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Review

Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy

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A B S T R A C T

The rapid technical evolution of additive manufacturing (AM) enables a new path to a circular economy using distributed recycling and production. This concept of Distributed Recycling via Additive Manufacturing (DRAM) is related to the use of recycled materials by means of mechanical recycling process in the 3D printing process chain. This paper aims to examine the current advances on thermoplastic recycling processes via additive manufacturing technologies. After proposing a closed recycling global chain for DRAM, a systematic literature review including 92 papers from 2009 to 2019 was performed using the scopus, web of science and springer databases. This work examines main topics from six stages (recovery, preparation, compounding, feedstock, printing, quality) of the proposed DRAM chain. The results suggested that few works have been done for the recovery and preparation stages, while a great progress has already been done for the other stages in order to validate the technical feasibility, environmental impact, and economic viability. Potential research paths in the pre-treatment of recycled material at local level and printing chain phases were identified in order to connect the development of DRAM with the circular economy ambition at micro, meso and macro level. The development of each stage proposed using the open source approach is a relevant path to scale DRAM to reach the full technical potential as a centerpiece of the circular economy.

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1. Introduction

Plastic materials offer a variety of chemical and mechanical properties to be useful for a wide array of applications. Unfortunately, the plastic waste pollution poses a major threat because of the issue of non-degradability affecting the ecological environments (Hopewell et al., 2009; Ryberg et al., 2019; Thompson et al., 2009). Indeed, recycling rates remain small (approx. 14%) in the plastic packaging field on a global scale (Hahladakis and Iacovidou, 2018). Even in Europe, which tends to lead on environmental stewardship, the recycling rate is about 32.5 wt% (Plastics, 2019). However, these values take into account the amount of plastic waste collected, rather than the total amount in circulation (Kranzinger et al., 2018). To tackle this accumulation of waste problem, the european strategy for plastics in the circular economy (CE) is gaining attention in the policy and business debate surrounding sustainable development of industrial production (European Commission, 2018; Geissdoerfer et al., 2017). CE tackles a central societal issue concerning the current principle "take, make, dispose" (linear economy) and its negative effects caused by the depletion of natural resources, waste generation, biodiversity loss, pollution (water, air, soil) and non-sustainable economics (van Buren et al., 2016). The validation (technical, economic, legislative) of waste plastic as a secondary raw material in industrial processes is considered now a core target to integrate CE into the plastic value chain (Simon, 2019). Strategies of open and closed-loop recycling as well as upcycling and downcycling functionality approaches can offer paths to validate the secondary raw materials (Zhuo and Levendis, 2014).

On the other hand, additive manufacturing (AM) -also known as 3D printing- and its direct (or distributed) manufacturing capabilities is becoming a key industrial process that could play a relevant role in the transition from a linear to circular economy. AM technologies are expected to transform the production process (Chen et al., 2017; Jiang et al., 2017; Rahman et al., 2018) thanks to their ability to transform a numerical model into a deposition of material (points, lines or areas) to create a 3D part (Bourell et al., 2017). The expiration of the first patents has contributed to an increased interest, creating consumer value and potential for disruption (Beltagui et al., 2020; West and Kuk, 2016). In economic terms, the global additive manufacturing market is expected to reach USD 23.33 billion by 2026 (Data, 2019). However, determining when and how to take advantage of the benefits is a challenge for traditional means of production. From a societal viewpoint, Jiang et al. (2017) reported that the product development could change from traditional stage-gate models to iterative, agile processes changing the scenario by 2030. A large number of products can already be manufactured with AM, which affects the geographical spread and density of global value chains (Laplume et al., 2016). It is expected that the reach of AM printable products will be much greater in the future, as the production of multi-material and built-in functionalities (e.g. electronics) will be possible to a large extent. In addition, the production of spare parts can be carried out on-site, modifying the role of suppliers in the production lines (Zanoni et al., 2019). Matt et al. (2015) explored the stages of distributed model factories and decentralized production types ranging from distributed capabilities to cloud production. Thus, the need of transport will be much more carefully because of the fact that AM will enable decentralization of production to localities near customers or in the most extreme distributed scenario at the customer's premises (Bonnín Roca et al., 2019; Petersen and Pearce, 2017; Wittbrodt et al., 2013). Moreover, AM technology makes it possible to reduce market entry barriers, reduce capital requirements and achieve an efficient minimum scale of production to promote distributed, flexible forms of production (Despeisse et al., 2017). This enables an alternative option from an economy-of-scale to an economy-of-scope, where the products are highly personalized satisfying niche communities or even individuals (Hienerth et al., 2014; Petrick and Simpson, 2013). For these reasons, the AM technology could be a driver for a shift in manufacturing from globally distributed production to local facilities. Significant efforts are being made by industry and the scientific community to move AM techniques from rapid prototyping and tooling stages towards direct digital manufacturing (DDM) (Gibson et al., 2010; Holmström et al., 2016), with the concomitant environmental and social benefits. Nevertheless, Niaki et al. (2019) demonstrated that environmental and social benefits are not the key preferential factors in the adoption of AM technologies in different industrial sectors. Only the economic factor remains relevant in the AM implementation, considering time- and cost-saving as the most important reasons.

