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jmr&t
Journal of Materials Research and Technology
www.jmrt.com.br

Original Article

Sustainability of additive manufacturing: the circular economy of materials and environmental perspectives

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ARTICLE INFO

Article history:
Received 20 December 2019
Accepted 22 April 2020
Available online 9 June 2020

Keywords:
Additive manufacturing
3D printing
Circular economy
Sustainability
Recycling
Life cycle assessment

ABSTRACT

This research is a comprehensive review of the sustainability of additive manufacturing, from the circular economy and recycling of materials to other environmental challenges involving the safety of materials and manufacturing. There has been important progress in this area, with an increasing number of papers that cover diverse environmental aspects, including the circular economy, recycling and the life cycle assessment of materials. This increase is due to the importance that scientists, industry, government and society are now giving to these topics. This review seeks to develop a greater awareness in relation to the possibilities and implications in the use of the AM, as well as to encourage sustainable development by raising awareness in relation to the taking of necessary actions to achieve compliance of the Sustainable Development Goals. Similarly, current trends are examined in relation to the practices that are currently being adopted in order to ensure that AM is consolidated as a sustainable and convenient practice in the economic, social and environmental spheres. In general, polymers, ceramics, metals and composite materials are now undergoing intensive research to improve their use. Although this research shows that significant progress has been made on several relevant issues, using materials optimization to minimize energy and waste is still far from a global solution.

1. Introduction

Additive manufacturing (AM) known as 3D printing (3DP), is a technique defined by ASTM as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. AM includes seven AM process categories: powder bed fusion, material jetting, directed energy deposition, material extrusion, sheet lamination, vat photopolymerization, and binder jetting [2].

AM has the advantage of being able to build parts from digital designs using almost all materials and complex shapes. Materials include metals [3], composites [4], ceramics [5], cement and concrete [6], polymers [7], food [8], clays [9], metamaterials [10], and organ tissue [11]. Very diverse parts have been printed so far, including electronics [12], houses [13], tur-

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https://doi.org/10.1016/j.jmrt.2020.04.062

bines [14], organs [11], urban furniture [15], art [16], robots [17], prosthesis [18], engines [19], electromagnetic shielding [20], and architecture [21]. AM is changing manufacturing worldwide [22] in many ways, taking design and production to a place where it is accessible to everybody.

The environmental impact of a technology is now one of the most significant criteria that determine whether it is feasible and sustainable. AM has undergone analysis in terms of its energy demand [23], metrology [24], recycling [25] and circular economy [26]. This research is an open review based on the information provided by the Scopus database. It looks at the following topics that contribute to the sustainability of AM: engineering of materials, circular economy and other environmental aspects.

2. Methods

This bibliographic search was conducted with the information found up to September of 2019, through a detailed documentary review in journals indexed in the Scopus database. From this search, 960 publications published from 2011 to those approved for publication in 2020 and available in September of 2019 were examined. The search was orientated in relation to four types of publications, namely: (1) review articles; (2) review articles at conferences; (3) conference articles; and (4) research articles. Results were extracted from the following keywords: circular economy, life cycle assessment, recycling and environmental aspects, as detailed in Fig. 1. This bibliographic review was carried out in September 2019. Using the keywords "circular economy" AND ("additive manufacturing" OR "3D printing"), the search yielded 32 publications related to circular economy. From these publications, 15 were research articles, 10 were conference articles and 7 were review articles, 3 of which were in journals and 4 were from conferences. In relation to the issue of life cycle assessment, the search was conducted with the key words "Life cycle assessment" AND ("additive manufacturing" OR "3D printing"). This search yielded 63 documents, from which 35 were research articles, 21 were conference articles and seven were review articles, three of which were published in journals and four were from conferences. Of these publications, 13 articles were published as open access. The search in relation to recycling in AM yielded 225 articles, from which 133 were research articles, 70 were conference articles, 13 were conference review articles and 7 were journal review articles. 46 of these articles were published as open access. Finally, a search was carried out in relation to environmental aspects in AM. This search yielded 640 documents, with 358 journal articles, 200 conference articles, 23 magazine review articles and 59 review articles. From whole of publications exhibited by the Scopus database, a classification of the most relevant papers in each of the topics evaluated was made, taking into account the relevance of the title and the summary. Based on the previous classification, 280 papers were taken for thorough evaluation, which were examined in detail, and from which the references cited in the present paper were extracted (Fig. 2).

