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Review

Exploring circularity in ceramic 3D printing: Possibilities and implementation

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A R T I C L E I N F O

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A B S T R A C T

Nowadays, concepts such as recycling, reusing, and sustainability are gaining ground in a wide range of fields and sectors, including manufacturing. This paradigm shift from "produce-dispose" to "produce-reuse" is pushing manufacturers and producers to move from a linear economy to a circular one. This change in perspective seems more readily applicable to the world of additive manufacturing, as it offers the potential not only to reduce waste generation, but also to reintroduce discarded and recycled materials into the production chain. This implementation of a circular manufacturing approach could be applied to ceramic additive manufacturing. Is it a straightforward process to implement a circular solution into the production chain? Which are the implications for costs, energy requirements, emissions, and waste management? This open discussion aims to identify potential starting points and gaps for further evaluation of future application of circular economy concepts in the ceramic industry.

1. Introduction

Looking at recent literature, many authors investigated the relationship between circular economy and additive manufacturing, especially how the 3D printing technologies can be considered a sustainable approach for objects fabrication and the impact that their introduction in production process chain could have. However, a lack of practical examples of circular system implementation in the ceramic additive manufacturing context has been found. The aim of this work is to summarize the examples that can be found in literature up to now and introduce an open discussion about the possibility for the future of ceramic additive manufacturing industry in circular economy context. In the next paragraphs, a short overview of some additive manufacturing technologies for ceramic 3D printing is presented, then a brief definition of circular economy and recycling is introduced. Subsequentially, a preliminary evaluation, based on the restricted number of sources available in the literature databases on the topic, of a possible approach for circularity in ceramic manufacturing through 4 different additive technologies is reported, considering recycling as the starting point for this purpose.

1.1. Additive manufacturing of ceramic materials

The term additive manufacturing (AM) refers to every fabrication process that involves the joining of material layer by layer to obtain a final component, starting from a 3D virtual model. This methodology differs from the traditional subtractive and formative manufacturing techniques because there is no need for material removal from a massive block or the use of molds and forms. Instead, the addition of new material at each fabrication stage is required [1]. AM technologies, commercially known as 3D printing technologies, have been applied in different fields over the years, thanks to their flexibility and to the expansion of materials availability.

Notably, the use of AM in the production of ceramic parts has garnered significant interest. Shaping ceramics through traditional manufacturing processes poses several challenges, mainly linked to defect-free manufactured parts, high tool wear and difficult complex structure generation. Grinding, molding, pressing, machining and heating processes carry with them high tool costs, time consuming fabrication chains, low complex manufactured parts and low process yield, especially in technical ceramics manufacturing, like metal oxides,

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carbides and nitrides [2–4]. Moving from traditional shaping techniques to AM technology in ceramic material manufacturing has shown various advantages. Firstly, there has been a notable reduction in tooling costs and fabrication time, as multiple shaping stages are not required in the production of the component [2]. Moreover, AM technologies application in ceramic materials manufacturing enables the fabrication of porous and lattice lightweight structures, reducing cracks formation thank to the optimization of printing parameters and post processing treatments [3]. Other pros in the use of AM with ceramic materials are the mass customization and high precision, resolution and accuracy fabrication of parts. Optimized topology with incorporated specific functionality can be easily produced using AM as shaping technologies for ceramics, ensuring high performances parts for different applications [4,5]. Additionally, ceramic AM (CerAM) technologies ensure a versatile and shorter supply chain, whose production part can be managed all in-house [5]. This is also linked to the production and diffusion of desktop-size printers, leading to the reduction of storage, packaging and transportation needs for ceramic objects [4]. The general process chain in CerAM can be depicted as in the Fig. 1.

Several AM technologies have been introduced into the ceramic world for material shaping steps.

According to ISO/ASTM 52,900:2021 classification, AM technologies include material extrusion (MEX), binder jetting (BJT), vat photopolymerization (VPP) and material jetting (MJT), powder bed fusion (PBF), direct energy deposition (DED) and sheet lamination [1], and some of them have been directly transformed from polymeric AM into CerAM. The explanation of all the ASTM categories of AM technologies is out of the scope of this work, that would be mainly focused on the description and analysis of 4 main AM technologies applied in the field of CerAM, together with the possible combination of them with circular economy concepts. Choosing between them is strictly related to the materials composition, resolution, and dimensional accuracy desired.

Working with CerAM means to consider a general rule: during Computer Aided Desing (CAD), consider that a dimensional variation happens at the end of the process, due to printing, debinding and sintering stages as well as to every type of post processing step applied [6]. Depending on the specific CerAM technology, some differences in the workflow can appear, because of raw materials preparation, composite preparation, printing process; but each CerAM technique requires thermal post processing, to eliminate every residue of non-ceramic materials (debinding, a crucial step for subsequent densification of the material, that can be solvent – based too) and to consolidate the part (sintering). Lastly, some machining processes could be applied to the dense body in order to finish the final part [7].

Firstly, having an insight into CerAM technologies is essential to understand the requirements and the possible implementation of the fabrication chain.

Here below, a short summary of the already cited technologies is reported (Table 1 and Fig. 2), followed by some images of ceramic parts printed through different technologies (Fig. 3).

1.2. *Circular economy today and 5R principle*

Nowadays, there is a growing demand for switching from a linear economy, that refers to the traditional process chain “take-make-dispose” [21], into a circular economical system. Circular economy (CE) concept has been deeply analyzed in literature, with the objective of defining what can be considered circular or not, and a fairly comprehensive definition of CE could be found in Kirchherr et al. [22] work. They assessed that this model is “*a regenerative economic system which necessitate a paradigm shift to replace the ‘end-of-life’ concept [...] with the aim to promote value maintenance and sustainable development, creating environmental quality, economic development and social equity, to the benefit of current and future generation*”. Their definition of CE came from

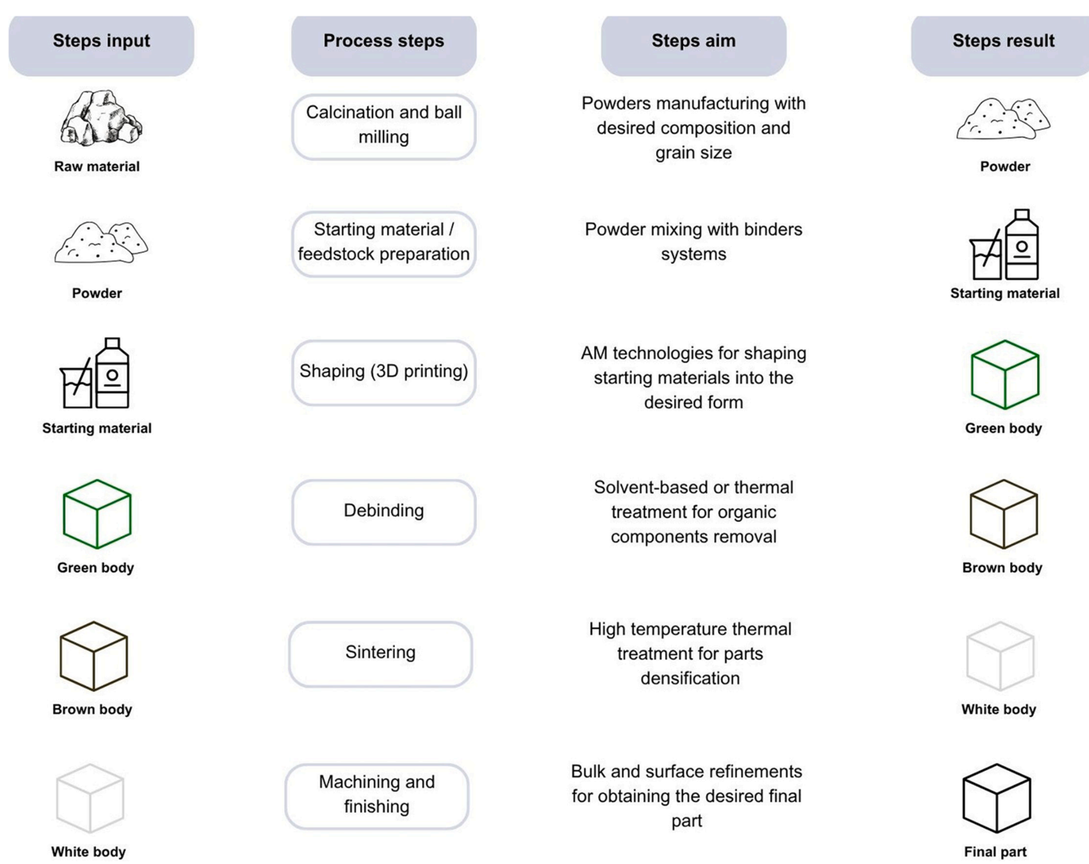


Fig. 1. General process chain in fabrication of ceramic objects, with AM technologies as shaping methodology (CerAM).

Table 1
Summary of CerAM processes, advantages and disadvantages, that represents the background of this study.

