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Feature article

A perspective on ceramic recycling

Stephan Sarner [a,b], Olivier Guillon [a,b,c,*]

[a] Institute of Energy Materials and Devices: Materials Synthesis and Processing (IMD-2), Forschungszentrum Jülich GmbH, Jülich, Germany
[b] Institute of Mineral Engineering, RWTH Aachen University, Aachen, Germany
[c] Jülich Aachen Research Alliance JARA-Energy, Jülich, Germany

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ABSTRACT

Enabling the transformation of the current linear economy into a circular one, different strategies such as reuse and recycling must be integrated as fundamental aspects in the design of new products and the handling of those already in use. Ceramics are particularly stable materials and ceramic components usually have long lifetimes, contributing to sustainability. Due to the growing relevance of ceramics and their high embodied energy they are worth being recycled, independently from the presence of critical elements. We present the current state of ceramic recycling, highlighting recent progress. We also discuss about the challenges associated with establishing sustainable practices and provide an outlook on the opportunities ahead.

1. Introduction

Ceramics can be found everywhere: from the durable tiles beneath your feet to the high-tech components driving modern technologies – think only about the portable electronic devices around you. Ceramics are thus a fundamental part of both our daily lives and of future innovation. Each ceramic product is designed with specific functionality to suit its intended purpose. Ceramic tiles are designed to balance water absorption and impact resistance while guaranteeing thermal insulation. Dental implants must offer biocompatibility, hardness, mechanical stiffness and fracture toughness, and an aesthetically pleasing appearance. Refractories are built to withstand extreme heat and remain inert under high temperatures and corrosive environments, and the electrolyte of a solid-state battery must enable lithium-ion transport while providing electronical insulation as well as electrochemical stability with the electrode materials.

The variety of materials, their tailored properties and final application fields seem limitless. Traditional ceramics typically rely on more abundant and easily accessible raw materials. For example, a standard floor tile is typically based on 50 % clay, 40 % feldspar, and 10 % quartz [1]. These materials are natural and can often be mined without any complex extraction processes. Their widespread availability and relatively simple processing contribute to lower energy consumption and a smaller ecological footprint compared to the resource-intensive processes [2] needed to obtain critical raw materials (CRMs), which are used in many advanced ceramics. The list of these critical, or in some cases strategic materials, has been continuously extended by the European Union over the years [3]. If we consider the synthesis of advanced ceramics, a large number of precursors such as oxides, hydroxides, and carbonates are needed. As a very common example, the production of zirconia begins with the extraction of zircon sand ($ZrSiO_4$) from regions such as South Africa and Australia, which is then transported to China for further processing. The mineral undergoes energy-intensive and chemically demanding treatments, including reactions with NaOH and HCl, followed by crystallization, washing (to remove impurities like Hf, Th, and U), and drying to produce zirconium oxychloride ($ZrOCl_2$) [4]. This process not only requires extensive transportation across continents but also consumes significant resources including large amounts of water. This situation is not specific to zirconia and can be applied to most of the elements needed for advanced ceramics.

However, despite the lower specific costs (per part or kg), CO_2-footprint, and environmental hazard potential, the high demand for traditional ceramics in the construction and building sector leaves a massive imprint on both the economy (Fig. 1) and the environment as firing relies mainly on the combustion of fossil fuels. The firing is the most energy-intensive step in ceramic production and accounts for the largest share of CO_2 emissions in the manufacturing process, with approximately 265 kg of CO_2 emitted per ton of fired tiles [5]. Around 90 % of the CO_2 emission comes from the three sectors of wall and floor tiles, bricks and roof tiles, and refractories.

* Corresponding author at: Institute of Energy Materials and Devices: Materials Synthesis and Processing (IMD-2), Forschungszentrum Jülich GmbH, Jülich 52425, Germany.
E-mail address: o.guillon@fz-juelich.de (O. Guillon).