The opportunities of AM on CE are only beginning to be explored. It is necessary to understand what are the contributions and barriers for the integration of AM development with CE requirements. More specifically, to understand the opportunity that AM brings to plastic waste issues (Garmulewicz et al., 2018). As traditional centralized plastic recycling processes have proven to be inefficient (Kranzinger et al., 2018), the sustainability dimension of AM needs to be performed at early phases as the diffusion of this technology will continue to grow in the years to come. The implementation of AM into circular economy purposes enable the possibility to use local materials supply chains (Despeisse et al., 2017) promoting in-situ recycling (Ford and Despeisse, 2016) with highly distributed sources of consumer waste could lead to a reduction in transportation (Kreiger et al., 2013) and the environmental impact of intensive resource exploitation. Hence, AM can be seen as a recycling tool to reuse a thermoplastic waste material, and then influencing the structure of material supply to improve resource consumption efficiency. Indeed, using open source technology is an important driver to boost the local recycling process (Buitenhuis et al., 2010; Santander et al., 2020).

Nevertheless, at this stage a better understanding of the global recycling chain value is needed for additive manufacturing. Different issues such as the technical and logistical feasibility of distributed recycling via additive manufacturing (DRAM) needs to be globally clarified (Hart et al., 2018). Moreover, the different stages required to transform the plastic wastes into secondary raw materials for AM are required to be highlighted. Therefore, this work presents a systematic literature review study based on the specific research question: *What are the advances and barriers on thermoplastic recycling processes via additive manufacturing technologies?* In this paper, firstly, a closed recycling global chain specific for AM process is proposed. And secondly, the advances at each stage of this recycling chain are mapped in the scientific literature in order to have an overview of the opportunities and challenges to overcome. Many authors have pointed out the practices of the R framework as core principles of CE (Milios, 2018; Morseletto, 2020; Rosa et al., 2019). In this way, AM could be a driving technology enabling the implementation of local niches of the R framework at a local scale.

This paper begins in Section 2 by providing a background on the plastic issues and an overview of the related environmental aspects on additive manufacturing context. Section 3 presents the overall methodology used in the literature review including a global framework and the steps followed in order to identify relevant documents considered in this review. Then, Section 4 presents the results considering each phase in the recycling chain value. Then Section 5 presents the discussion of the result focalised in three elements: Section 5.1 is focalised on the pre-treatment of the recycled material at local level, Section 5.2 is related on the printing process chain and use of the recycled parts and in Section 5.3 is about on the open source as driver of the DRAM approach. Finally, conclusions and perspectives are presented in Section 6.

2. Theoretical background

2.1. Plastic issues

The European Commission identified plastic materials as a priority area, with the aim of making all plastic packaging recyclable by 2030 (European Commision, 2015; European Commission, 2018). Different challenges have been identified as political (e.g. China's decision to restrict imports of certain types of plastic waste (Brooks et al., 2018)), economical (e.g. weak or non-existent markets for recycled plastics (Milios, 2018)), social (e.g. cultural mindsets and attitudes towards resources recovered from wastes (Blomsma, 2018)), technical (e.g. design for recycling (Horvath et al., 2018)), and legal aspects (e.g. standardization, recycling symbols (Hennlock et al., 2015; Milios et al., 2018)). Therefore, the creation of a context that improves the economics and quality of plastic recycling are essential issues to solve in order to create value from these secondary resources. Specifically, the quality assessment of materials, components and products upstream and downstream of the point where they are disposed of as wastes are more important aspects to be determined (Iacovidou et al., 2019)..