Technology name	Deposition process	Advantages	Disadvantages	Ref.
Binder Jetting (CerAM BJT)	Selective deposition of a liquid polymeric bonding agent into a dry ceramic powder bed.	Large size parts, high design flexibility, no support structures requirements, wide ceramics availability, high throughput, stacking of parts during printing, scalable printing set up.	Low surface quality, high porosity (dense parts need an additional infiltration step, e.g. SiSiC) and low density, high shrinkage, low resolution due to powder grains size.	[1,6,8–10]
Material extrusion (CerAM MEX)	Selective deposition of materials through a nozzle or orifice, which extrude material, in form of feedstocks, filaments (Fused Filament Fabrication – FFF) or suspensions (Direct Ink Writing - DIW), continuously.	Low equipment costs, high performance, multi-material capability, high dense ceramic parts, wide spreading (large community of users) - FFF. Porous or dense components with complex geometries and relatively high precision, fast, cheap and versatile technology, open-source machines, low scales- DIW.	Low resolution, low surface quality and poor finishing, high surface roughness, long printing times are required for complex geometries, supports are required for overhangs, lack of information about the mechanical properties.	[6,9–13]
Material jetting (CerAM MJT)	Selective deposition of a dispersion of ceramic materials in a polymer-based medium or a water-based one through a drop-by-drop process.	High accuracy, low surface roughness, high resolution, enhanced shape retention of printed parts, possibility of using support material and a construction one with an MMJ approach.	High costs and low productivity, poor mechanical characteristics (related to anisotropy and dependency on printing orientation), bumps and staircase effects on the surface, long printing time, possible nozzle clogging.	[1,6,7,10,14]
Vat Photopolymerization (CerAM VPP)	Selective irradiation of a photoreactive polymer-based resin stored in a vat, through a laser (typical from stereolithography, SLA) or a projector equipped with a digital micromirror device (DMDs) chip typical for digital light processing (DLP). The growing orientation could be top-down or bottom-up, depending on printers.	High resolution and accuracy, allowing the fabrication of relatively small objects with very complex geometry, highly dense parts, thin layer thicknesses.	Relatively small building volume, high costs for equipment and materials, low productivity, limited materials availability, material dependency from optical properties.	[1,6–8,10,11,14–16]

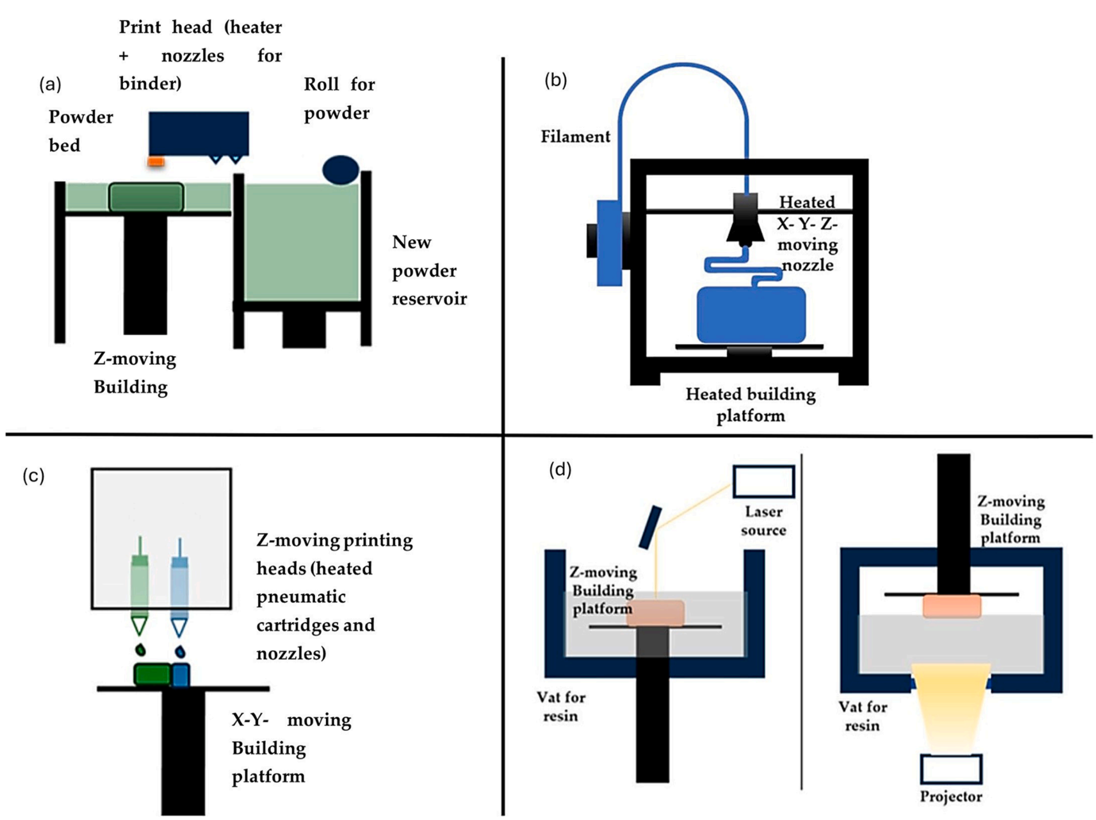


Fig. 2. Working principles of different CerAM technologies: (a) BJT technology; (b) MEX (FFF) technology; (c) MJT technology; (d) VPP technologies, in particular SL on the left side and DLP on the right side. Graphics (b) and (d) are reprinted from [11].

the literature screening that they performed, by combining their queries and the relative results. Nevertheless, despite the lack of consensus on the CE definition, there is a general agreement that it is based on the idea of rethinking the cradle-to-grave approach [23], setting up a regenerative economy recognizing the highest possible value and the longest life to products, materials and components. As exposed in the Ellen MacArthur Foundation analysis [24], this aim could be pursued considering the pillars of CE, which were identified as: controlling over the natural resources' exploitation, reaching goods maximum yield through circulation, eliminating external negative impacts. Furthermore, the authors

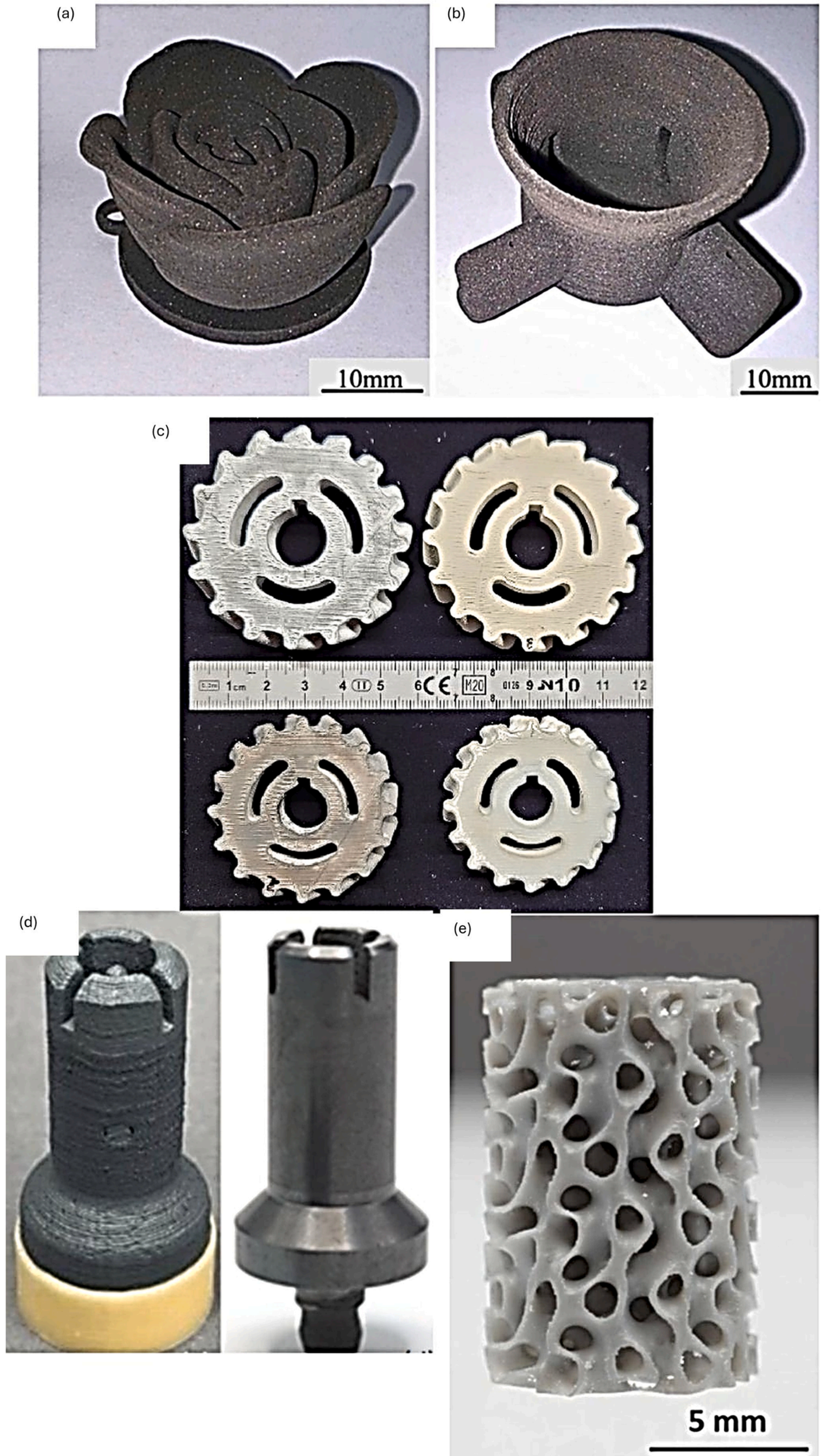


Fig. 3. Example of CerAM printed objects, through different technologies: (a) and (b) a rose and an impeller-like structure in Al_2O_3 fabricated through CerAM BJT; (c) gears in SiC (on the left) and Si_3N_4 (on the right) fabricated through CerAM MEX (FFF), before and after sintering; (d) a ceramic plasma plug fabricated through CerAM MMJ; (e) triple periodic minimal surfaces component in Si_3N_4 fabricated through CerAM VPP. (a) and (b) are reprinted from Additive manufacturing, vol. 79, Z. Yang, L. Yang, P. Wang, Z. Peng, Y. Niu, W. Jiang, Z. Fan, "Effect of sintering aid combined vacuum infiltration on the properties of Al2O3-based ceramics via binder jetting", 2024, with permission from Elsevier [17]. (c) is reprinted from [18]. (d) is reprinted from [19]. (e) is reprinted from Journal of the European Ceramic Society, vol. 43, issue 2, E. Schwarzer-Fischer, E. Zschippang, W. Kunz, C. Koplin, Y. M. Löw, U. Scheithauer, A. Michaelis, "CerAMfacturing of silicon nitride by using lithography-based ceramic vat photopolymerization (CerAM VPP)", 321–331, 2023, with permission from Elsevier [20].