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Due to the rapid urbanization, the global tile market reached an estimated value of approximately 107 billion USD by 2024, with an expected annual growth rate of around 7.2 % from 2019 to 2024 [7]. Given the high material consumption in traditional ceramics, circular economy strategies have gained increasing attention over the past two decades. The circular economy is a systemic approach to resource management that aims to preserve the value of materials and products through strategies such as reuse, repair, remanufacturing, and recycling. These strategies follow a hierarchy in terms of sustainability, where closing loops at earlier stages—such as through reuse or repair—typically results in lower environmental burdens compared to more resource-intensive options like recycling. Nevertheless, recycling remains a key pillar of the circular economy, particularly in the ceramic sectors, where it not only reduces dependence on primary raw materials but also has the potential to lower overall energy consumption and greenhouse gas emissions. To enable effective recycling of both traditional and advanced ceramics, five fundamental questions must be addressed:

i. What types of waste are emerging? (e.g. production waste, End-of-Life products, pure or mixed with other materials?)
ii. Where does the ceramic waste go? (e.g. remaining on site, collected centrally or decentralized?)
iii. Which processes can be applied to recover the ceramic materials? (closed or open recycling loops?)
iv. In which applications can the recycled material be used? (e.g. for the same product, alternative products, or in downcycling processes?)
v. Can the recycled product meet the requirements and properties of new/standardized products?
vi. How efficient is the recycling process on an economical and environmental level? (e.g., how much greenhouse gas emissions and waste water can be avoided, which costs can be saved along the whole lifecycle?)

Rather than offering a comprehensive sector-by-sector analysis, this article aims to draw attention to the relevance of circular economy principles within selected areas of the ceramics industry, highlighting opportunities and paving the way for more targeted research and action in the future.

2. Methods for ceramic recycling

To address the questions raised in section 1, an overview of the existing and emerging processes for ceramic recycling are presented. Given the diverse nature of ceramic materials, we again highlight examples concerning End-of-Use (EoU) and End-of-Life (EoL) products. While the terms EoU and EoL are often used interchangeably, they represent different stages in a product's lifecycle. For instance, in the case of vehicle batteries, EoU is typically reached when the battery's performance falls to about 70–80 % of its original capacity, at which point it is no longer suitable for its primary function but may still hold value for secondary uses [8]. To extend the functional lifespan of products further, repair technologies can be employed. For example, Vorkötter et al. [9] demonstrated a laser-cladding-based additive manufacturing process (Clad2Z) for repairing ceramic thermal barrier coatings, offering a targeted and efficient approach for addressing localized damage. However, self-healing and repair strategies for ceramics remain extremely limited and are not yet widely implemented. EoL, on the other hand, marks the final phase, when the product can no longer serve any function and must be properly recycled or disposed. Therefore, recycling is particularly relevant at the EoL-stage, when the product has no remaining potential for secondary use/repair.

2.1. Recycling of construction ceramics

Interestingly, recycling of traditional EoL ceramics has been a well-established practice for many years. Construction and demolition waste (CDW) from the building sector is reused to a significant extent. Data collected between the years 1999 and 2006 indicate that reuse or recycling rates of CDW averaged between 66 % and 86 % in European countries [10]. However, the materials are typically not reused for their original purpose but rather downcycled or even dumped into landfills [11].

For instance, bricks, tiles and concrete are commonly crushed into aggregates and repurposed as backfilling material for applications such as road base layers, the levelling of pipe trenches, and as additive for plant substrates. During mechanical reprocessing, impurities like insulation wool, steel, gypsum, and plastics must be usually separated and sorted [12]. On the other hand, the direct reuse of ceramics for their original purposes poses significant challenges: For example, cleaning used bricks is time and cost consuming, and cement-rich mortars are often difficult to remove. Variability in material quality further complicates matters, as European construction standards demand stringent compliance with precise specifications. For masonry bricks, requirements such as durability and performance are defined in EN 771–1, with standardized tests outlined in EN 772 to evaluate properties like compressive strength and water absorption. In this context, an environmental hierarchy of end-of-life strategies becomes evident: landfilling results in the highest environmental burden, followed by downcycling into low-value applications such as road base layers. In contrast, recycling into higher-quality applications such as aggregates for new concrete offers significant environmental advantages and can lead to environmental impact reductions (person equivalent) of up to 59 % compared to landfilling [13]. These challenges are not unique to bricks but are common across most ceramics, where the implementation of closed-loop recycling remains rare due to the complex trade-off between technical effort, costs, and environmental benefit.