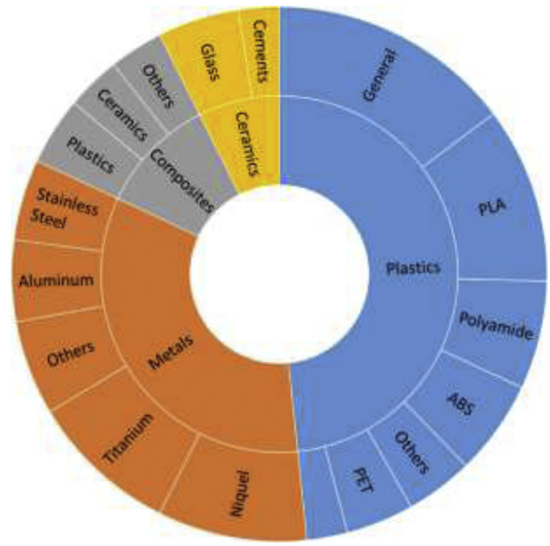


Fig. 2 – Type of engineering materials found in papers that discuss the sustainability of AM.

The number of published articles related to AM and classified according to document type is shown in Fig. 3. These

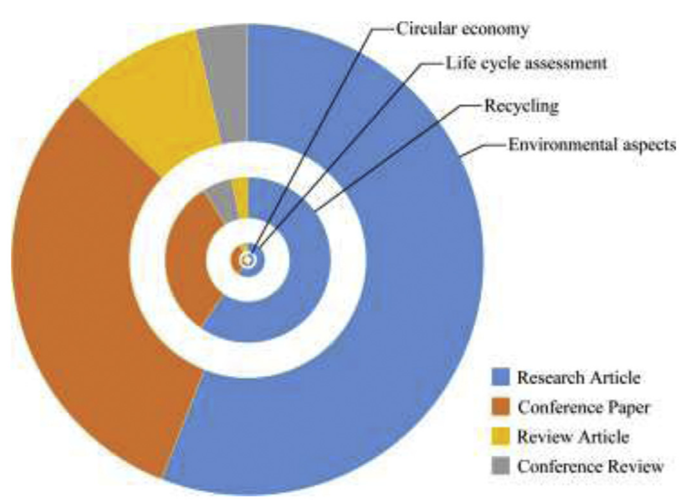
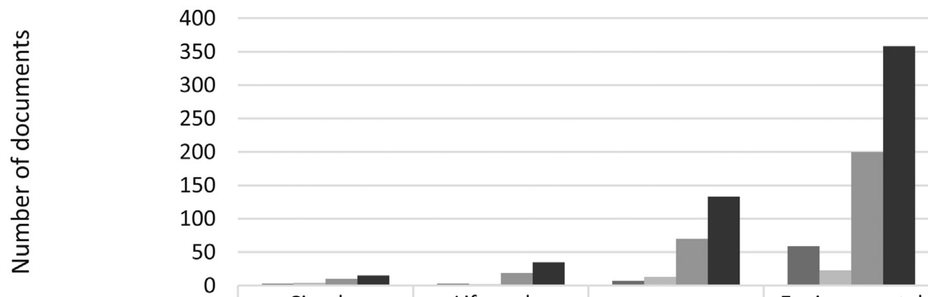
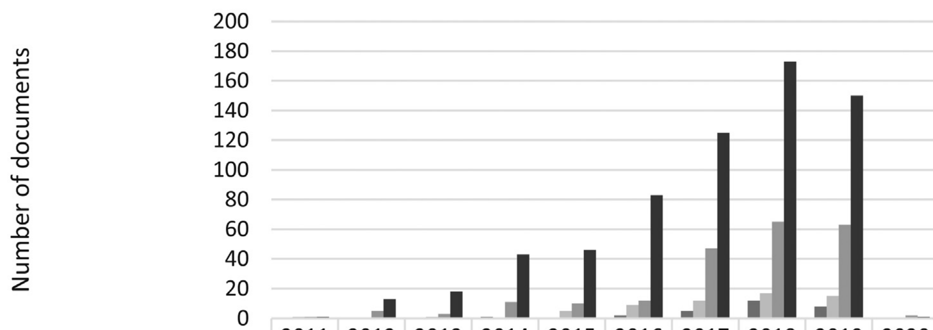


