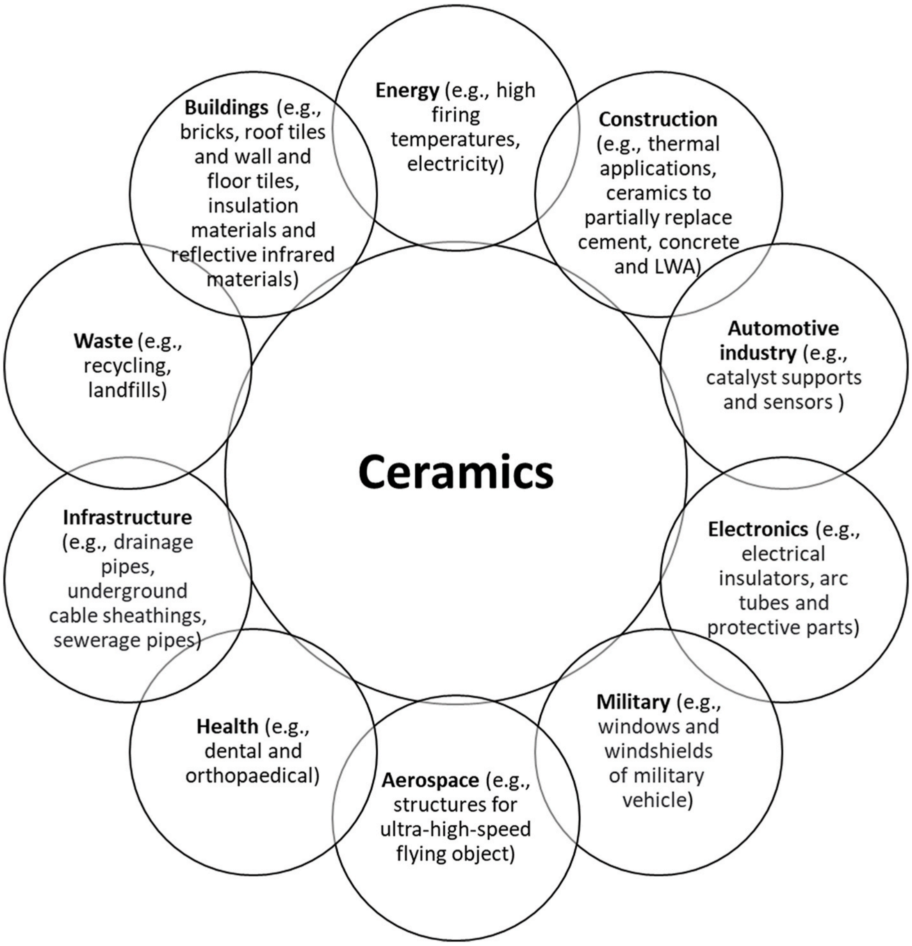

Fig. 14. Compelling interconnections of ceramics to other sociotechnical systems. Source: authors.