delineated how to reach the goal, highlighting the basis of CE, like minimizing wastes, using renewable energy sources, adapting product costs to real production cost, enhancing cooperation within bigger and smaller companies, and between companies and real world. The benefits of CE approach are reported in the work of Shanmugam et al. [25]; they claimed that applying CE model can help innovation, raw material saving, improve efficiency, reduce CO_2 emission and extend product lifetime. To achieve a concrete example of circularity, it is important to keep in mind the 5R principle (Redesign, Reduction, Recovery, Reuse, Recycle), which define the path for a more sustainable design, fabrication and use of fabricated objects [23,26].

-. Redesign means the re-thinking of the parts/objects with the objective of extending their lifespan, also ensuring an easier repair of damaged structures.
-. Reduction implies a decrease in wasteful and non-recyclable materials, as well as in the exploitation of natural resources.
-. Recovery, also known as renew, stands for the use of objects/parts that are considered wastes for a certain application with a new purpose, avoiding their disposal and giving them a second life.
-. Reuse entails using objects as many times as they can withstand. This includes any repairs that may be necessary.
-. Recycling is the best-known “R”, it includes the recovery of waste, from fabrication processes or from the end-of-life parts to create new objects.

These 5 actions involve resource costs in terms of energy, money and emission, whether large or small; choosing between them means choosing the best compromise. In this context, many initiatives were presented all over the World, as the European Commission’s ‘Circular Economy Action Plan’ of March 2020, whose aim was to reduce waste, to promote redesign and to encourage repairing, prolonging devices lifetime in the resources intensive sectors [27].

AM technologies can represent a possible way to implement circularity, as suggested from several literature examples. A complete overview of the benefits and the limits associated with the application of AM for CE is presented in the work of Tavares et al. [28]. The work presented a systematic literature review and interviews of experts in the field on the topic, highlighting the possible ways to overcome current limitations. The results of their research are presented in the Fig. 4.

As shown in Fig. 4, the benefits were divided into 6 categories: regenerate – share – optimize – loop – virtualize – exchange, derived from ReSOLVE framework [24]. Instead, the barriers were divided into general and specific barriers; the first comprising problems related to the general introduction of circularity in a certain context, the latter related to ReSOLVE structure. The AM technologies benefits reported can be considered the driving forces for CE, thanks to the promotion of biodegradable materials use in AM (Regenerate), the extension of product life through an improved design phase (Share), the improvement in production chain efficiency (Optimize), the promotion of remanufacturing of components (Loop), the dematerialization (Virtualize), the substitution of old manufacturing material with advanced one (Exchange). What emerges from their review is that AM could be useful in the CE context, seeing all the benefits shown, but more efforts should be made to let consumers understand the value of the circular model. Nonetheless, more money should be invested to let AM technologies development advance, addressing current limitations [28].

The concept of CE is frequently associated with that of sustainability. This is because CE enables the identification of priorities, such as process carbon footprint, material consumption, products environmental impact, as well as business and policy changes, as stated by the World Business Council for Sustainable Development (WBCSD) [21]. AS for CE, there is no universally accepted definition of sustainability, it is only possible to look at its underlying three principles to derive a meaning for this concept. Sustainability is strongly dependent on the economy, society and environment. By examining the economic, social, and environmental implications of a process, object, or solution, it is possible to define if a process/objects/solution can be considered sustainable or not, obtaining a trade-off between them [29]. To better understand if a process can fit the sustainability requirements, it is possible to rely on the 17 Sustainable Development Goals (SDGs), proposed by the United Nation in 2015, for styling sustainable approaches for global welfare

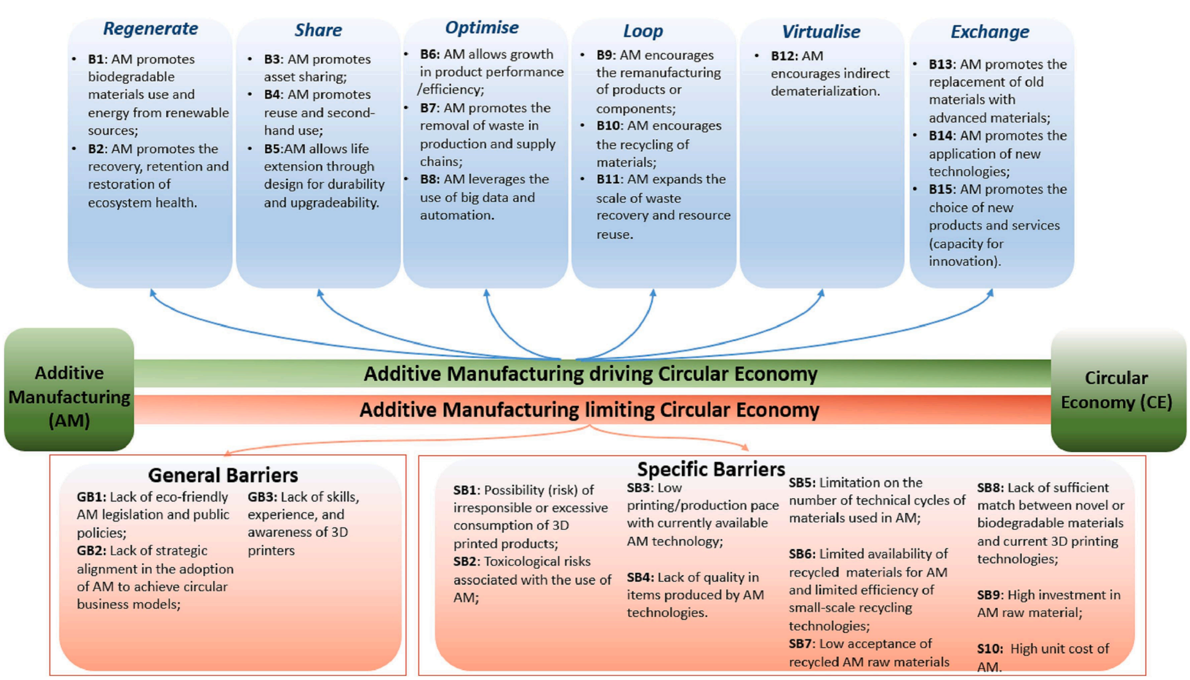


Fig. 4. Correlation between CE and AM, with in blue the benefits related to the use of AM considering CE framework, and the barriers that should be overcome to really implement CE through AM technologies in red. Reprinted from Sustainable Production and Consumption, vol. 37, T. M. Tavares, G. M. D. Ganga, M. G. Filho, V. P. Rodrigues, “The benefits and barriers of additive manufacturing for circular economy: A framework proposal”, pag. 369–388, 2023, with permission from Elsevier [28].

[30].

Many authors have already discussed the sustainability of AM, like Calignano and Mercurio [31], who questioned about the impact of AM introduction into industry, highlighting the related effects on different levels. The scheme in Fig. 5 below summarizes the elements that contribute to enhance sustainability of AM technologies, like reduction in critical raw materials (CRM) exploitation.

Focusing on CerAM, a first evaluation of its sustainability can be found in the work of Villa et al. [32], that analyzed the economic, social and environmental impact of these fabrication processes, connecting them to CE approach and underlying their strict correlation, as they showed in the Fig. 6.

One of the typically used approaches to evaluate sustainability and the compliance of a process/product/part with the CE values is Life Cycle Assessment (or Analysis, LCA). It is an evaluation process that considers all the environmental effects throughout its entire lifetime, including not only its production steps but also its disposal [33]. As for other fabrication processes, LCA for AM considers several stages, from raw materials to end-of-life parts, following the subsequent steps [34]:

- Primary material production, from raw materials extraction up to their processing into workable shape, that will be used to produce AM feedstock material (powders, wires, or filaments, etc..).
- Feedstock material production, when the primary material is used for obtaining the feedstock, through stages like gas/water atomization, extrusion of plastic filaments, and so on.
- Production, that covers all the design and physical fabrication of the object, from CAD, to slicing up to the deposition of feedstock material layer-by-layer.
- Post-processing, that includes the removal of support structures, if present, solvent cleaning, thermal treatment, especially in CerAM, and finishing of surfaces and parts inspection.
- Use, involves not only the practical and regular use of the fabricated object, but also its distribution, purchase, installation, maintenance, and repair.
- End-of-life represents the final part of life cycle, that implies object's disposing, reusing, recycling, refurbishing, or remanufacturing.