Regarding industrial ecology of polymers, primary, secondary, tertiary and quaternary recycling are the four main approaches for recycling plastic solid wastes (Al-Salem et al., 2009; Clift, 1997; Hopewell et al., 2009; N. Singh et al., 2017c). The primary and secondary recycling is performed as a mechanical recycling process. Mechanical recycling includes the physical treatment to reprocess plastic waste into new products where it entails technologies for sorting/separation, decontamination, size reduction, remelting and production (Al-Salem et al., 2009; Fisher, 2004; Hopewell et al., 2009; Perugini et al., 2005; N. Singh et al., 2017c). Several studies showed the relevance of mechanical for single plastic/bioplastic waste streams in terms of environmental impacts (Arena et al., 2003; Perugini et al., 2005) and energy(Lazarevic et al., 2010; Piemonte, 2011). Moreover, it is a key enabler to circular economy for closing the loop on polymer wastes (Ragaert et al., 2017). However, mechanical recycling meets several obstacles as management and collection are complex and technical considerations of the plastic degradation (Al-Salem et al., 2009; Hopewell et al., 2009). The incompatibility between most polymers makes the sorting process essential for satisfactory properties (Signoret et al., 2019). The separation of laminated flexible structures (e.g., food packaging) for recycling is not economically viable, which explains that the packaging applications, the largest contributor to the production of plastic waste, are sent to landfills (Craighill and Powell, 1996; Curtzwiler et al., 2019). From a logistical point of view, the recycling process is less economically viable given the low weight/volume ratio and the complex heterogeneity of mixed waste which implies an investment in transport, storage and sorting facilities. Additionally, the price of recycled plastic is a function of the prevailing oil price (Hopewell et al., 2009). Therefore, chemical recycling is a preferable option for complex and contaminated wastes (Ragaert et al., 2017).

From a technical perspective, the final quality is the main issue for mechanically recycled products. Fig. 1 presents a technical characterization framework with three major elements for a holistic quality assessment of recycled material (Badia and Ribes-Greus, 2016; Karlsson, 2004; Vilaplana and Karlsson, 2008).

They can be defined as follows:

Structural and morphological (SM): determines the chemical nature of recycled polymer constituents

Feasibility of production and stability (FP): it refers to macroscopic properties such as thermal, mechanical and rheological of the recyclates.

Low molecular weight compounds (LMWC): it concerns the analysis of degradation products (additives, impurities, contaminants) in the polymer structure.

For each element, Badia and Ribes-Greus (2016) proposed a multi-scale characterization framework including experimental and analytic techniques. This framework enables to map the quality from the micro- to macro properties of the recycled material.

2.2. Polymers under the additive manufacturing context

Additive manufacturing is defined as a process of joining materials to manufacture objects from 3D models, where the manufacturing process is made layer by layer (ASTM, 2015). According to the ISO standard, the seven main process categories are: (1) binder jetting, (2) direct energy deposition, (3) material

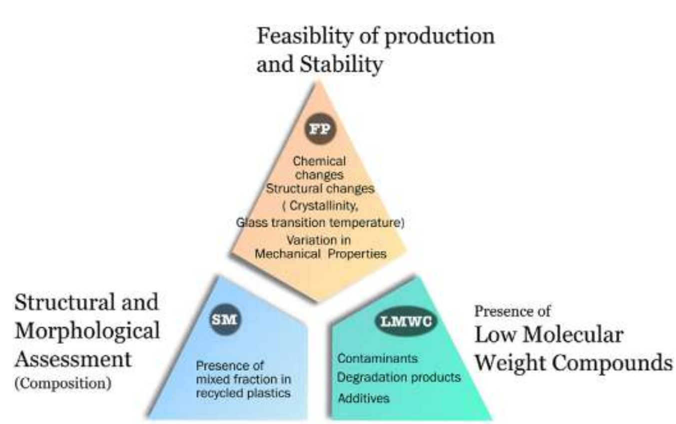

Fig. 1. Technical framework for quality assessment of recycled plastics. Adapted from (Karlsson, 2004; Vilaplana and Karlsson, 2008).

extrusion, (4) material jetting, (5) powder bed fusion, (6) sheet lamination, and (7) vat photo-polymerization. From the polymer perspective, Fig. 2 presents the overview of the classification of the AM technologies that use polymer materials and the physical principle exploited in the process.