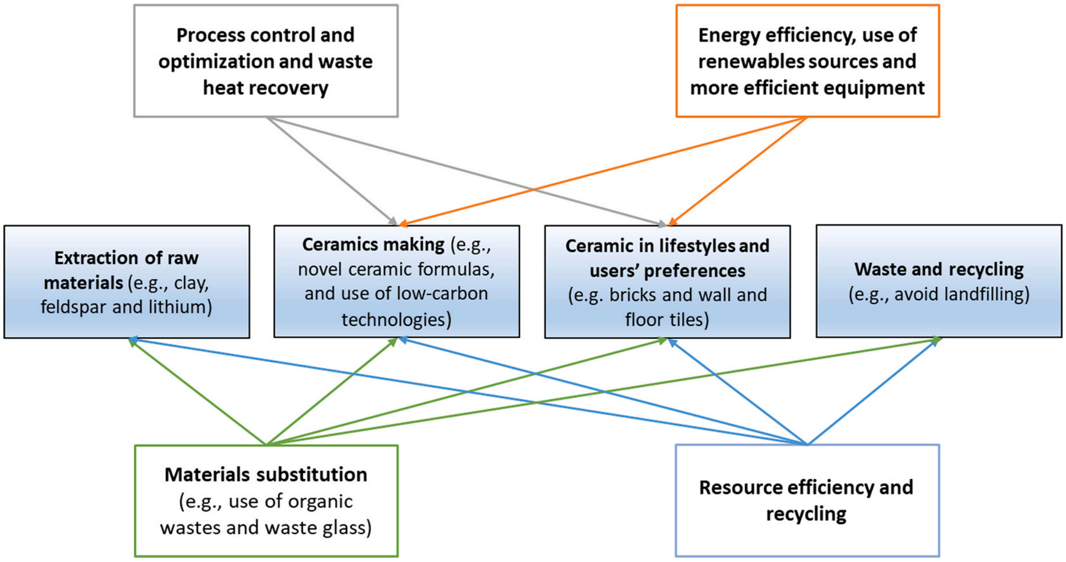

Fig. 15. Visualizing crosscutting options for the decarbonization of the ceramics system. Source: authors.

path for decarbonization based on these cross-cutting solutions as well as commercially options available (see Section 5 and Table 6). Moreover, these cross-cutting interventions can simultaneously influence multiple product groups and sectors. In turn, we believe more research on cross-cutting options should be pursued.

8. Conclusion

To investigate the decarbonization of the ceramics industry, we employed a critical review with a systematic searching protocol and the guiding conceptual lens of sociotechnical systems. Our study shows that ceramics are intrinsically associated with human development as they are used as materials for the buildings we live in, sanitary appliances, domestic decorative objects, and a wide range of other infrastructural, technical and cultural artefacts. Ceramics are also a key component in fostering a low carbon future through applications such as energy storage and CO_2 absorption. This review also showed that the ceramics industry does not exist in a vacuum, instead, it is closely tied to other industries (i.e., military, automotive and aerospace). Therefore, ceramics are associated with other sociotechnical systems that create compelling interdependencies among industries.

Nevertheless, regardless of these benefits, ceramics can be highly damaging to social and natural systems during their lifecycle. For instance, in the EU, the manufacture of ceramics emits around 19 Mt CO_2, bricks manufacturing is responsible for 2.7% of carbon emissions annually, and in Asia alone, it is estimated that the brick sector consumes more than 110 million tonnes of coal per year. In this sense, Fig. 16 displays (in white) ceramics' environmental and social impacts, ranging from the extraction of raw materials (e.g., land, crops, and soil degradation and biodiversity loss) to their final disposition.

Regardless of how intricate, environmentally, and socially damaging this sociotechnical system can be, Fig. 16, presents the many possibilities (shown in green) that can help to reduce emissions and alleviate social and environmental impacts. Options for extracting raw material vary from finding alternatives to ceramics and resource efficiency to implementing stringent soil use and resource extraction regulations. Concerning the second step presented in Fig. 16 (ceramics making), our review provides 32 technologies and processes as well as waste recovery options that can promote more energy-efficient processes to mitigate emissions from this industry. Nevertheless, we determined that there is no consensus on a single most promising strategy and/or technology to substantially reduce product emissions based on the collected evidence. Instead, our analysis indicates (see Section 7.5) that to reduce emissions dramatically, the ceramics industry must implement a cross-cutting approach that goes beyond energy-efficient initiatives, but it also considers measures related to recycling, resource efficiency and materials substitution.

In Fig. 16, we show the barriers to decarbonizing the ceramics industry. Although the main obstacles are perhaps financial and economic, we also noted other hindrances. For instance, the lack of knowledge from local manufacturers to implement low-carbon processes represents a key hindrance. From the perspective of small manufacturers, another barrier is the lack of willingness to adopt more efficient technologies (i.e., switch kilns) due to lack of incentives and/or regulations to stimulate upgrading assets with long-lives. While from a user perspective, a generalized lack of understanding of household comfort and aesthetic preferences might operate as a barrier to developing more efficient ceramic products. Fig. 16 also summarizes the benefits of change in the ceramics sociotechnical system. The figure shows that for ceramic producers, financial and economic opportunities exist. Most notably, such benefits are translated into energy savings and more efficient manufacturing processes. At the individual company level, more stringent regulation of workers' wellbeing and polluting technologies can improve workers' health while ensuring that human rights are preserved.