Nonetheless, literature on ceramic tile production provides many examples of successful closed-loop recycling. While approximately 300

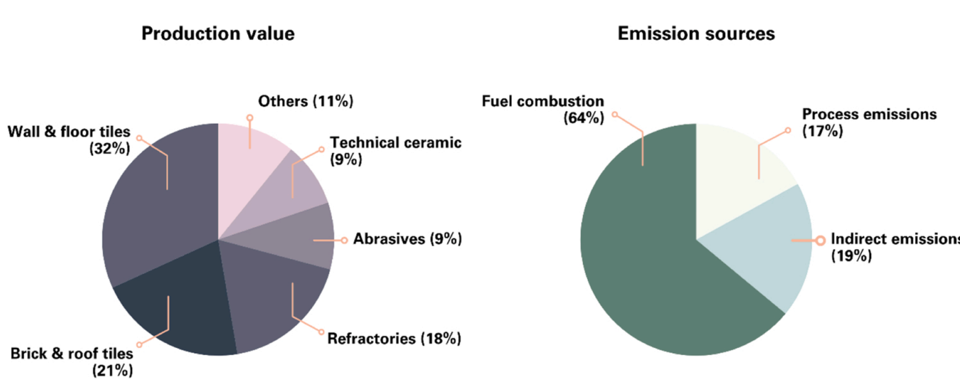

Fig. 1. Ceramics production value by sector and CO_2 emission sources in the European Union, adapted from Cerame-Unie [6].

published studies exist, this represents just the tip of the iceberg, as much of the work conducted by manufacturers and suppliers remains unpublished [14]. A notable example is a study by Rambaldi [15], which demonstrated the effective recycling of soda-lime scrap and unfired scrap tiles into porcelain stoneware on a pilot scale. The resulting material, with 85 wt% recycled content, retained critical properties such as water absorption and mechanical strength, meeting ISO standards for traditional stoneware. In this study, the recycling process achieved a cost reduction of approximately 33 % and significantly lowered the environmental impact. The relative contribution of CO_2-equivalent emissions from the spray-drying step, for example, was reduced from 24 % in conventional ceramic powder production to just 1 % in the recycled variant. This percentage refers to the share of total emissions associated with raw material supply, transport, and manufacturing.

2.2. Recycling of structural ceramics

Another example is the recycling of refractory materials such as magnesia-carbon (MgO-C) bricks. Arainpour et al. [16] investigated a closed-loop remanufacturing process for spent MgO-C bricks derived from electric arc and ladle furnaces. In their study, up to 30 wt% of virgin raw material was replaced with recycled aggregates, which were reprocessed to achieve comparable particle sizes. Despite minor variations in apparent porosity, the physico-mechanical properties of the partially recycled refractories remained largely unaffected. Similarly, Ludwig et al. [17] and Lauermannová et al. [18] confirmed that incorporating 30–50 wt% recycled material maintained material performance. Additionally, they validated the application of a non-hazardous binder system (lactose- and tannin-based) in the manufacturing process.

Similar principles apply to the recycling of advanced materials such as tungsten carbide with cobalt (WC-Co) and silicon carbide (SiC), which are widely valued for their exceptional hardness, thermal stability, and wear resistance, making them indispensable in industrial cutting tools and abrasives. For WC-Co, the recycling of grinding sludges, which contain abrasives, lubricants, and hard metal chips, is the predominant approach. Direct recycling processes, which bypass chemical treatments and reuse materials directly, are less common but offer potential for further development, as highlighted by Pacini et al. [19]. For SiC, innovative recycling technologies have been developed to address industrial by-products effectively. A notable example is the *RECOSIC©* process, patented by ESK-SiC GmbH [20]. This method recovers SiC from by-products of the Acheson process or other high-SiC-content materials, refining them into silicon carbide with a purity grade of 99 % or higher.

In contrast to direct reuse, Hossain and Roy [7] reviewed various studies that explored the integration of different production wastes and industrial by-products into new ceramic materials. This includes the use of rice husks as a replacement for coal and quartz in the production of silicon carbide (SiC), the substitution of feldspar minerals with glassy waste for sanitary ware manufacturing, and the incorporation of eggshells as a precursor material for the preparation of hydroxyapatite (HAp), used in biomedical bone grafting (Fig. 2). These methods can even be considered as a form of upcycling, where waste materials are not merely repurposed but transformed into higher-value products.