Fig. 1 – Publications organized according to area of AM sustainability.



	Circular economy	Life cycle assessment	Recycling	Environmental aspects
Review Article	3	3	7	59
Conference Review	4	2	13	23
Conference Paper	10	19	70	200
Research Article	15	35	133	358

Fig. 3 – Number of articles published since 2011, classified according to document type.



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Circular economy	0	0	0	1	0	2	5	12	8	0
Life cycle assessment	1	0	1	0	5	9	12	17	15	0
Recycling	1	5	3	11	10	12	47	65	63	2
Environmental aspects	1	13	18	43	46	83	125	173	150	1

Fig. 4 – Number of publications per year since 2011.

articles have been published since the year 2011, from when there was an increase in publications in the areas discussed in this paper. Fig. 4 shows the number of publications per year. The most significant aspects of this systematization are shown below.

3. Circular economy of materials and valorization after their use

Four of the studies found in this search were related to an open source industrial 3D printer called "Gigabot X". These articles deal with issues related to the evaluation of the printer's economic potential [27], a chopper for pelletizing [28], a study of the potential for the extrusion of particulate material [29], and a solution robust open source for large format printing [30].

One of the oldest studies related to the circular economy found in this review is the work carried out by Giurco et al. [26]. Here, the advent of two parallel trends known as 3D production systems are analyzed; one is responsible for mineral supply chains and the other is responsible for AM. Likewise, Angioletti et al. [31], showed that by using AM technologies, production and services guided manufacturing achieved greater production efficiency in terms of manufacturing costs within a circular economy framework. On the other hand, Leino et al. [32], studied current research on the use of AM for the repair, renovation and remanufacturing processes of metal products.

Subsequently, Desppeisse et al. [33], proposed carrying out research on more sustainable modes of production. Angioletti et al. [34], proposed a methodology to quantify the circularity of a product through a simplified life cycle perspective and accounted for the exchange of resources between systems. Reijonen et al. [35] applied the concept of circular economy to AM for selective laser fusion. Alghamdi et al. [36], introduce a conceptual framework to reduce the stochastic and diffuse nature of engineering attributes during the remanufacturing planning process. Despeisse et al. [33], proposed six well-defined research areas to understand how 3DP can allow more sustainable production and consumption methods, and still release value in the EC.

In 2018, Voet et al. [37], successfully manufactured prototypes of complex shapes with biologically based acrylate photopolymer resins, with a commercial 3D stereolithography printer device. Unruh [38] applied the Biosphere Rules, a management framework inspired by biomimetics for circular economy initiatives, to the emerging field of AM and 3DP. Garmulewicz et al. [39], examined how 3D technology could create a circular economy by disrupting the value chain of existing materials. Navarro et al. [40], summarized the main policies that motivated the transition to a circular economy from the linear economy model, within this, to the CO_2 reduction effords. Clemon and Zodhi [41], proposed a framework to reduce product development time and costs in material recycling and 3D filament reuse. Santander et al. [42], carried out a review of the literature that considered the economic and environmental aspects of the collection process in a closed loop supply chain network of distributed and local plastic recycling processes to produce 3DP filaments. Sauerwein and Doubrovski [43], analyzed the development of a method to link locally available materials with AM processes and the use of important applications to take advantage of the circular economy. Minetola and Eyers [44], identified opportunities for 3DP using the Make-To-Order approach, some of which can be exploited today and others that may be of greater importance in the future. Lahrour and Brissaud [45], presented an additive remanufacturing framework and key steps to allow the remanufacturing of products using AM technologies. Baiani and Altamura [46] analyzed a research program on the application of the circular economy to the built environment that works via two different by also complementary concepts: reuse (superuse) and recycling (upcycling).