In addition to breaking down how the ceramics sociotechnical system can be enhanced, our review also suggests promising avenues for future research. For instance, investigation of forced-labour conditions and violations of human rights in brick manufacturing could have positive social impacts. Moreover, we suggest that future research should

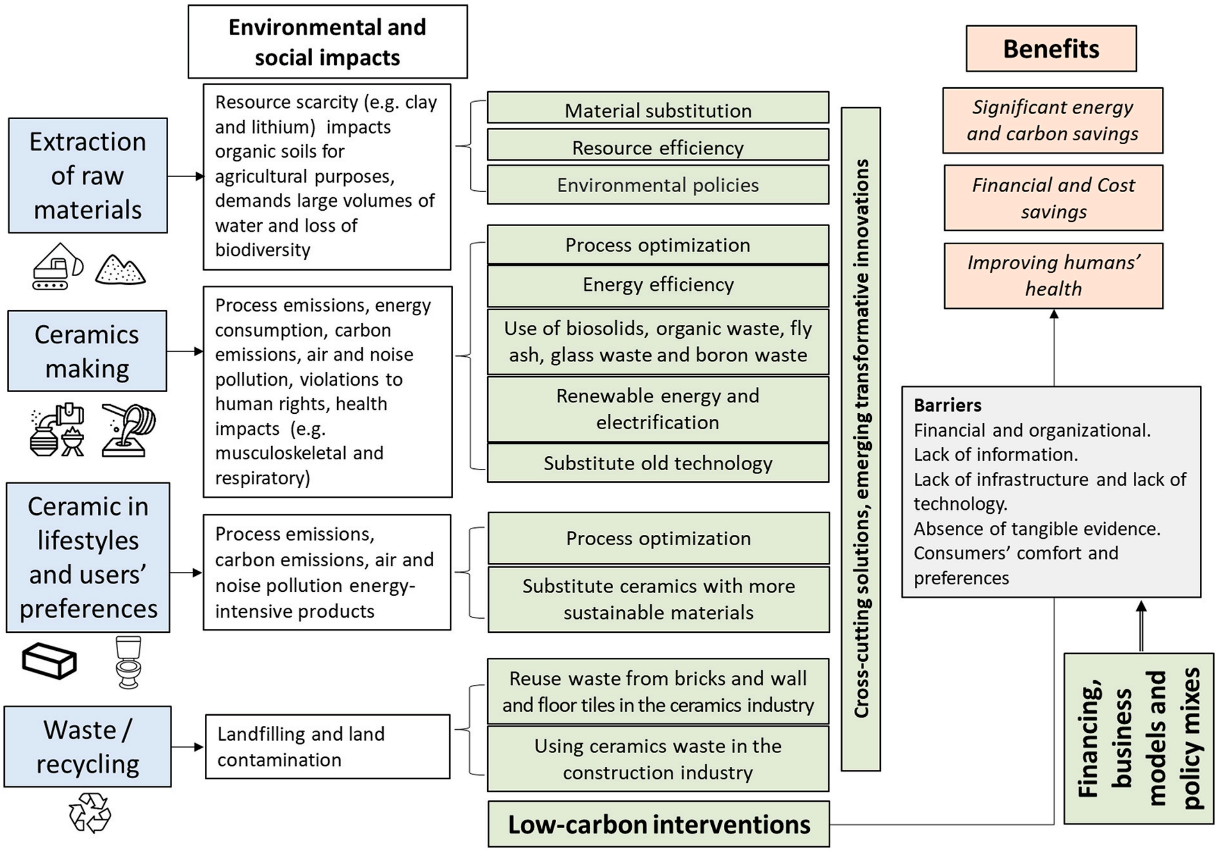

Fig. 16. Interventions, benefits, barriers and policies for decarbonizing the ceramics sociotechnical system (Source: Authors).

explore other subsectors from the ceramics industry, that is, beyond bricks and wall and floor tiles. Another promising avenue for research would be to assess substitutes for increasingly scarce resources like lithium in ceramics production and evaluate related ecological impacts. Employing such analyses could very well ensure principles of sustainability and justice embedded alongside the contributions that the ceramics industry continues to make in our modern lifestyles.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Aoife. M Foley third author on this paper is Editor in Chief of RSER, she was blinded during the review process and the paper was handled by another Editor

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