In the LCA framework, some indicators were introduced to represent the whole impact of the process under evaluation. Different levels can be considered in the evaluation, micro- level, that involves the material circularity indicator (MIC), or macro-level, like material flow analysis (MFA). Even tho the mentioned indicators provide useful information in the evaluation of process circularity, these are not enough to determine the total sustainability of a product [35]. This is the reason why further investigation into the selection of new solutions for measuring the products impact at different levels, i.e. social, economical and environmental, are still ongoing [36].

Part of LCA is also the study of potential fine particles release and their carcinogenicity. This evaluation scope is to calculate an index that identifies where efforts should be focused, whether on the materials, the process or the waste. Applying this approach to AM fabrication processes shows that AM technologies guarantee higher efficiency and effective manufacturing costs management, in line with CE framework [37]. It is also true that some concerns arose about the human health effects of AM technologies, especially for ultrafine particle emission and volatile organic compounds generation, reducing the social and environmental sustainability of AM. However, the impact of these factors

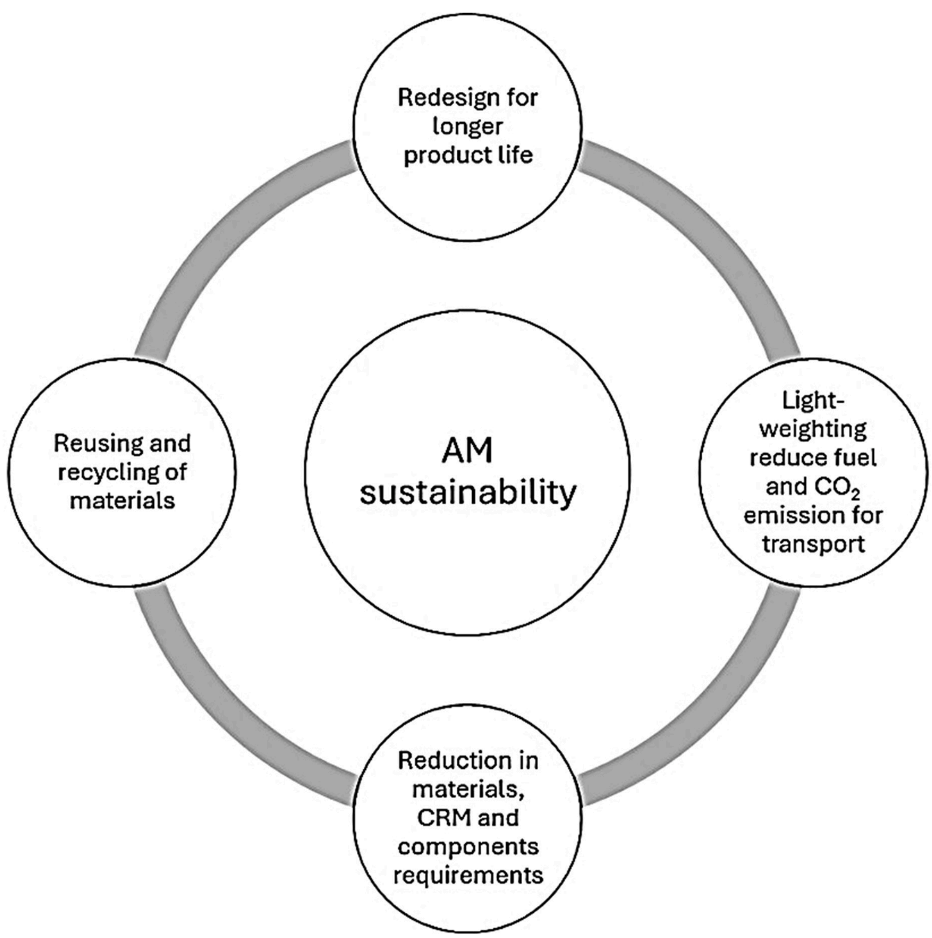


Fig. 5. Elements that make AM technologies sustainable fabrication methodologies.

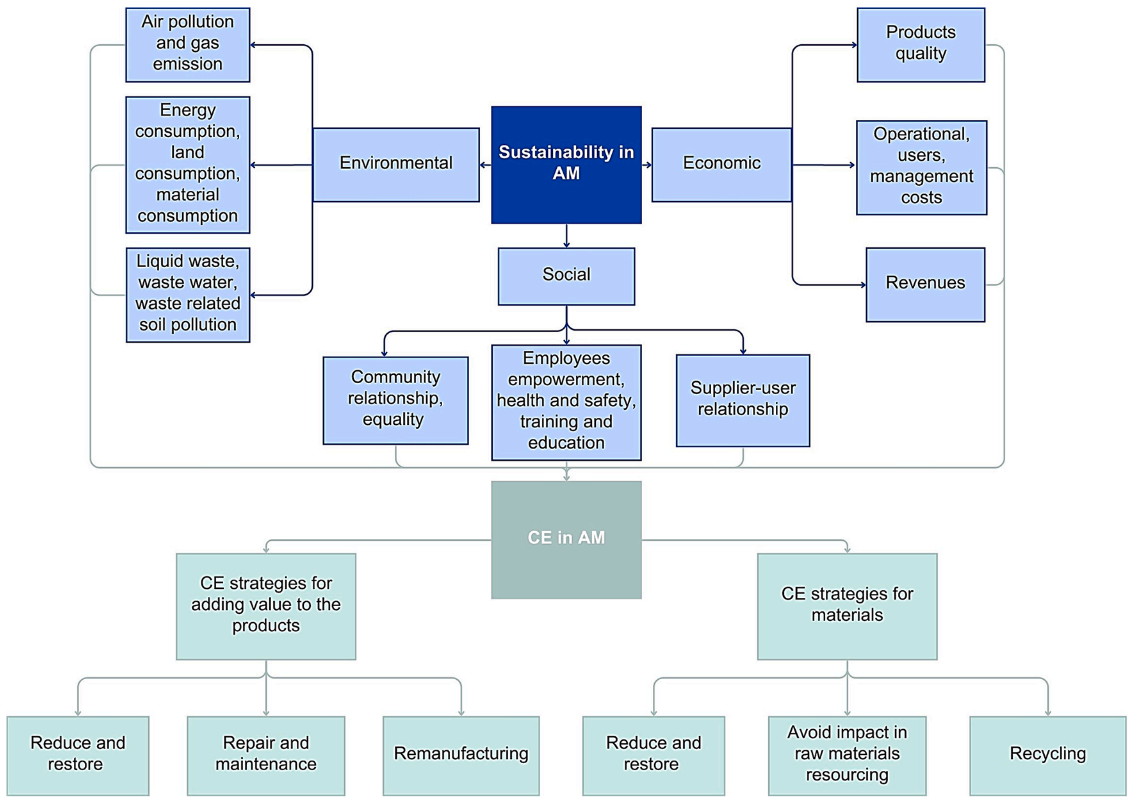


Fig. 6. The three pillars of sustainability in AM and their linkage with circularity of AM technologies.

can be mitigated using well-ventilated spaces and other ventilation systems, which facilitate the removal of indoor contaminants [38].

Nonetheless, a gap in literature arises when looking for sustainability and CE feasibility for CerAM field, indicating that further evaluation have to be performed on the topic, so first approach could be implementing one of the 5R, Recycling.

2. Recycling as circular economy implementation in ceramics

As previously stated, recycling is based on wastes valorization, but first, a definition of them is necessary. Waste identifies any product or material that is considered no longer suitable for a specific purpose [23]. Nowadays, many efforts worldwide are focused on the reduction of waste in production processes and their reutilization in several sectors, valorizing them and creating virtuous examples of CE, that helps the technical advancements at the same time [39]. This close-loop approach allows manufacturers to attain a lower environmental impact production process and to reduce costs, particularly those associated with waste management. A way to achieve the aim is the direct reintroduction of materials manufacturing wastes as secondary raw materials in the production cycle, avoid extra costs of object manipulation for preparing them for the new process [40].

Moving to ceramic industry, a lot of work has to be done in recycling waste, considering that ceramic materials represent about 50 % of construction wastes [41], and that they are widely used in several sectors due to their own physical, chemical and mechanical properties. Few studies investigated the possible reuse of ceramic waste, and most of them focused on the tiles fabrication or slip casting process, few preliminary studies introduce recycling in CerAM. Studies about recycling in traditional ceramic industries assert that recycling ceramics is possible, through a variety of strategies, that involve the mixing of the waste materials with new ceramic powder [40] or with other additives and solvents [42], without compromising final mechanical and physical properties and ensuring a reduction in energy and resources consumption [40,42]. Researchers have tried to identify what could be the possible application of ceramic wastes, pointing several alternatives out like manufacture of concrete or electrical insulators, thermal insulators, abrasive materials, the regeneration of coral reefs, and additive manufacturing techniques [41]. Effect of wastes recycling in ceramic manufacturing technologies or of final properties of the recycled products, as well as technical performances of final part and conformity to standards, environmental and economical sustainability, the presence of impurities that affect the behavior of final components are aspects to consider when designing recycling strategies and materials reintroduction [43]. Nevertheless, studying how to recycle ceramics through AM technologies can shed light on the sustainability of CerAM and the fusion between innovation and CE [32].