More recently, Saboori et al. [47], presented a general description of the directed energy deposition (DED) process and its role in the repair of metal components. Wu and Wu [48], presented 3DP design and circular economies that significantly affect ecological technologies in terms of waste management and material processing. Sauerwein et al. [49], explored whether the opportunities offered by AM for sustainable design are also useful when designing processes for a circular economy, and to what extent AM can support the design of a circular economy. Nascimento et al. [50] explored how the emerging technologies of Industry 4.0 and circular economy (CE) practices could be combined in order to establish a business model that reuses and recycles materials such as scrap or electronic waste. Turner et al. [51], explore the viability of a redistributed business model for manufacturers that uses manufacturing technologies such as AM or 3DP as part of a sustainable and circular production and consumption system.

4. Life cycle assessment of additive manufacturing

Life cycle analysis (LCA) is a process that allows the environmental load associated with a product, a process or an activity to be evaluated. LCA identifies and quantifies matter, energy and emissions released into the environment, to determine their impact and evaluate and implement environmental improvement strategies [52].

LCA must take into account all raw materials, auxiliary services and waste generated throughout the production process, or the generation of waste in a service. It aims to establish an indicator that evaluates key environmental aspects, allowing organizations to identify where their efforts to improve environmental performance should be concentrated, whether they be in the selection of raw materials, in the process or in waste generated.

In the literature, five state-of-the-art reviews were identified. Liu et al. [53] reviewed the qualitative and quantitative environmental impact of 3DP to provide a comprehensive understanding of 3DP and better guide research on the subject. They proposed a framework to evaluate and improve the sustainability of the 3DP processes through the integration of CAD and LCA. Secondly, a review by García et al. [54] analyzed the environmental performance of AM, showing that most authors are concerned about the energy consumption of AM equipment. Subsequently, the review by Rastogi and Kandasubramanian [55], focused on evaluating the evolution, advances and predictions of the 4D printing life cycle. It concentrated on intelligent materials and associated characteristics such as their response to stimuli, along with future challenges. The review by Agrawal and Vinodh [56], looked at the state-of-the-art of sustainable AM and classified 63 articles into three areas: environment, economy and society. Finally, a review conducted by Lunetto et al. [57] to evaluate the economic and environmental sustainability of AM techniques analyzes diverse literature sources, including standards proposed by different regulatory organizations located worldwide, highlighting the importance of models for the construction of risk indicators.

In several studies examined in this literature review, comparisons were made between conventional machining processes (CM) and AM using LCA as a comparison tool.

In 2015, through the analysis of energy consumption in both injection molding (IM) and AM, Kianian and Larsson [58] focused on the potential of AM technology to create a more efficient and clean type of manufacturing. Later, in 2016 Huang et al. compared AM processes against CNC milling processes for the manufacture of light metal airplane components [59]. They estimated the net changes in main energy occurring in the life cycle of these components and reported the associated greenhouse gas emissions. Hofstätter et al. [60] studied the environmental impact of AM in comparison with three traditional methods for the manufacturing of brass, steel and aluminum inserts for injection molds. Tang et al. [61] compared the environmental impact of the CNC manufacturing process and the binder-jetting fabrication process. Paris et al. [62], compared the environmental impacts of AM and subtractive (milling) technologies in the manufacture of an aeronautical turbine. Barros and Zwolinski [63] studied the Personal Fabrication (PF) and the Industrial Manufacturing (IM) using LCA, where results suggest that the use/user profile in the LCA of 3DP products should be considered.