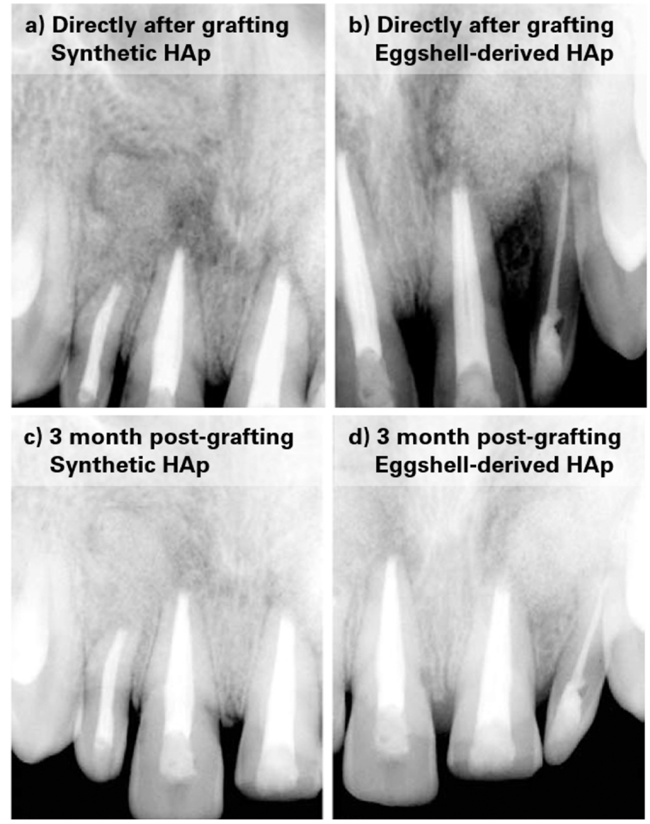

Fig. 2. Intraoral radiographs showing bone defects treated with commercially available hydroxyapatite (HAp) and eggshell-derived HAp. (a,b) Directly after grafting. (c,d) Three month post-grafting. Image adapted from Kattimani et al. [21].

2.3. Recycling of ceramics in energy technologies

With the growing interest and expansion of renewable energy technologies, the demand for advanced ceramics in applications such as batteries and electrolyzers has risen significantly. The recycling processes for these materials, however, vary greatly depending on their composition and the technology used.

First, let us take a look at common practices in Li-ion battery recycling: after disassembling the battery's housing, primary separation steps, such as crushing, flotation and mechanical separation are used to break down the battery into its components [22]. In some processes, pyrolysis is employed and organic components, such as electrolytes and binders, are thermally decomposed and lost. The remaining fraction is known as "black mass." The black mass consists mainly of cathode active materials in form of secondary particles. These metal oxide particles contain CRMs such as Li, Co, Mn, Ni, and, in some cases, rare earth elements (REEs). For the recovery of these valuable metals, two main recycling methods are commonly employed: pyrometallurgy and hydrometallurgy. In pyrometallurgical recycling, high-temperature smelting is used to melt the ceramics and separate the various materials based on their different melting points. On the other hand, hydrometallurgical processes involve the use of aqueous solutions to leach valuable metals from the ceramics, followed by recovery via precipitation reactions or electrochemical methods. Direct reuse without any elaborate pre-treatment is not yet established on an industrial scale but shows promising results in research, such as the successful regeneration of spent $LiFePO_4$ cathodes via room-temperature lithiation with ethanol, as shown by Nadir et al. [23]. It has also been successfully applied to solid-state battery production wastes containing lithium lanthanum zirconate garnet by Kiyek et al. [24].

Although recycling processes of EoL batteries usually requires multiple separation and extraction processes, there are indeed several companies dedicating efforts to recycling at large-scale. One example is the company Li-Cycle, which operates a network of recycling facilities, known as *Spokes*, in North America and Europe. These facilities have the capacity to process up to 80,000 tonnes of battery material annually. At these *Hub* facilities, the black mass obtained undergoes further refinement to recover battery-grade materials for reuse (Fig. 3) [25].