Polymer materials are a key area in the field of AM and are by far the most used material type (Bourell et al., 2017; Ligon et al., 2017). They include thermoplastics, thermosets, elastomers, hydrogels, functional polymers, polymer blends, composites, and biological systems. Recent works presented a completed review on polymer materials in AM (Ligon et al., 2017), including a focus on 4D printing (González-Henríquez et al., 2019) and elastomers (Herzberger et al., 2019). The additive principle applies to all AM technologies, however, in function of the building principle of each technique, there are different physical aspects in order to join the material. This implies that different functional material requirements and parameters need to be considered in order to guarantee a holistic technical comprehension of the material/process/properties relationship. Most of the thermoplastic (amorphous) materials are processed by material extrusion which is the most extended AM technology (González-Henríquez et al., 2019). Material extrusion systems deposit molten and semi-molten polymers using a movable nozzle or orifice serving as printing head. Fused filament fabrication (FFF) and its proprietary cousin fused deposition modeling (FDM) are the most popular techniques in material extrusion systems. In these techniques, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) are among the most used materials (Carneiro et al., 2015). However, general polymers that can be melted at an adequate temperature without degradation are usually useful candidates for material extrusion systems (González-Henríquez et al., 2019).

Technical requirements of material extrusion processes include interfacial adhesion and undisturbed polymer entanglement to manufacture nonporous objects with mechanical properties similar to products made by conventional techniques (Turner and Gold, 2015). In this case, rheology, thermal and mechanical properties need to be characterized to validate the use of a particular material. In the scientific literature, there have been many advances to characterize the geometric characteristics (Cruz Sanchez et al., 2014; Hebda et al., 2019), mechanical properties such as tensile (Dizon et al., 2018; Jasiuk et al., 2018; Tanikella et al., 2017), fatigue (Safai et al., 2019; Yadollahi and Shamsaei, 2017), flexion (Phan et al., 2019) an thermal properties (Turner et al., 2014). Moreover, multiple applications have successfully used polymer materials including dental (Stansbury and Idacavage, 2016), tissue engineering (Bose et al., 2013), drug delivery (Goyanes et al., 2014), medical (Culmone et al., 2019), humanitarian (Savonen et al., 2018).

Nevertheless, from a technological perspective, different challenges have been identified for the development of polymers' AM in order to improve their competitiveness (Ligon et al., 2017). This competitiveness is related to the functionality of the printed object, evolving from rapid prototypes or tooling to the user-final product. Thus, mechanical properties are one important factor. Efforts have been made to reduce the anisotropy of the printed parts (Torrado et al., 2015). Often, products produced by AM have inferior mechanical properties compared to other manufacturing techniques in many cases, particularly in the direction of build (Ko et al., 2019). Also, manufacturing speeds are inferior to those of traditional processing like injection molding. On the other hand, the current development of 4D printing is an important way to develop smart polymeric materials. Shape memory polymers, hydrogels or active polymer based composites are currently explored in multiple studies in order to evolve the static 3D printed part to change their shape given a specific trigger or environment (González-Henríquez et al., 2019). Objects with complex shapes, compositions (e.g. multi-material), gradients (e.g. multi-color) and multi-functional (e.g.