In 2017, Huang et al. [64] evaluated the supply chain delivery times, life cycle primary energy consumption, greenhouse gas (GHG) emissions and life cycle costs (LCC) for AM. Kafara et al. compared the environmental impact of conventional manufacturing and AM for mold cores, which are used in the production of polymer-carbon fiber composites [65]. Mrazovic et al. [66], evaluated the environmental impact of AM and CM to assess the manufacturing time and manufacturing cost of metal components. Cerdas et al. compared a conventional mass-scale centralized manufacturing system for the production of a frame for glasses, with a distributed manufacturing system compatible with 3DP [67]. The study indicated that optimization potential is focused on energy consumption at the unit process level, and revealed a close link with the printing material used. Peng et al. compared the environmental impact of different impeller manufacturing methods, including immersion milling (CM), laser coating formation (AM combined with CM) and remanufacturing of additives (RM). They worked in a scientific method for the selection of manufacturing methods that contributes for a sustainable manufacturing of an impeller production [68].

In 2018, Liu et al. [69] compared the consumption of energy and environmental impact of direct energy deposition against traditional machining processes. Le and Paris [70,71] compared the environmental impact of EBM + finishing machining with the conventional approach used to fabricate exactly the same part. Gaikwad et al. [72] studied the effects of recycling up to four extrusion cycles over electronic waste and virgin plastic filaments, proposing a mechanism for integral semi-quantitative degradation supporting in NMR and TGA results. Ingarao et al. [73] compared different manufacturing approaches used aluminum alloys components manufactured by AM (selective laser sintering) and other traditional processes. The results revealed that, for the case studies analyzed, AM is only a sustainable solution for producing aluminum components for the following specific scenarios: when creating high complexity shapes, when significant weight reduction is required, and when they are to be used in transport systems. Bekker and Verlinden [74] evaluated the environmental impact of additive wire and arc manufacturing (WAAM) based on robotic welding, a 3D metal printing technique, and compared it with green sand molding and CNC milling. Through the literature and databases, they concluded that the results might vary significantly determined by the product's shape, its function, the materials used and the configuration of the process.

In addition, in 2019 Yang et al. [75], provided suggestions on the development of an ideal sustainable assembly design by comparing the energy consumption and its environmental impact of AM direct energy deposition with other traditional manufacturing processes. Böckin and Tillman [76] presented the potential benefits of AM implementation and compared conventional manufacturing with 3DP manufacturing using the Powder Bed Fusion (PBF) of metal parts. Kwon et al. [77] analyzed the material extrusion process (Fused Deposition Modeling, FDM), the powder bed fusion (Laser Sintering, LS), and the material injection processes (Poly-Jet, PJ) for 200 NIST test artifacts, showing the effects of these processes on the environment. The environmental performance of 3DP and geopolymers in concrete manufacturing was evaluated by Yao et al. [78]. The objective was to identify possible ways to improve the 3D concrete printing process to reduce both the consumption of raw material and the generation of waste. Jiang et al. [79] investigated the sustainability of laser engineered net shaping (LENSwith respect to computer numerical control machining (CNC) for gear manufacturing, and proposed several countermeasures with the aim to enhance the sustainability of the involved manufacturing technologies. Faludi et al. [80], developed and tested new materials for 3D printing extrusion-based of pulp and analyzed the environmental impact of the entire system with standard ABS extrusion, achieving a significant reduction in printing energy.

The LCA technique has also been used to evaluate environmental issues related to AM. In 2011, Kellens et al. [81], evaluated the AM processes selective laser sintering (SLS) and selective laser fusion (SLM), identifying their most significant environmental impacts. Subsequently, in 2013 Le Bourhis et al. developed a method that considered all the flows involved (material, fluids, electricity) in order to obtain the environmental impact assessment [82]. This method was developed based on a flow consumption predictive model to produce a particular part that was defined by the manufacturing route and the CAD model.

In 2015, Malshe et al. [83] performed a LCA to quantify the environmental aspects of the AM process fast mask-image-projection based on stereolithography (Fast MIP-SL). Using a hierarchical weighting method, they established the damage to the availability of resources and the types of damage to human health for each part evaluated. Furthermore, Burkhart and Aurich [84] developed a frame of reference to estimate the environmental impact of AM in the commercial vehicle life cycle. The objective was to estimate the necessary numbers to reduce the environmental impact of AM, and guide manufacturers on how to reduce the adverse environmental effects of their AM products.