The knowledge and advancements achieved in battery recycling can serve as a benchmark for developing effective recycling strategies for complex material compounds involving ceramics. Solid oxide cells

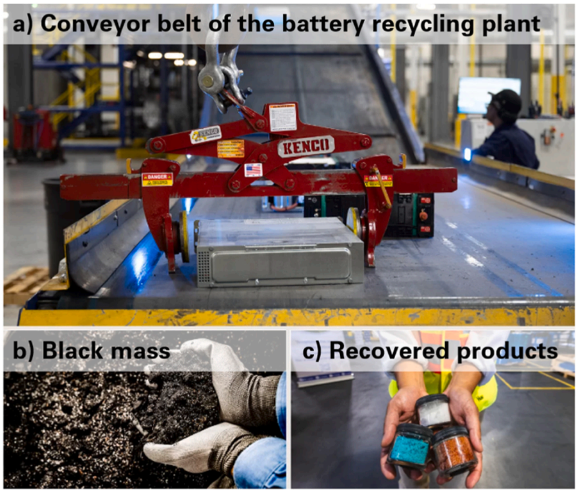

Fig. 3. Insights into the battery recycling plant of the Canadian company Li-Cycle. Image adapted from Li-Cycle Holdings Corp [25].

(SOCs), a rapidly growing technology in green hydrogen production by high-temperature steam electrolysis and energy conversion as fuel cells face similar challenges. While SOCs are still in the early stages of market adoption, establishing EoU/ EoL handling processes and applying an eco-design approach at this stage is crucial.

SOCs rely heavily on specialized stainless steels and advanced ceramic cells, which incorporate similar CRMs such as Ni, Co, Sr, and REE-stabilized zirconia (e.g. Yttria-stabilized zirconia, YSZ). Like in the batteries, these materials are both high-value and resource-intense, making efficient recycling pathways essential. Drawing lessons from battery recycling, SOC recycling must emphasize automated dismantling, separation and suitable recovery processes for the ceramics in the near future. Recent studies have demonstrated the feasibility of closed-loop recycling for ceramic components of SOCs. For example, Sarner et al. [26] showed that after an initial leaching step, significant quantities (about 85 wt%) of EoU ceramics remains, which can partially be reintroduced into the production of new substrate material. While slight variations in shrinkage behavior and effects on the microstructure evolution were observed, these differences were found to be predictable and manageable, depending on the proportion of recycled powder is used to replace the pristine raw materials (Fig. 4).

From the examples highlighted in this section, it becomes clear that closed-loop recycling or even upcycling approaches of ceramics remains (generally) rare, especially for advanced ceramics and complex components consisting of multilayers like capacitors, batteries and SOCs.

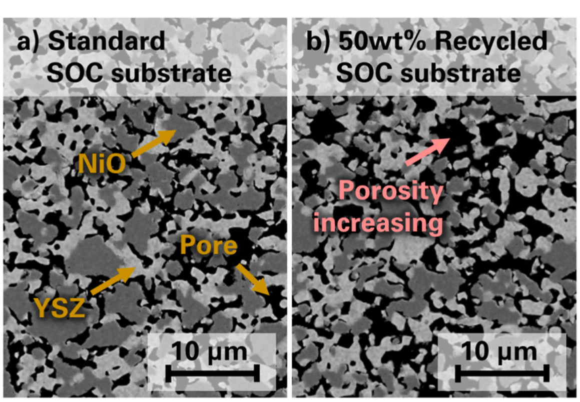

Fig. 4. Microstructure of non-recycled (a), and 50 wt% (b) recycled solid oxide cell substrates (SOC), processed at Forschungszentrum Jülich. YSZ = yttria-stabilized zirconia. Image adapted from Sarner et al. [26].

While innovative and promising methods have demonstrated the feasibility of recycling for various ceramic applications, significant scale-up is currently observed only in the field of batteries. Why is widespread ceramic recycling not yet a reality? To answer this, we must explore the technical, economic, and regulatory hurdles that limit broader adoption of recycling processes across the ceramic industries.

3. Challenges and future directions

We have repeatedly emphasized that the versatile application fields of ceramics contribute significantly to the complexity of recycling processes, particularly when considering the diverse materials involved in devices and manufacturing methods involved.