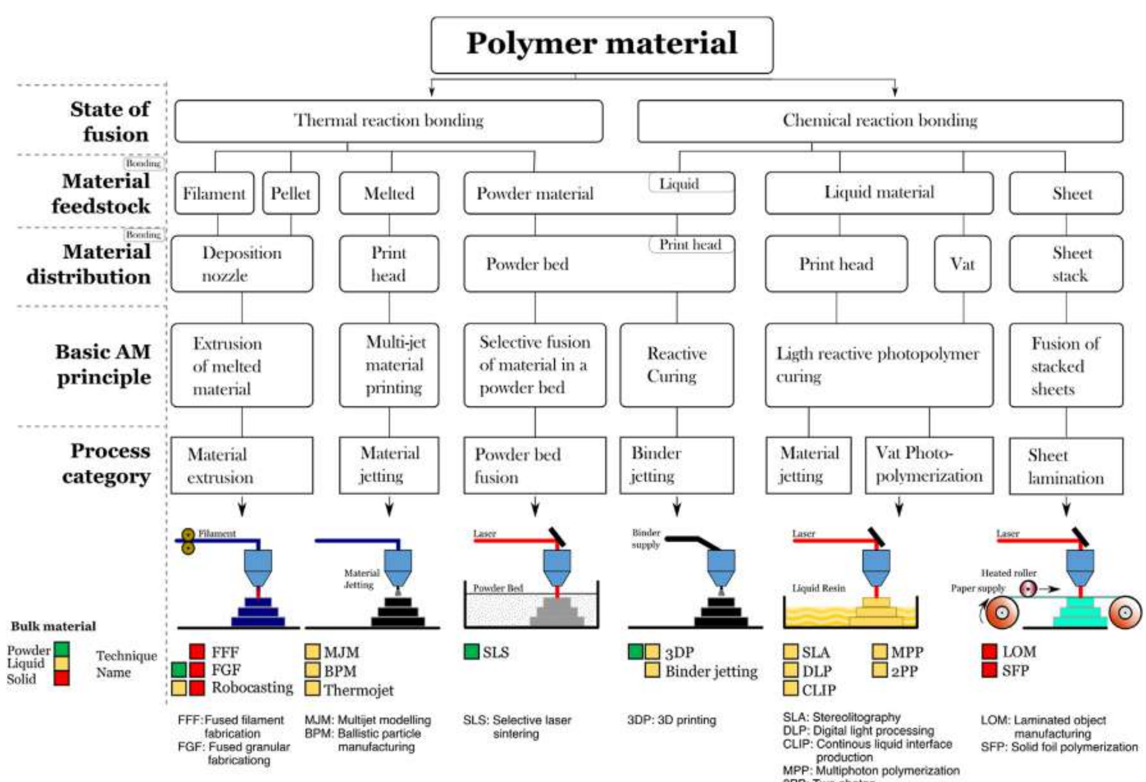

Fig. 2. Overview of single-step AM processes that uses polymer materials. Adapted from (González-Henríquez et al., 2019; Singh et al., 2017a,b,c).

hard-soft) in a single step is an important challenge, which is becoming more common in advanced AM systems.

2.3. AM and environmental issues

Considering the different specificity of AM processes, a broad field of opportunities emerges to develop more sustainable means of production at different levels of the chain values (Ford and Despeisse, 2016; Khorram Niaki et al., 2019). This shift goes from design and manufacturing optimization (part/assembly) until the synthesis of advanced materials into the final product (Chen et al., 2015; Drizo and Pegna, 2006; Freitas et al., 2016). There are possible impacts in the upstream phase (e.g. supply chains) as well as the downstream phase (e.g. reparability, recycling and end of life) (Drizo and Pegna, 2006; Morrow et al., 2007; Subramanian Senthilkannan Muthu, 2016). Ford and Despeisse (2016) proposed a framework identifying sustainability benefits of AM, differentiating four main stages: (1) Design, (2) Production, (3) Consumer/Prosumer, and (4) End of Life as illustrated in Fig. 3:

Considering environmental aspects, the clear advantage of AM at the design stage (Fig. 3) is the opportunity to produce more complex and optimized components reducing assembly operations. Higher flexibility compared to traditional manufacturing reduces the product development time and cost, while improving human interaction and consequently, improving the product development cycle (Guo and Leu, 2013; Vaezi et al., 2013; Wong and Hernandez, 2012). Nonetheless, operational requirements and constraint processes limit the absolute geometric freedom (Mellor et al., 2014; Peng et al., 2018).

In the production phase (Fig. 3), Peng et al. (2018) underlines three main aspects: (1) resource consumption, (2) waste management, and (3) pollution control. In resource consumption, several studies have measured the energy consumed by AM equipment and auxiliary subsystems (Baumers et al., 2011; Mognol et al., 2006), material consumption (Bourhis et al., 2013) and comparison between traditional and additive processes (Morrow et al., 2007; Yoon et al., 2014). Considering the waste management, certainly the principle layer-by-layer improves the material yields (ratio of final product weight/input material weight). However, examples of waste include powdery materials that are no longer useable, waste generated by unexpected defects and/or supporting structures created in the printing process. Singh et al. (2017a) reported a complete review on zero waste manufacturing in which additive manufacturing represents an opportunity to implement this roadmap. This opportunity could be realized through the development of direct digital manufacturing (Chen et al., 2015). Finally, considering the pollution control, AM uses fewer auxiliary harmful chemicals than conventional manufacturing (e.g. forging lubricants, cutting fluids or casting release compounds). Emission rates for FFF are relatively low, it does not lead to a traceable pollution in a well-ventilated room (Steinle, 2016). However, precautions should be taken when operating many printers and styrene- and nylon-based filaments without the aid of filtration systems and in poorly ventilated spaces (Azimi et al., 2016; Kim et al., 2015; Stephens et al., 2013).