In 2017, Le et al. [85], proposed a procedure of combining AM and subtractive manufacturing technologies to develop new remanufacturing/manufacturing strategies with minimal environmental impact. Ma et al. [86], addressed the powder role in the material's feed and in the utilization factor of the material, in order to determine the environmental impact of laser metal deposition. Agustí-Juan and Habert [87,88] identified the environmental guidelines to be taken into account during the digitally manufactured architecture design. The corresponding key parameters have been extracted using LCA from three case studies.

Based on the holistic model of the additive and subtractive manufacturing approaches, Priarone et al. [89], focused on the more suitable tools that could be implemented to identify the production route with the lowest demand of energy and the lowest CO_2 emissions. This model represents the main process variables, as well as the impact caused by redesigning AM to create components made of titanium alloy. Nagarajan and Haapala [90] characterized the factors that influence the environmental performance of AM as a final energy use, employing exergy and LCA analysis.

5. Recycled materials for use in additive manufacturing

The recycled materials used in 3DP can be classified into four large groups based on raw materials: plastics, metals, ceramics and composites. It should be noted that there are some materials that do not fit properly into any of these categories.

A summary of the most relevant research on each of these categories is presented below.

5.1. *Plastics*

The recycling of plastic materials requires that this waste is recovered and eventually reused as a raw material for new products, converted into fuel, or used in new chemical products [91]. Polylactic acid (PLA) is the one of the most mentioned plastic material in the greatest number of publications. Several authors have carried out research related to the mechanical properties of recycled PLA [92–98], which is obtained from printed pieces of virgin PLA that are subsequently re-extruded into filaments suitable for use in 3DP. Likewise, research has been reported which proposes to improve the properties of recycled PLA for specific applications [99,100]. The performance of other plastic materials after several recycling cycles has also been evaluated in the literature. These materials are: Acrylonitrile Butadiene Styrene (ABS) [101–106], polyamides (PA) [107–112], Polyethylene Terephthalate (PET) [113–116], High-Density Polyethylene (HDPE) [117–119], polycarbonate (PC) [72,120] and poly(ethylene-2,5-furandicarboxylate) (PEF) [121]. Similarly, some papers seek to recycle plastic waste for 3DP applications, including Hart et al. [122] who propose the recycling of polymeric packaging and Quetzeri-Santiago et al. [123] who describe a method to recycle rubber through AM.

5.2. *Metals and alloys*

Metal materials include pure metals and c alloys. There are 86 metals with different properties, a small number of which are of engineering importance [124]. Metals are materials that have a high degree of recyclability. The bibliographic review carried out for this study shows that some metals have been subject to exhaustive analysis. Among these is titanium. Recently, the effects of recycling this metal have been widely studied [125–133]. Other materials that have been the subject of recent studies for 3DP applications are nickel alloys [26,134–142], aluminum [143–148], stainless steel [149–153], copper [154,155] and magnesium [156]. Additionally, in this bibliographic review two studies were found which evaluate the recycling of rare earth metals. In the first one, Khazdozian et al. [157] propose to produce recycled samarium and neodymium magnetic filaments for the 3DP of permanent magnets. The second study, developed by Harooni et al. [158], relates to the recycling of rare earth metals and proposes the manufacture of additives based on the fusion of zirconium powder. The microstructure and mechanical properties in thin-walled structures generated by AM are then evaluated.

5.3. *Ceramics*

The specific nature of ceramic materials favors their use in multiple engineering applications. Their special characteristics, such as heat resistance, allow them to be used for many applications in which materials like metals or polymers are not suitable. This is why ceramic materials are applied to a wide range of applications, including the guided transmission of light waves. There were few studies found in this literature review that focused on the recycling of ceramic materials, and of these the only material that was the object of study was glass. In one of these studies, Marchelli et al. [159] provide a general description of a process for the adaptation of virgin glass and recycled glass to three-dimensional printing (3DP). Klein et al. [160,161] describe the formulation of a new material that could be used in a 3D printer extrusion process to create optically transparent glass-based objects. Ting et al. [162] and Andrew et al. [163] propose the use of recycled glass as an aggregate for 3D concrete printing applications.