Ceramic waste collection is one major issue and typically occurs through a variety of channels: In industrial settings, waste from manufacturing processes is often captured and sorted at the production site. In the case of traditional ceramics such as tiles or bricks, manufacturers typically separate defective products or off-cuts during production, which are then stored for reuse or sent for recycling – this is considered the easy part. However, post-consumer ceramic waste, such as old tiles or broken sanitary ware, electronic waste, etc. requires a more complex approach. At industrial level, dedicated recycling centers are responsible for collecting and sorting these materials. The sorting process is often done manually or mechanically, with materials first being crushed or broken down into smaller pieces for easier handling. For certain types of ceramics, like tiles or bricks, sorting can involve separating different types of ceramic materials based on their composition or surface treatment. Some recycling facilities implement advanced sorting technologies, such as sensor-based sorting systems (e.g., X-ray or infrared), to differentiate between ceramic types or to remove contaminants like metals, plastics, and glass, which may be present in composite materials, components and devices [27]. One significant hurdle in collecting ceramic waste is that ceramics are not typically separated at the source. Unlike metals or plastics, which are often segregated at the point of disposal, ceramic waste may be mixed with other materials such as glass, plastic, or concrete, making the initial sorting phase more cost-intense. In the case of advanced ceramics, such as those used in electronics, batteries or electrolyzers, this problem is even more pronounced, as these materials often contain valuable CRMs or specialty metals that require precise sorting and separation to recover efficiently.

In response to these challenges, the European Union introduced *Directive 2008/98/EC*, which set a target to recycle at least 70 % by weight of non-hazardous C&D waste by 2020. However, this weight-based approach is not suitable for the recycling of advanced ceramics. Since CRMs are embedded in small fractions within larger systems (including metal parts and balance-of-plant components), a more targeted approach to recovery is necessary. This is exemplified by the Regulation *(EU) 2023/1542 on Batteries and Waste Batteries*, which mandates the recovery of specific CRMs fractions. The regulation also sets a minimum collection rate for certain types of batteries, such as 51 % for light-duty vehicle batteries starting in 2028. Furthermore, the introduction of a digital product passport for future batteries will enable the identification and tracking of battery components throughout their lifecycle. This framework provides a clear and well-structured foundation for material recovery and is not only effective for batteries but also offers valuable insights and a potential blueprint for advancing the recycling of other complex ceramic materials.

Even if the hurdles of sorting, separation, storage, supply chains, and information management can be overcome, two major challenges still persist as highlighted by Wesselkämper and Delft [28]. First, despite being widely marketed, products like batteries still face low return rates. It's difficult to predict product lifecycles accurately, as they depend on usage and other unpredictable factors. This current lack of input complicates the collection and recycling systems, leading to inefficiencies in material recovery and hindering the establishment of closed-loop systems. Second, recycling efficiency is not only about the purity of the recovered materials. The composition and structure of the products play a significant role. Advanced ceramics often contain complex material mixtures, sometimes with additional protective coatings, engineered interfaces and grain boundaries. Without standardization in product design and material composition, recycling processes can be inconsistent and require different costly approaches for each product. Achieving high-quality material recovery in terms of chemical composition and physical properties, is already a major challenge. Standardization could help address this issue, but for now it remains a barrier in the recycling industry.

Finally, to ensure the future success of ceramic recycling, a shift toward recycling-friendly design is essential. This is often referred to as *Design for Recycling*. It emphasizes the creation of products that are easier to disassemble, separate, and recycle at EoL-stage. By integrating this philosophy into the design process, manufacturers can enhance the efficiency of recycling systems and improve material recovery rates. Standardization of materials composition could definitely help, at the cost of product differentiation. Additionally, designing architecture, joining and housings that enable easier separation of different components would also help streamline the disassembly process for a better recover and reduced contamination. The development of standardized guidelines for ceramic product design, combined with innovation in material science, will likely drive the adoption of recycling-friendly principles. Direct recycling at the production site will also need to be integrated, leading to substantial cost reduction and reduced environmental footprint. Companies will need to collaborate with recyclers to better understand the challenges involved and to ensure that the materials used are compatible with existing or emerging recycling technologies. In addition, it is crucial to employ automated assessments, such LCA, to accurately evaluate the environmental impacts of recycling processes, as not all recycling approaches inherently lead to environmental gains. Some may inadvertently cause issues like wastewater generation or other unintended consequences, which could undermine the potential benefits of recycling.