3. Evaluation of recycling in CerAM process chain

This CerAM process chain analysis aims to elucidate the potential integration of recycling concept into each stage of the fabrication process, while also identifying the limitations associated with such integration, to highlight what is the starting point for “greener” CerAM processes.

3.1. Raw material

Considering CerAM material requirements, ceramic powders have to respect some criteria for preparing the starting materials, especially particles diameters. Particles dimensions, together with the relative particle size distribution, and the grains morphology represent some of the constraints, especially for BJT. These properties affect final part sinterability and densification, as well as the particle-particle interactions [44]. Aside for powders dimensional and shape requirements, CerAM technologies seems to not have real restriction on other powder parameters strictly related to printability, like purity, so authors started to propose them as possible application for recycled ceramic materials from other processes [41]. Nevertheless, an evaluation of the final parts characteristics is essential to assure the suitability of the new source of raw materials for the intended application of the final parts. Standard norms define quality requirements and testing methodologies, especially for fine ceramic powders, helping in the decision-making process for fabricating ceramic objects [45–47]. These ISO indications should be respected by producers if they want to sell products made of recycled ceramics materials, even tho they should be reformulated to pave the way to alternative sources.

Concerning ceramic powders, examples of CerAM starting from recycled materials are hard to find, as evidenced also by the work of Romani et al. [48]. In this literature review, only two examples are focused on the recovery of ceramic wastes for CerAM fabrication of new products, both related to construction and furniture manufacturing. In the first project, tiles for rooftops and facades were produced through extrusion-based CerAM technology of a ceramic waste based starting material. In the second project mentioned, new furniture, like lamps, were 3D printed starting from recycled clay for the preparation of feedstock [48,49]. Here below a resuming Table 2 that summarizes the requirements for powders, divided for CerAM technologies.

3.2. Starting materials

Starting material composition and characteristics strongly depend on the chosen AM technology.

3.2.1. Binder jetting starting material characteristics

Looking at BJT, starting material is composed of the powder bed and the binder that should be deposited at each layer. Another point to consider for the starting material is the binder composition, usually an ink applied through an inkjet deposition method as drops of 20–50 μm in diameter [6]. Typically, the bonding agent is made of organic compounds, mainly polymers, that could be biodegradable, water-soluble, or recyclable [53]. They are selected considering some properties that determine the binder penetration and jetting behavior, surface finishing and microstructures, in addition to process parameters and the type of powder used. Theoretically, the binder should show a low viscosity, stability against shear stress during the ejection phase, it should guarantee a good strength of the printed green part, it should be eliminated through burn out at the end of the printing process [44]. Furthermore, powder and the selected binder should be compatible, to ensure binder penetration and wetting of the powder surface. In this context, the open question is the recyclability of the powder bed and the binder impact.

There are some elements to consider in this scenario; first, the defects already present in the powder bed. If it presents high level of moisture or sintering starting points in the areas close to the printed parts, they will affect the print job, so it is not possible to directly reuse the powder bed, but other treatments should be performed before its reintroduction in the process chain. Another point to consider is the possible chemical change introduced during the printing process, that could lead to changes in particles size and shape, so a total recovery of the powder bed is never achieved; maximum recovery rate is around 74–80 % after sieving, as reported by manufacturers [53]. Binders for BJT can take with them some environmental concerns related to the emitted gases generated during the thermal treatments, that are mainly due to the chemical composition of these compounds. If these gases are not controlled and are released into the environment, they could affect plants, soil, air, as well as human health [54].

Table 2
Summary of ceramic powder requirements for CerAM technologies, divided for fabrication technologies.

Technology name	Power size and morphology	Additional requirements	Ref.
Binder Jetting (CerAM BJT)	Powder diameter > 30 μm, round shaped, in a wet or dry state.	Good flowability, low inter-particles friction forces, low humidity level, packaging rate, due to a cumulative effect related to layers pressure.	[6,8,9,44]
Material extrusion (CerAM MEX)	Sub-micrometric diameter particles, mainly round shaped, even tho some works presented higher particles size (up to 10 μm) and irregular shape grains.	Spherical particles are still preferred for the lower viscosity that they can ensure to the filament.	[9,50]
Material jetting (CerAM MJT)	Sub-micrometric particles, with an average particle size under 10 μm.	Control of the size is necessary because bigger particles can clog the extruder while finer ones can impair the material flow, leading to irregular extrusion.	[51]
Vat Photopolymerization (CerAM VPP)	Sub-micrometric particles (< tens μm, sometimes << 1 μm), preferably round shaped.	Surface area is a critical parameter to consider, if it is too high particles interact with each other, preventing the possibility to increase the solid content of the suspensions, while low surface charges impede low viscosity resins with high solid loadings.	[52]

3.2.2. Fused filament fabrication starting material characteristics

CerAM FFF filaments show, together with the ceramic part, a plastic matrix, containing also a surfactant and a plasticizer which facilitates the dispersion of the ceramic powders [9]. Some material requirements that restrict the number of usable filaments are mainly attributed to printability and starting material functionality, two characteristics often in opposition to one another. Considering filled filaments, increasing filler volume content increases final material functionality, but it decreases the printability due to the alteration in mechanical and rheological filament properties [55]. High solid loading, approximately up to 60 % vol., involves the use of a blend of polymeric binders, primarily high molecular polymer, low molecular weight lubricants, surfactants, and plasticizers, ensuring filaments flexibility, printability and correct viscosity for continuous extrusion, even if attention has to be paid to possible nozzle clogging [56]. These components ensure good extrusion properties, smooth printed surface and proper interlayers bonding, guaranteeing optimal printing results and fully dense final parts, together with the correct set of printing parameters [56]. One common issue related to CerAM FFF too, is starting material storage, since the filament polymeric matrix properties can be affected by the external environment factor. Some commonly used polymers, like polylactide acid (PLA) or acrylonitrile butadiene styrene (ABS), show changes in their mechanical properties and printability if they are exposed to high humidity environment (as for PLA, that starts its own degradation due to chains hydrolysis) or to UV rays (as ABS, that becomes more brittle). These environmental effects can be emphasized by ceramic fillers, that can promote ageing or water absorption processes, contributing to filament degradation and printing process failure [55]. One possible recycling strategy of aged filaments could be the polymeric part complete degradation through heating treatments and the reusing of powders for new filament preparation, even if additional tests should be performed on the collected fillers to evaluate the presence of possible contaminants or moisture on the surface. However, a first attempt to save as much materials as possible is the proper storage of filaments, to guarantee the absence of humidity and light and avoiding wasting materials.

3.2.3. Material jetting starting material characteristics

In MJT, especially MMJ, the feedstock material is represented by a thermoplastic system composed of paraffin and/or beeswax where ceramic powder is dispersed [7,13,57]. The mixture preparation takes place at high temperature (~ 100 °C) to melt the waxes, then desired material is added and the whole is continuously mixed through a homogenizer. The final system should present a high solid loading volume for good green body properties, ensuring shear thinning behavior during printing at the same time [57,58]. Starting material characteristics in MJT are close to the low-pressure injection molding (LPIM) of ceramic feedstock, concerning viscosity, yield point flowability [58]. As in LPIM, attention has to be paid to the use of dispersants that can help powder dispersion, but they can also strongly affect rheological behavior. That's why MJT feedstock composition should be tuned in accordance with a trade-off between printing requirements, like low viscosity materials with high flowability, and green parts desired characteristics, like high particle concentration for good debinding resistance and density [59]. Open point is the storage of these wax-based systems and their reusing for MJT, because a time dependency of the rheological properties of these materials was demonstrated [59], affecting the printing results. Considering materials composition, a possible recovering of the ceramic part seems to be possible as for CerAM VPP resins, through the organic part burning out and powders reusing. However, no documented evidence of this process has been reported in the existing literature for MJT. The reusing of starting materials lost during printing due to the formation of agglomerates, or the necessity of extrusion tests appears to be a viable option, given that chemical alterations should not occur during the printing process. Reintroducing these spare elements in the cartridge, after a second mixing step into the homogenizer, could be a first trial of recycling of the feedstock, reducing printing waste at the same time.

3.2.4. Vat photopolymerization starting material characteristics

Concerning CerAM VPP technologies, they rely on photocurable resins, whose main parameters to tune are viscosity, rheological behavior, dispersion stability and curing properties. The suspension should present a shear thinning behavior, with low viscosity values in the shear rate operating range (depending on the used printing technology. Suspension stability is guaranteed thanks to the use of dispersants, whose concentration is optimized based on the solid volume loading in the resin. For green bodies good quality, some elements should be considered during ceramic resins preparation, like the solid loading and particles size, that should be high enough to ensure right density and minimum shrinkage values of the final body, additives concentration, that can affect suspension rheology, and ceramic material optical properties, which determine resin-light interaction and absorption [60]. The open question in this area is whether it is possible to recycle resins from CerAM VPP technologies. To answer this question, the group of Sarwar et al. [61] attempted to use a DLP printer with a coating technology based on a continuously coated tape. A zirconia resin was applied to the tape from a tank by two successive doctor blades, then the build platform was recoated by the resin on the running tape, and the excess resin was collected by another recycling blade that fed the material through a sieve and finally into a reservoir. They evaluated the resin recovery efficiency and the effect of its reusing for printing, demonstrating a change in the resin solid loading and in the relative density of the final parts, mainly due to agglomeration removal during the sieving stage. These agglomerates seemed to be related to the scattering effect in the surrounding areas around the built platform. They also tried to reuse recycled resin by mixing it with new one in the tank, still noting a reduction in the solid lading [61]. It is a common practice to reuse as much as possible an already prepared resin batch, after sieving eventually, if some agglomerates are found in the material after printing, avoiding the resin excess discard. Another way to reply to the question was proposed by Su et al. [62]. They proposed to recover zirconia resin by burning out polymers and recollecting powders, to apply it in the manufacturing of dental prosthesis. Following powder ball milling and de-agglomeration, the resin was prepared using the same procedure as for the new powder, and printing tests were then performed. It was determined that printing with layer thicknesses below 40 μm was no longer applicable due to the viscosity and inhomogeneity of the starting material, even if it meant possible gaps and voids between layers. Those resulted in porosities, an increased shrinkage ratio, a reduction in flexural strength and a lower Young's modulus, taking them to conclude that recycling the zirconia resins seemed to be possible, but the material was no more suitable for aforementioned dental prosthesis applications and should be changed [62].