5.4. *Composites*

Composite materials provide high quality and long service life for parts, high strength, low weight, less maintenance and they favor recycling processes. Therefore, they are highly used to replace metals and ceramics in numerous applications. One of the components that is most used as reinforcement in composite materials is carbon fiber (CF), because it is a fabric of great strength, durability and flexibility. As a result, there are several studies aimed at evaluating the characteristics of composite materials using CF as a reinforcement material and different polymers as a matrix. Some examples of studies on composite materials are those by Hunt et al. [164] and Tian et al. [165,166], who evaluated the behavior of CF-based composite materials in a PLA matrix. Likewise, Wang et al. [167] evaluated the feasibility of a process using a filament composed of milled carbon fiber with recycled polyamide 12. Wang et al. [168,169] investigated the machinability and the configuration of materials in recycled and printed carbon fibers in a 3DP process. Similarly, Cholleti and Gibson [170] compared the results of tests performed on multiple-wall carbon nanotubes in ABS resin composites.

There are also studies on other materials used to reinforce composites. Veer et al. [171] investigated the possibility of using a recycled polypropylene (PP) fiberglass-reinforced mixture in 3DP processes. Farina et al. [172] studied the behavior of a cement-based mortar reinforced with recycled 3D-printed nylon fibers and manufactured via the extrusion of nylon grains obtained from fishing nets. Melugiri-Shankaramurthy et al. [173] incorporated a stainless steel micropowder to increase the mechanical strength of a cement paste mixture. Pan et al. [174] studied the addition of nanocrystalline powders of iron (Fe), silicon (Si), chromium (Cr) and aluminum (Al) in a recycled PP/HDPE plastic matrix for 3DP filament extrusion and compared them to the original recycled filaments. Singh et al. [175] evaluated the performance of thermoplastic polymers for ceramic particle reinforcement and concluded that they have mechanical properties on par with ABS without reinforcement. Corcione et al. [176] made a composite biomaterial from a matrix of polylactic acid (PLA) and recycled Lecce stone (LS) remains. Likewise, Singh et al. [177] investigated the thermomechanical properties of a filament based on silicon carbide (SiC) and aluminum oxide (Al2O3) in a reinforced HDPE matrix.

6. Environmental aspects of additive manufacturing

3D printing promises a net reduction of environmental load compared to conventional machining, especially with respect to the materials and energy consumption, because it greatly decreases the amount of waste generated in the process [178].

However, some materials used in 3DP, such as ABS, PLA and nylon, can generate health hazards in the form of volatile organic compounds such as styrene, cyclohexanone, butanol, and ethylbenzene [179]. In this sense, the extruder temperature plays an important role in particle emissions [179–182], as does the malfunction of printers [180,184,185]. On the other hand, the particulate material (PM) and the concentrations of volatile organic compounds (VOCs) show a higher concentration when the printer has just been turned off and the cover is taked out in order to remove the printed object [179,186]. In addition, slight differences in VOC emissions can be observed in filaments fabricated from the same polymer (for example, bur provided for diverse manufacturers, for different filament diameters, or for differences in additives or aggregates) [179].

The total ultrafine particle emission rates (UFP) are approximately an order of magnitude greater for 3D printers using a thermoplastic ABS material than those using a raw PLA material. However, both materials can be characterized as "high emitters" of UFP, and thus, care must be taken when these filaments are used in indoor environments without ventilation or with inadequate filtration systems. [187]

The particles emitted by most filaments have a mean diameter (count median diameter CMD) of about 30 nm, except for PETG (59, 82 nm) and HIPS_ (41 nm) based filaments. Styrene is the main VOC, succeed by substances such as benzaldehyde and ethylbenzene [188].