In the consumers phase, the adoption and diffusion of additive manufacturing (Niaki et al., 2019; Rylands et al., 2016) by different communities from the user-driven innovation paradigm (Hienerth et al., 2014; Hippel, 2005), have resulted in growing interest for the personal fabrication (Mota, 2011), do-it-yourself (DYI) (Fox, 2014) and peer-to-peer (Kostakis and Papachristou, 2014) practices practices at open spaces such as fablabs, hacker/maker spaces and innovation laboratories (Osorio et al., 2020). Different authors have stated that the capacities of digital manufacturing (Kostakis et al., 2018; Nilsiam and Pearce, 2017) are undergoing a democratization process (i.e. widespread use of the technology). Which on the consumer side, allows private and industrial users to design and produce their own goods (Rayna and Striukova, 2016), enhancing the concept of 'prosumer' (Birtchnell and Urry, 2013; Toffler, 1980). In the prosumer context, four drivers were identified to promote environmental sustainability in personal fabrication: (1) product longevity, (2) co-design, (3) local production and (4) technology affordance (Kohtala, 2015; Kohtala and Hyysalo, 2015). A strategy of cleaner prosumption takes into account the 'what, how, and why' of the produced element. Nevertheless, it is found that the lack of knowledge about AM impacts on the social and environmental aspect is an issue for AM adoption (Matos and Jacinto, 2019). AM practitioners might not be aware of the environmental dimensions when choosing a AM technology (Niaki et al., 2019).

The end-of-life stage (Fig. 3) attempts to close the loop that can be achieved at different levels in AM. Repair and maintenance ability that AM could contribute to in order to extend the product life span as a key feature. This cost-effective approach has been usefully exploited for metal parts giving great potential in the repair of damaged components (Yin et al., 2018). Likewise, reverse engineering is an approach to foster repairing and refurbishing while reducing the cost and risk of developing new products (Paulic et al., 2014; Zhang and Yu, 2016). Although it should be pointed out as more businesses adopt an open source business model, reverse engineering processes will become unnecessary (Pearce, 2017a). Finally, concerning the recycling process, several initiatives have been reported in open source communities in order to create low cost extruders to produce plastic filament for FFF 3D printers (Baechler et al., 2013; Filabot, 2012; Lyman, 2016; Woern et al.,

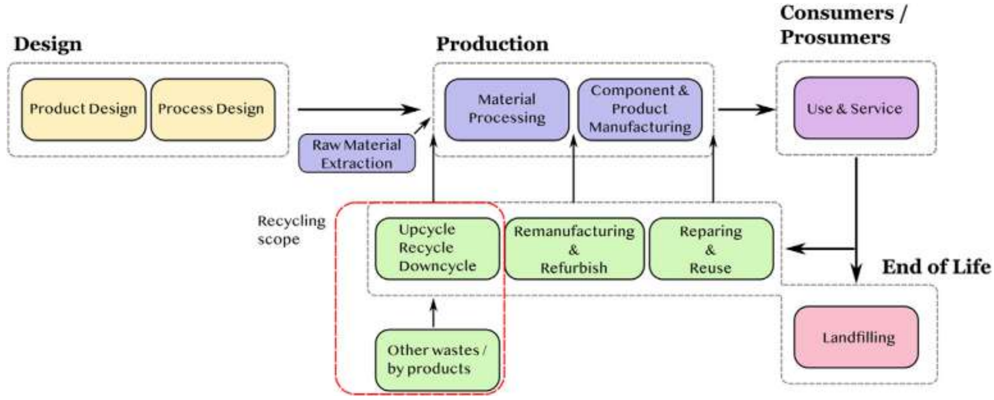

Fig. 3. Life cycle perspective for identifying sustainability benefits. Adapted from (Ford and Despeisse, 2016).

2018b; Braanker et al., 2010; McNaney, 2012). Companies start to sell recycled filaments and some organizations and entrepreneurial initiatives (Bank, 2020; Hakkens, 2016; LF2L, 2020; Plast'if, 2020; PPP, 2020; Qactus, 2020) are appearing to recycle waste plastic towards products with a higher added value.

Zander (2019) explored the current use of recycled filaments in material extrusion and biodegradability of 3D printing filaments as replacement of oil based feedstock. However, there remains a need for understanding the continuum stages that should be studied in order to create a closed-loop recycling chain for additive manufacturing. The study of the global recycling chain enables a holistic analysis in order to determine the stages that need to be solved in order to scale-up the use of recycled materials. Based on that, the next section presents a systematic literature review about the recycling via additive manufacturing. The context of this literature review is to clarify the recycling scope from Fig. 3 (in red line).