3.3. Green body

Printed parts show all the same characteristics, they are mainly composed of ceramic powder and a polymeric matrix to be removed with the debinding step, in order to obtain a fully ceramic component. During parts fabrication, some printing errors could happen, causing nonfunctional objects or no longer usable broken elements. How to save this waste is the next question to answer. For many of the technologies presented, the printed parts are mostly composed of polymeric matrix. The polymeric matrix could be eliminated thermally, reaching high temperatures as for debinding, but attention should be paid to not induce sintering begins, otherwise it will be impossible to have again the powder size desired [57,58]. If ceramic fillers need to be recovered, after polymeric matrix burning out parts should be grinded to refine the powders dimensions and to break agglomerates that can be still inside the material. This step could be done through a planetary ball milling, to ensure better control on the final powder dimensions, even if some agglomerates and bigger particles could remain, affecting the printing parameters during printing stage of recycled materials [62]. In the Table 3 below, suggestions on possible strategies to recover damaged green bodies and recycle them are reported, for each technology.

3.4. Brown body

The objective of the debinding process is to decompose and eliminate the polymeric binders present within the green body, primarily through pyrolysis and carbonization of these binders. Carbon atoms released during the pyrolysis of polymers may be oxidized by the atmosphere, particularly if the process is conducted in air. This can result in the formation of gaseous CO_2 which may increase the inner pressure of

Table 3
Strategies for recovery of green bodies.

Technology name	Green body comp.	Suitable solution	Ref.
Binder Jetting (CerAM BJT)	High percentage of ceramic powder and a small quantity of binder.	Thermal decomposition of polymeric binder for recollecting the powder.	[65]
Material extrusion (CerAM MEX)	Medium to high ceramic percentage (40 to 60 %).	Thermal or solvent debinding, for eliminating the matrix and collecting powder.	[63,64]
Material jetting (CerAM MJT)	Wax matrix with up to 50 % of ceramic filler	Melt and mix again printed parts with new feedstock to refill the cartridges. Not applicable to MMJ, where more than one ceramic is present	[66]
Vat Photopolymerization (CerAM VPP)	Up to 50 % of ceramic filler into a photocured resin	Burn out of the polymeric matrix, and subsequent grinding of the solid residues. A solvent removal could be imagined, after assessing toxicity of suitable solvents.	[67]

ceramic parts, now full of void channels and pores, and induce cracks formation ceramic powder, but some polymeric residues can still be inside them. Is it possible to reintroduce the debinding failed parts in the process chain? To answer the question, a deeper analysis of their final composition should be conducted, evaluating the matrix quantity left and the need for an additional thermal treatment. To obtain the powder again and to destroy agglomerates, a grinding phase should be performed.

These considerations can be applied exclusively to a single material component. In the case of multi-material fabrication, alternative methods for the separation of the two materials must be identified; otherwise, the recovery of the powders is impossible. Nevertheless, further research is required on this topic, as there is a lack of information in existing literature. This is necessary in order to evaluate not only the feasibility of this process, but also the characteristics of the final printed part produced using recycled powders.

3.4.1. Binder jetting brown body

Debinding step in CerAM BJT helps the removal of binder, which is not taking part to printed object consolidation, so removing it prevents any final part contamination with other material than ceramic one. However, due to the binder evaporation, warpage and deformations can occur, making the brown body unusable [68]. This damaged part could be potentially used for recovering the powder, after grinding the solid residues, but a second thermal treatment should be performed, because of the presence of some polymeric residues left on the particles surface during decomposition [68].

3.4.2. Fused filament fabrication brown body

CerAM FFF green bodies are debinded with different strategies, to remove all the polymeric matrix that they present, ensuring the removal of any residual carbon and the optimal quality of the final product. A first step could be the solvent extraction of polymers, which occurs through a series of dissolution and diffusion phases that are influenced by factors such as temperature, time, and the shape and dimensions of the particles involved. However, this step could lead to some defects in the parts, like bubble formation and bloating, that are linked to an insufficient solvent removal rate. Other defects, like cracks and voids, can be produced during the subsequent thermal debinding, that is necessary to remove the residual backbone of non-soluble and degradable polymers [69]. At the end of these processes, failed brown bodies could be used for powder recovering, grinding it if necessary.

3.4.3. Material jetting brown body

As for the other technologies, debinding is essential for wax matrix removal in the green parts fabricated through CerAM MJT. A possible way could be the solvent extraction, due to the wax solubility in petroleum-based solvent, and a subsequent thermal treatment could be applied to remove any residual [70]. As for the already mentioned examples, this step could affect the result, it could cause defect in the brown body, making it nonfunctional anymore. These failed parts could be used for powder recovery too.

3.4.4. Vat Photopolymerization brown body

CerAM VPP fabricated green bodies are subjected to thermal debinding, both in nitrogen atmosphere or air, to remove the polymeric part avoiding cracks formation [67]. However, this long process is hardly defect free, warpages and cracks can easily appear on the surface of parts, even if new solutions have been proposed. One of them is the use of supercritical CO_2 as extraction solvent, to speed up the process ensuring a defect free brown body. The aim of this process is the creation of channels for gaseous polymeric residues evaporation through the pre-conditioning of the parts with a supercritical CO_2 flux, that also prevents the part collapse filling the pores in the samples [71]. Nevertheless, flawless parts are frequently accompanied by damaged ones, that could be used as powder recovery sources, with an additional thermal treatment for residues removal, if necessary.

3.5. Sintered parts

Sintering is usually the last step for a complete densification of ceramic parts. It promotes a change into physicochemical properties of the brown body, due to the high temperature. During sintering, temperature increases at each stage, after a certain dwelling time, inducing the decomposition of organic residues left on the parts and pushing the ceramic grains to interact. Their interaction mechanism relies on the migration of atoms, which receive high energy doses, between crystals and the formation of grains junctions, through sintering necks that allow the parts to become fully dense. This process takes at grains growth and pores closure, obtaining a hard ceramic component [72]. Void and open porosity could be found in the described white body, due to the grains boundary migration and diffusion, and a consequent grain growth. To obtain a highly dense part, a second sintering step could be applied, reducing the grains growth through: microwave sintering, pressure-assisted sintering, and field-assisted sintering, or a two-step sintering approach, based on two subsequentially thermal processes, at different temperatures [73].

Even if ceramic parts are well-known for their strength and resistance, it happens many times that they break because of handling or wear, or also because of some errors in manufacturing. These broken parts could be used for other printing jobs, after pulverizing them, to avoid new ceramic powder extraction or synthesis. How to pulverize them was suggested by Brandaleze and Silpituca [74], where they tried to recover zirconia broken nozzles from steel continuous casting. Zirconia wastes were pulverized through milling, using a Herzog mill with two rings for 40 s at 1470 rpm and then sieving the powder with several sieves with different nominal apertures. The obtained powder was used as filler for material extrusion starting material, and the printed parts showed good results in debinding, but additional study should be performed on sintering, for better final densification and strength [74].

Pulverizing parts to obtain powders again from sintered objects seems to be interesting for all the CerAM technologies presented in this work, but one problem arises immediately. Considering the strength of ceramics, is this solution applicable for each type of ceramic material? Is it feasible for post processed white bodies too (as finished parts or decorated ones)? Which are the application limits of these solutions? Which is the most suitable solution considering production costs, energy requirements and related emissions? These are the open questions that it is challenging to respond through pure literature analysis.

3.5.1. Binder jetting sintered body

CerAM BJT brown bodies are sintered and densified through thermal sintering and post-processing densification methods like pressure less sintering, but retaining the shape and obtaining a fully dense object without any distortion and cracks is challenging [75]. The sintered parts BJT printed are hardly fully dense, if any other processes are not applied to complete densification, it may be a viable option to utilize a failed sintered body for powder recycling through parts ball milling. This is one of the possible solutions that could be taken into consideration for ceramic material recycling.

3.5.2. Fused filament fabrication sintered body

Sintering of FFF printed parts could be influenced by the previous debinding phase, because a weak debinding could be the main cause of deformations and cracks in the parts teresting in recycling perspective, if they are brittle enough to be milled easily, allowing the powder recovering.

3.5.3. Material jetting sintered body

As already stated for other technologies, any flaws in the previous stages can influence the final result of sintered bodies, like the formation of crack and delamination, open porosities and presence of precipitates, that affect the final characteristics of the MJT printed objects [76]. These sintered bodies can present high density, especially if the starting green body shows high density too, so the feasibility of powders recovery through milling should be evaluated.