4. Conclusion

The future of ceramic recycling will depend on a shift towards recycling-friendly design principles, where manufacturers prioritize disassembly, material simplicity, and compatibility with existing recycling technologies. Collaborative efforts among governments, industries, and recyclers will be crucial to overcoming technical, economic, and regulatory challenges.

As raw material suppliers face increasing pressure from tightening resource availability and more stringent regulatory frameworks, there will likely be a growing interest in viewing recycling as a viable business model. This shift could provide new economic opportunities, as the demand for recycled materials intensifies. Additionally, tailoring products for specific customer uses and applications may create challenges in balancing recyclability with performance. In many applications, the limits of the maximum allowable content of recycled materials still need to be explored, as the ideal balance between performance and recyclability is yet to be fully defined. Moreover, we currently lack a clear understanding of what happens after multiple recycling loops, especially in the final stages of recycling, where material degradation or the accumulation of impurities could impact quality.

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CRediT authorship contribution statement

Sarner Stephan: Writing – original draft, Investigation. **Guillon Olivier:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] S. Fu, J. Lee, Recycling of ceramic tile waste into construction materials, Dev. Built Environ. 18 (2024) 100431, https://doi.org/10.1016/j.dibe.2024.100431.
[2] A. Manhart, R. Vogt, M. Priester, et al., The environmental criticality of primary raw materials – a new methodology to assess global environmental hazard potentials of minerals and metals from mining, Min. Econ. 32 (1) (2019) 91–107, https://doi.org/10.1007/s13563-018-0160-0.
[3] European Commission, Directorate-General for Internal Market I Entrepreneurship and SMEs, Grohol M, Veeh C. Study on the critical raw materials for the EU 2023 – Final report, Publ. Off. Eur. Union (2023), https://doi.org/10.2873/725585.
[4] C. Perks, G. Mudd, Titanium, zirconium resources and production: A state of the art literature review, Ore Geol. Rev. 107 (2019) 629–646, https://doi.org/10.1016/j.oregeorev.2019.02.025.
[5] H. Jouhara, D. Bertrand, B. Axcell, et al., Investigation on a full-scale heat pipe heat exchanger in the ceramics industry for waste heat recovery, Energy 223 (2021) 120037, https://doi.org/10.1016/j.energy.2021.120037.
[6] Ceramic roadmap to 2050. Brussels: Cerame-Unie - The European Ceramic Industry Association; 2021.
[7] S.S. Hossain, P.K. Roy, Sustainable ceramics derived from solid wastes: a review, J. Asian Ceram. Soc. 8 (4) (2020) 984–1009, https://doi.org/10.1080/21870764.2020.1815348.
[8] L.C. Casals, B.A. García, C. Canal, Second life batteries lifespan: Rest of useful life and environmental analysis, J. Environ. Manag. 232 (2019) 354–363.
[9] C. Vorkötter, D.E. Mack, R. Vaßen, O. Guillon, Additive manufacturing of columnar thermal barrier coatings by laser cladding of ceramic feedstock, Adv. Mater. Technol. 7 (10) (2022) 2200098.
[10] Report on the management of construction and demolition waste in the EU. European Commission (DG ENV), Bio Intelligence Service; 2011.
[11] C.K. Purchase, D.M. Al Zulayq, B.T. O'Brien, et al., Circular economy of construction and demolition waste: a literature review on lessons, challenges, and benefits, Materials 15 (1) (2022) 76, https://doi.org/10.3390/ma15010076.
[12] S. Bosoc, G. Suciu, A. Scheianu, I. Petre. Real-time sorting system for the Construction and Demolition Waste materials. *2021 13th International Conference on Electronics, Computers and Artificial Intelligence (ECAI)*. 2021:1–6. 10.1109/ECAI52376.2021.9515117.
[13] A. Di Maria, J. Eyckmans, K. Van Acker, Downcycling versus recycling of construction and demolition waste: Combining LCA and LCC to support sustainable policy making, Waste Manag. 75 (2018) 3–21, https://doi.org/10.1016/j.wasman.2018.01.028.
[14] C. Zanelli, S. Conte, C. Molinari, R. Soldati, M. Dondi, Waste recycling in ceramic tiles: a technological outlook, Resour. Conserv. Recycl. 168 (2021) 105289, https://doi.org/10.1016/j.resconrec.2020.105289.
[15] E. Rambaldi, Pathway towards a high recycling content in traditional ceramics, Ceramics 4 (3) (2021) 486–501, https://doi.org/10.3390/ceramics4030036.
[16] F. Arianpour, F. Kazemi, F.G. Fard, Characterization, microstructure and corrosion behavior of magnesia refractories produced from recycled refractory aggregates, Miner. Eng. 23 (3) (2010) 273–276, https://doi.org/10.1016/j.mineng.2009.11.001.
[17] M. Ludwig, E. Śnieżek, I. Jastrzębska, et al., Recycled magnesia-carbon aggregate as the component of new type of MgO-C refractories, Constr. Build. Mater. 272 (2021) 121912, https://doi.org/10.1016/j.conbuildmat.2020.121912.
[18] A.-M. Lauermannová, O. Jankovský, T.M.J. Stadtmüller, E. Storti, C.G. Aneziris, Eco-friendly lactose/tannin-based binder in MgO–C refractories produced from MgO–C recyclate, Ceram. Int. 50 (21, Part A) (2024) 40823–40829, https://doi.org/10.1016/j.ceramint.2024.07.372.
[19] A. Pacini, F. Lupi, A. Rossi, M. Seggiani, M. Lanzetta, Direct recycling of WC-Co grinding chip, Materials 16 (4) (2023) 1347, https://doi.org/10.3390/ma16041347.
[20] M. Hausmann, W. Klietz, J. Garbes, Method for purifying silicon carbide, European Union EP3997033A1 (2022).
[21] V. Kattimani, K.P. Lingamaneni, P.S. Chakravarthi, T.S.S. Kumar, A. Siddharthan, Eggshell-derived hydroxyapatite: a new era in bone regeneration, J. Craniofacial Surg. 27 (1) (2016) 112, https://doi.org/10.1097/SCS.0000000000002288.
[22] Y. Miao, L. Liu, Y. Zhang, Q. Tan, J. Li, An overview of global power lithium-ion batteries and associated critical metal recycling, J. Hazard. Mater. 425 (2022) 127900, https://doi.org/10.1016/j.jhazmat.2021.127900.
[23] T. Ouaneche, M. Courty, L. Stievano, et al., Room temperature efficient regeneration of spent LiFePO4 by direct chemical lithiation, J. Power Sources 579 (2023) 233248, https://doi.org/10.1016/j.jpowsour.2023.233248.