3. Methodology

Considering the mentioned challenges of plastic waste and regarding the recycling scope in Fig. 3, the Fig. 4 shows the proposed closed-loop framework in order to identify the scientific literature at each phase based on the literature on polymer recycling (Chong et al., 2015). This will allow us to identify advances in the global value chain that enables DRAM.

The *Recovery (I)* phase concerns the logistic operations to consider in order to collect the plastic wastes to be reused in DRAM. The *Preparation (II)* phase corresponds to the actions and strategies to identify, separate, sort, size, reduce and clean waste plastic to guarantee adequate quality for DRAM. The *Compounding (III)* phase refers to the development of mono- and composite-materials. The *Feedstock (IV)* phase identifies the actions to fabricate the material useable for the printing process, either filament for FFF or the particle size for fused granular fabrication (FGF). *Printing (V)* stage identifies applications and process improvements for the recycled printed part. Finally, the *Quality (VI)* phase identifies the multi-level technical characterization performed to the recycled material.

A systematic review protocol is used to carry out the selection of the studies based on the guidelines of Siddaway et al. (2019). This approach minimizes the risk of publication bias and enables researchers to perform future reviews to identify new research paths (Budgen and Brereton, 2006). The review protocol is composed of the following steps:

1. **Search strategy**: It defines the type of studies, keywords, search equations and the databases to be considered in the review.
2. **Study selection criteria**: It describes the inclusion and exclusion principles that are useful to subset the retrieved documents.
3. **Study selection procedure**: It describes how the selection criteria is performed. The steps and the features to analyze in order to accept or reject a particular study are defined.
4. **Data extraction strategy**: Defines the information that is extracted from the studies.
5. **Study quality assessment**: Evaluates the pertinence of a study regarding the research question. Quality checklists are used to guide the evaluation of the study.

Table 1 presents in detail the elements considered for each step in the review protocol. The procedure to select the articles is illustrated in Fig. 5. The search is limited to peer-reviewed journal articles and proceeding conferences published in English. At the beginning, a total of 1143 studies were identified using the respective search engine of each scientific database. The repeated studies were deleted and a total of 1068 studies were screened in order to select those related to our objective. Title, abstract and keywords were analyzed resulting in 715 papers (67% of total) being rejected by applying the inclusion criteria. So, 353 full articles were obtained for a deeper reading including the introduction and conclusion to verify the relevance to our scope based on study selection criteria. Finally, 92 articles were selected for this research. The presentation of the results is made in the next sections.

4. Results

The table A1 presents the detailed description of the set of 92 studies considered in this review according to the protocol described above.

Fig. 6a presents the temporal distribution of the documents. It should be noted the literature review for this study occurred at the end of June 2019, which explains the drop off in the last year shown in Fig. 6. However, a growing interest since 2016 in the subject is observed with an increase of published documents. A total of 64 journals were identified. Fig. 6b illustrates the ranking of journals

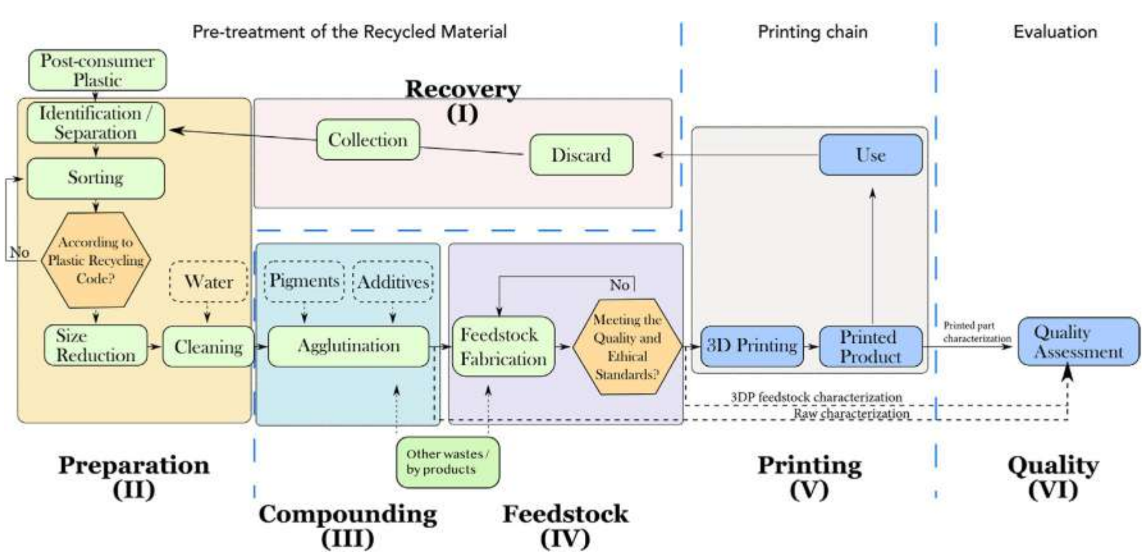

Fig. 4. Closed-loop recycling framework for distributed recycling via additive manufacturing (DRAM) process.