3.5.4. Vat Photopolymerization sintered body

Following the debinding stage, the printed objects produced using CerAM VPP are subjected to a sintering stage. During this stage, the remaining carbon residues are fully eliminated, recrystallization and densification of material take place. The temperatures selected for the sintering process vary depending on the materials used. In general, there is a lower limit below which the particles are unable to interact effectively, and an upper limit that defines the acceptable warpage rate [77]. The fully dense objects, with cracks and deformations, could be subjected to grinding step, trying to recover powders, but the possibility should be evaluated considering the materials used.

3.6. Evaluation of recycled materials: additional suggestions

Once ceramic powders are recovered, from green bodies, brown bodies or white bodies, it is a good practice to firstly analyze the obtained material, evaluating any possible contamination (using energy-dispersive x-ray analysis, resonance frequency analysis or x-ray diffraction, etc.…) and obtained grains sizes and shapes (relying on scanning electron microscopy, particle size distribution, etc..), in order to meet, as much as possible, the requirements for the specific CerAM technology in which to apply the retrieved material. When recovering the feedstock material, instead, additional analysis should be focused on the requirements for feedstock preparation for the CerAM technology involved, like viscosity and curing depth measurement, in case of resins for CerAM VPP. Lastly, for a complete determination of ceramic recycled material suitability for the selected application, mechanical testes should be performed, as four point bending, for determining the strength of obtained parts, or thermal conductivity measurements for assessing the thermal behaviour of printed and sintered objects.

All the collected information should be compared with the guidelines from standards and norms, considering the possible reduction in performances of recycled materials together with the application field in which these recovered ceramics will be applied.

4. Recycling economic solution for AM

Applying ceramic wastes recycling into CerAM process chain could be considered a cost saving solution? The answer is not so easy to find, it is strongly dependent on the manufacturing process itself and on the other materials processes that have to be performed for recycling ceramics.

4.1. Costs

AM technologies have revolutionized manufacturing processes, thanks to their ability to reduce prototypes fabrication time and to speed up their modifications, through design flexibility, no need for molds or tools that also means no additional costs. That is also true that this approach is not cost efficient for large scale mass production, looking at costs per number of units, but any design related changes into the production line could be quite expensive in traditional production methods. So, AM costs should be always related to the manufacturing chains, and a tradeoff between costs and design freedom should be found. Another AM connected change is the product customization, companies could fabricate consumers personalized parts without additional costs but generating high profits at the same time, due to the high-value-added products. It also means that small batches of printed parts could be manufactured, moving to a make-to-order approach, reducing inventory risk and ensuring better capital management. Furthermore, the use of AM technologies for fabricating parts enables the reconfiguration of supply chains, implementing the so-called decentralized model. In this approach, the fabrication is operated near to the final customer, reducing or eliminating the need for transportation, that implies reduction in costs, eliminating or reducing the need for storage, and relative costs, reducing delivery time. However, high initial investments are required to set up the fabrication sites and to prepare the specialized personnel. A way to overcome this problem could be outsourcing, that means the companies have only to provide the product concept, others will produce and deliver the final product, reducing the investments required in the beginning. Another path to follow could be renting or sharing AM machines between companies, that means splitting the costs between more than one society, reducing the initial investment [31].

Apart from AM costs, it is essential to assess material production and waste management costs in comparison to recycling costs. Examining one of the major alumina production markets, namely China, it can be observed that the production costs amount to approximately 2900 Yuan (407 $ in USA market) per ton whereas the sale price ranges between 2850–3000 Yuan (394 – 421 $ in USA market) per ton, that means alumina production costs is equal to or exceed the incomes. This is primarily due to the costs for raw materials utilized in the production process, namely bauxite and caustic soda. This pushes producers to reduce the amount of alumina produced, given the elevated availability on the market that further lowers the price. The raw materials prices are growing because of the decreasing number of bauxite mines in China, that takes to more importation from other countries [78,79].

It is also true that recycled parts cannot be directly reintroduced into the CerAM production chain, they have to be modified through some processes, like burning out of polymers (for resin recovery or printed error recycling) or grinding (especially for final parts), that means extra costs for purchasing machinery and maintenance. However, disposal of waste has a cost too, that influences the final product costs, so which solution has the lowest impact on selling price is a point to elucidate.

4.2. Energy requirements

Ceramic powder production requires energy, as with any other production process. This manufacturing field is considered one of the energy-intensive manufacturing sectors, considering the energy requirements for shaping and post-processing steps too. The high energy needs result in a big disadvantage for this field, not only on an economic scale, but also for the environmental impact of the production processes [80]. Looking at ceramic companies around the world (Table 4), it is possible to understand the huge amount of electrical and thermal energy used for these processes, and it is also evident that a big part of this energy is wasted during fabrication steps [81].

As an illustrative example, alumina extraction from bauxite requires around 2 GJ/ton theoretically, while the actual consumption is around 7.9 – 21.9 GJ/ton. Furthermore, the values are even higher (between 22 and 43 GJ/ton) when other processes, as non-bauxitic mineral extraction, are used for alumina synthesis [82].

Reducing the energy consumption associated with powder synthesis has the potential to reduce the energy requirements of the ceramic manufacturing sector. It is therefore pertinent to consider whether this objective can be achieved through recycling. The answer is significantly influenced by the manner in which recycled powder sources are produced. Energy requirements for material recovery and for waste disposal should be evaluated deeper, considering the big amount of ceramics

Table 4
Countries specific energy consumption, both thermal and electrical energy. Adapted from [81].

Country	Electrical (kWh/ton)	Thermal (million kcal/ton)
India	210	1.34
China	259	1.05
Italy	139	1.16

wastes, especially from the construction sector. Recycling these resources instead of disposing them could save energy, not only powder synthetizing one but also wastes disposal energy needs could be reduced. A more detailed assessment of energy consumption is required in the near future to facilitate improvements in the field of ceramic recycling research. An evaluation about the possible alternative sources of energy could be coupled with that assessment, considering if renewable energy or greener solutions for energy production can be applied.

4.3. Emission related to ceramic manufacturing

Ceramic manufacturing field has a negative impact on society and the environment, not only in terms of energy consumption. CO_2 emission reaches 19 Mt in EU every year, and the particulate release during production processes grazes 20 % of world's black carbon emission. This means health related issues for ceramic manufacturing workers and for surrounding area of the implants [83]. It also implies environmental damage, especially for ceramics produced through mineral extraction such as alumina, due to mines exploitation and soils pollution for wastes release [78].

A first attempt to mitigate the environmental and social impact of ceramic industry could be a decarbonization of the sector, employing CE principle to reduce the need for raw materials extraction. A list of possible routes for carbon footprint reduction is reported in the work of Del Rio et al. in the Fig. 7 below.

The study also evidenced that some limitations exist in decarbonization, primarily financial and economical one, because of the costs for new strategies and the lack of information about cost-benefits. More studies and evaluation about expensiveness and feasibility of these alternatives could probably push investments in sustainable solutions and innovative technologies development.

In terms of CO_2 emission, the environmental impact of CerAM technologies like CerAM VPP, CerAM BJT and ceramic fabrication from precursors was assessed by Liu et al.[84].. They found that 616.40 kg of equivalent CO_2 emissions are produced per kg of ceramics in CerAM VPP, while in CerAM BJT 3086.13 kg of CO_2 are produced per kg. The emissions go down to 2.23 kg of equivalent CO_2 per kg ceramic in case of preceramic material use, because of the absence of carbon pyrolysis. Additionally, they suggested a way to further reduce the greenhouse gas emissions (GHG) at 0.79 kg of CO_2 per kg of ceramics, using their novel ink for DIW, which contained a mix of aluminosilicates and reactive species, that help the subsequent self-sustained ceramization. Their evaluation and comparison of GHG emissions are reported in the Fig. 8 below

4.4. Management of waste

The management of waste products in the ceramic industry varies according to the specific production sector, mainly industry or research. Regarding research centers and universities, ceramic materials wastes are considered laboratory residual waste. They are stocked in landfills or incinerated following the national laws, modelled on international ones in European countries [85]. Looking at industry level, the amount of waste is significantly superior, that is why there is a growing interest in regulatory agencies, both national and international like the European Commission, to control their disposal. In the perspective of European commission, the Waste Framework Directive, which defines basic concepts related to waste management, recycling and recovery, helps the member countries to identify wastes categories and to select, throughout some criteria, wastes that could become a product, or a secondary raw material, following circularity principles [86]. The final implementation of the framework is demanded to the single country, that applies different solutions with respect to the scope. As example, Germany's "Umweltbundesamt" (Federal Environmental Agency) released so called "factsheet" that assessed that, even if it has been already considered the use of waste ceramics as secondary raw material, it is only rare exceptions the reintroduction of these discarded parts. An important sector that relies on ceramic materials is represented by the construction industry, that requires annually big number of ceramic tiles, i.e. 0,85 million tons in 2015 [87]. However, the document also reports that due to some technical reasons, only small quantities of these materials are recovered and reused. It is mainly related to the complex compositions and high-quality requirements, time required for recovering and labor-intensity. Another open problem is the presence of harmful sulphate in building materials like aerated concrete, sand-lime bricks and