[24] V. Kiyek, M. Hilger, M. Rosen, et al., Waste minimization in all-solid-state battery production via re-lithiation of the garnet solid electrolyte LLZO, J. Power Sources 609 (2024) 234709, https://doi.org/10.1016/j.jpowsour.2024.234709.
[25] Li-Cycle-Homepage, Li-Cycle Holdings Corp., accessed: November 2024. ⟨https://li-cycle.com/technology⟩.
[26] S. Sarner, N.H. Menzler, A. Hilgers, O. Guillon, Recycling and reuse strategies for ceramic components of solid oxide cells, ECS Trans. 111 (6) (2023) 1369, https://doi.org/10.1149/11106.1369ecst.
[27] G. Maier, R. Gruna, T. Längle, J. Beyerer, A survey of the state of the art in sensor-based sorting technology and research, IEEE Access 12 (2024) 6473–6493, https://doi.org/10.1109/ACCESS.2024.3350987.
[28] J. Wesselkämper, S. Von Delft, Current status and future research on circular business models for electric vehicle battery recycling, Resour., Conserv. Recycl. (2024).

Olivier Guillon: Following an engineering degree at the Alès School of Mines (France), Professor Olivier Guillon completed his PhD on the non-linear behaviour of ferroelectric ceramics. He then joined the group of Professor Jürgen Rödel at TU Darmstadt, Germany, and established a DFG funded Emmy Noether Group on new ceramic processes. After spending two years at the Friedrich Schiller University of Jena as Professor of Mechanics of Functional Materials, he became Director at the Institute of Energy and Climate Research (now Insitute of Energy Materials and Devices) - Materials Synthesis and Processing at Forschungszentrum Jülich, Germany and Professor at the RWTH Aachen University in 2014. He is fellow of both European and American Ceramic Societies and member of the World Academy of Ceramics. His research interests encompass sintering, solid-state batteries, solid oxide fuel/electrolysis cells, gas separation membranes and ceramic barrier coatings.