Although the organic chemicals emissions in 3D printing are not fully known at present, some research indicates that could produce adverse cardiovascular or respiratory effects. The emission levels are influenced by the design of the 3-D printer, the characteristics of the raw material and construction parameters [189], and by filament color [190] as well.

The temperature of the nozzle increases the concentration of particles; however, ABS filaments exhibit significant bigger particle emissions when compared with PLA due to the filament heating differences. A higher temperature in the nozzle causes a significant increase in the emission of particles. An optimization method consisting of the external warming of both platform and extruder shows a particle emissions decrease by 75% for ABS filaments when compared to the conventional procedure [181]. Other research indicates that the inhalation of ABS filament emissions during AM using an extrusion-based machine may be cause asthma outbreaks and acute hypertension in workers and rodents respectively [191].

3D printers that use ABS and PLA can cause ultrafine particles inhalation since most of the released particles have a grain size as low as 100 nm. Although the literature suggests that exposure to ultrafine particles can be dangerous to human health, the concentration of particles to which workers may be exposed during the operation of the 3D printer depends on several factors such as ventilation, room size and the printer cabinet. Research has shown that the use of ABS in 3DP may cause a higher exposure to a these small particles when compared to the exposure to particles produced by PLA 3D printing, as that the temperature of the nozzle affects the amount of particles emitted [183].

The adverse health effects associated with 3DP relate to the emission of chemical gases, which in well ventilated spaces appear to be low. Currently, there are growing concerns that the emission of ultrafine particles is related to inflammatory, pulmonary and cardiovascular problems, indicating that 3DP produces high concentrations of UFP. Therefore, future studies are required that develop safer materials and establish manufacturing safety recommendations [192]. Animals exposed to the inhalation of 3DP emissions have shown significant average blood pressure, corresponding to about 12% in resting arteriolar tone [184]. It is also known that emissions are affected by the type of consumables, filament types, filament color, printer type and part design. On the other hand, in case of laser printer, although there is still not well consolidated data, these UFP in large amounts were associated with a high risk of mortality, and therefore, it is prudent to reduce the exposure to these processes in public places such as libraries, homes, and schools [185].

The UFP adverse health implications and the VOC emission rates revealed significant concerns in terms of their associated effects on the human's health. Styrene, classified by the International Agency for Research on Cancer (IARC) as a human carcinogen, is emitted by all ABS and HIPS filaments; caprolactam, classified as probably not being carcinogenic to humans, is emitted by nylon, PCTPE, bricks and wood filaments. The lowest and larger UFP emission rates for 3D printings using filaments occurred for ABS and PLA filaments [193]. Zhou et al. [194] found that the main particle size produced by 3D printers when using ABS filaments is less than 10 μm, with the highest concentration having a size ranging from 0.25 to 0.28 μm.

7. Conclusion

In the present work an exhaustive review of the literature on the processes of AM was carried out, seeking to recognize and identify the relevant aspects in relation to the following areas: (1) valuation of materials after their use in AM; (3) recyclability of the materials currently used in AM; and (3) environmental aspects in relation to the AM. Similarly, this study highlights the importance of considering some aspects in relation to the circular economy and sustainability in relation to the productive processes related to the AM.

The increasing number of publications on the topics presented in this study shows that researchers are paying more attention to the sustainability of AM. This suggests that the limitations of AM in terms of the reuse and recycling of materials, health impact and sustainable processes will quickly be reduced.

Regarding the type of materials and their relationship with the environmental sustainability of the processes, as expected, metals are the most suitable for an optimal circular economy due to their high recyclability. However, more research is needed as energy optimization is still far from the ideal values. As presented in this research, plastics are among the materials most commonly reviewed because of their higher usage in AM. They are also the focus of intense research as a result of their negative impact on the environment. Other materials such as ceramics and composites have been less frequently reviewed, and therefore more research is required in these areas.

Materials with better recyclability, reuse or circularity will be more feasible for future use in AM, as national policies increasingly move manufacturing toward green materials and processes.

Conflicts of interest

The authors declare no conflicts of interest.

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