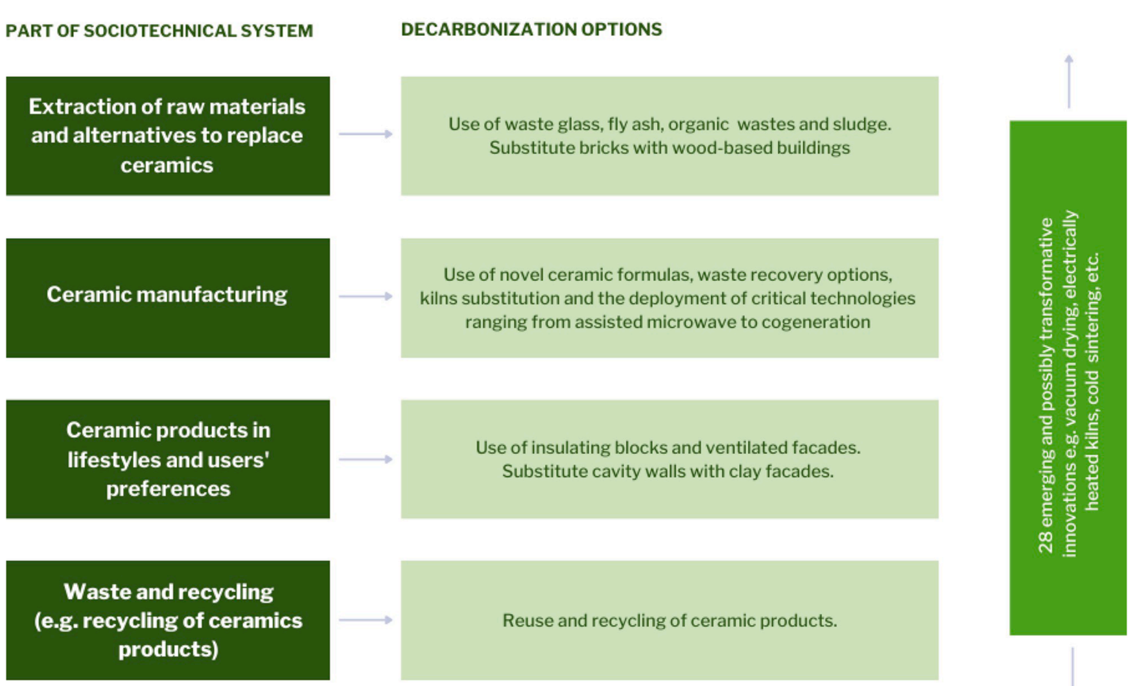
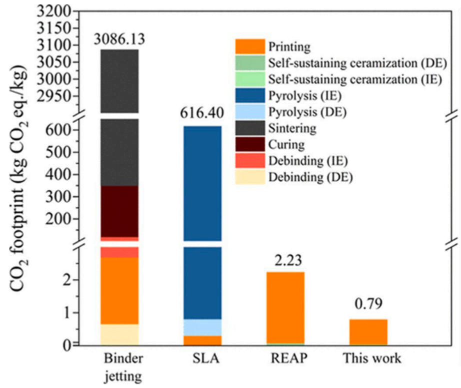


Fig. 7. Possible options for ceramic industry decarbonization, coupled with their area of influence in technical and social ceramic system. Reprinted from [83].



	Process	Operation power (kW)	Energy consumption (kJ)	CO_2 emission (kg)	Volume (cm^3)	Density (g/cm^3)	Process emission ($kgCO_2$ eq./kg)	Total emission ($kgCO_2$ eq./kg)
Binder jetting	Printing	1.65	115.09	0.014	3.1	2.2	2.03	3086.13
	Curing	0.5	10800	1.58	3.1		231.2	
	Debinding (DE)	-	-	-	-	-	0.66	
	Debinding (IE)	1	7200	0.86	3.1	2.4	116.13	
	Sintering	3.4	213180	25.58		3.02	2736.12	
Vat photopolymerization	Printing	0.06	756	0.09	50	0.17	0.31	616.4
	Pyrolysis (DE)	-	-	-	-	-	0.5	
	Pyrolysis (IE)	1.1	89773.2	10.77	50	0.35	615.59	
REAP	Photothermal assisted printing	0.232	464	0.056	10	2.6	2.14	2.23
	Self-sustaining ceramization (DE)	-	-	-	-	-	0.078	
	Self-sustaining ceramization (IE)	0.192	1.92	0.00023	10	3.2	0.0072	
This work	3D printing	0.072	43.20	0.0052	3.00	2.3	0.75	0.79
	Self-sustaining consolidation	0.192	2.30	0.00028	3.00	2.5	0.0363	

Fig. 8. Calculated footprint and emissions impact. Reprinted from [84].

vertically perforated bricks, that could be eliminated during recovering processes but still can lead to problems during shaping and drying processes. Future research in that field could help the construction industry to use more and more recycled ceramic materials, but it seems that the ceramic materials used for construction are not 100 % recycled yet, according to the factsheet of Umweltbundesamt [87].

Concerning others European countries, Italian landscape about tiles and ceramic materials for buildings appears different from the previous described one as European commission framework implementation. Ceramica.info, the web portal of Italian ceramic led by Confindustria Ceramica and Ceramic of Italy, reports two articles about the recycling of these materials and their rules. As exposed, in the tiles production field 100 % of waste, both resins and final products are reintroduced into the manufacturing process, reducing the number of raw materials required, reducing discharge and pollutant, reducing the natural resources requirements for production (as natural gases and water), and reducing the CO_2 emissions. This is possible by reintroducing manufacturing waste (resins and powder) directly into the production process and grinding again the final defective parts to put them again in the resin preparation. Through these solutions, in 2020 the ceramic manufacturing sector was able to overcome the expected outcome presented in the Best Available Techniques (BAT) document [88] by European commission and to reintroduce into production process wastes from other fields [89]. A boost to recycling, especially ceramic materials for construction, comes from the ministerial decree n.152, issued by the Ministry of Ecological Transition, that outlines the possible alternatives for waste materials from buildings, in the same field of application or into others like environmental recoveries, fills and backfills [90].

As it is possible to see from the reported example, a lot of efforts have been spent on the management of ceramic wastes in construction field, but a lack of studies and information is evident in the sector of technical ceramics [88], materials that have a big interest in CerAM. These materials give high added value to products, because of their properties but also for the energy intensive manufacturing processes, as already exposed, pushing the European Commission to ask for an increasing recovering of them. Some BATs from European Commission suggest how to handle these materials, like channeling dust emissions, reducing gaseous secondary compounds and volatile organic ones, reducing solid waste like used plaster molds, in order to reduce emission and resources exploitations [88]. However, some indications on how to reintroduce them in the production processes are missing, leaving the quest for a solution up to researchers and industries.

5. Conclusion and future outcomes

The possible methods for recycling ceramic materials all along the process chain presented in this work should be evaluated not only for their ability to give a second life to the ceramic materials, but also for the final parts characteristics. These evaluations, coupled with an environmental, social and economic impact study, could definitively say if ceramic materials recycling through CerAM technologies is advantageous or not. Undoubtedly, recycling represents an initial step in the direction of a reduction in the emissions connected with the extraction of raw materials and synthesis of ceramic powders. An open question remains about the actual carbon footprint reduction as well as on energy and resources consumption. LCAs of every possible strategy could say more about process impact and comparing them with a “traditional” make-use-dispose chain could explain which solution is advantageous in the context. However, some elements should be kept in mind, as the availability of extractable resources is constrained. Furthermore, the ceramic industry is not an isolated world, it impacts mineral extraction regions on economic and environmental level. It affects manufacturing areas, with CO_2 emission related to fabrication and transport of the final parts. It exploits resources all around the sites, in terms of energy, workers and natural resources [83]. Recycling could help to reduce these drawbacks related to ceramic production in the near future, especially coupling it with CerAM, whose advantages connected to sustainability have been introduced before. Some open questions remain, as already said, on several levels. Future of ceramic recycling in CerAM world needs to be assessed, that means developing the following research topics and replying to the open questions arisen.

- **Carbon Footprint and Energy Use:** There is a starting interest in comparing energy requirements and GHG emissions of CerAM technologies, deeper investigation on the impact of coupling them with recycling strategies can be the first step in determining the feasibility of ceramics recycling.
- **Recovered Powder Reuse:** Determining the suitability of recycled ceramic for new products fabrication through CerAM technologies is the second topic to investigate. It is not only limited to verify the compliance of the collected material with the ISO standards for ceramics, but also examinate the performance of the developed feedstock during the printing stages, as well as of the final dense parts.
- **Costs:** in the manufacturing field, raw materials costs, together with machining costs and waste disposal costs influence final product costs, so subsequent step should be the economic feasibility evaluation. It should comprehend not only remanufacturing of materials but also costs in terms of energy requirements for recycling stage.
- **Use of Recycled Polymers:** Using wastes for ceramic recovering is the first approach for reducing the need for waste disposal and managing, but coupling them with recycled polymers, implementing new alternatives for CerAM can be interesting in the framework of reducing the need for material extraction and synthesis. This further step of recycled material integration can push the reusing of high impact polymeric materials and reducing the need of their disposal.

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Matilde Aronne: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Eric Schwarzer-Fischer:** Writing – original draft, Resources, Data curation. **Valentina Bertana:** Writing – review & editing, Supervision. **Giulia Mossotti:** Writing – review & editing, Resources, Data curation. **Uwe Scheithauer:** Writing – review & editing, Project administration, Conceptualization. **Sergio Ferrero:** Funding acquisition. **Luciano Scaltrito:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

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

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