Table 1
Systematic review protocol for the literature.

Stage	Principle	Description
Search Strategy	Type of studies	Journal papers and conference proceedings.
	Keywords	● “3D Printing", "additive manufacturing”
		● Recycling
		● “Plastic", "Polymer","Thermoplastic”
	Search equation	(3D printing OR additive manufacturing) **AND** Recycl* **AND** ("Plastic" **OR** "Polymer" **OR** "Thermoplastic")
	Period of time	2009–June 2019
	Databases	Scopus, Springer, Web of Science
Study selection	Criteria	1) Articles related to the use of recycled thermoplastic for AM technology
		2) Studies should be focused on engineering, material or process design.
	Procedure	1) Title, abstract and keywords are screened
		2) Introduction section and conclusions were read
		3) Full article was reviewed
		4) Selection is made on the quality assessment
Data extraction	Closing the loop	● Source of the plastic waste
		● Parameter used as quality indicator before printing
		● Application intended for the recycled printed part
	Technical test	● Characterization test for raw, or 3D feed stock or recycled printed part
Quality assessment	QA 1	Is the study related to the phases I, II, III, IV, V or VI?
	QA 2	Is a recycling methodology presented in the experiment?
	QA 3	Does the study present implications of plastic recycling on AM technology?

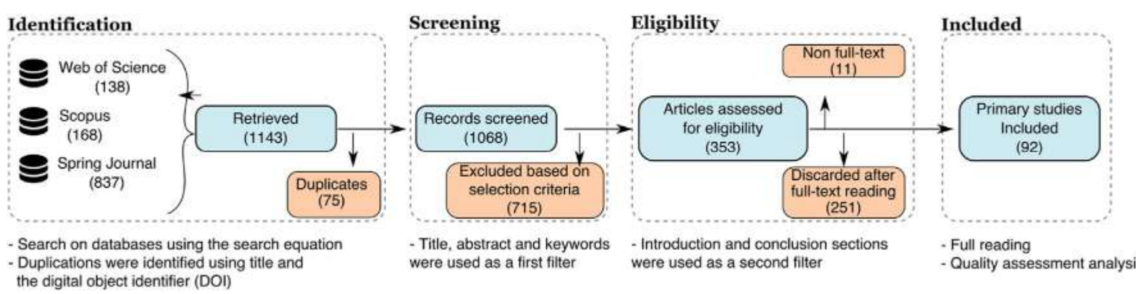

Fig. 5. Systematic literature review methodology. Adapted from the PRISMA principles (Moher et al., 2009; Siddaway et al., 2019).

with at least 2 documents considered in this review. Each study was positioned in at least one phase of the proposed framework, having as criteria the quality assessment from the review protocol. The data extraction was performed for the closing the loop purposes and the technical quality assessment presented in section 2.1. In addition, each study was mapped in terms of the sustainable dimension (technical, economic, environmental or social).

On the other hand, Fig. 7 summarizes the distribution of analyzed publications according to the recycling phase considered and their scope. It appears from the figure that most of the studies deal with technical aspects in the development and characterization of materials for DRAM (Compounding (III) phase). On the opposite side, the Recovery (I) and Preparation (II) phases are the least studied. Moreover, the technical aspect is the most studied in the literature. Nevertheless, social aspects have been only partially treated.

To better understand the advances, the results are presented in three main elements. First, section 4 presents the technical studies that are identified in the different stages considering the proposed framework (Fig. 4).

Then, section 5 proposes a discussion of challenges to overcome about DRAM on the circular economy purposes.

4.1. Recycling phase I: recovery

The focus of the recovery stage is on the collecting and logistics operations to collect the plastic wastes. One main point to highlight is that the discard stage was not sufficiently addressed in the literature. The use of a recycled material was given as an asset and not as an object of research discussion. On the other hand, one hypothesis at this stage is that distributed recycling can promote shorter and simpler supply chains where the reduction of the transportation impact is a main feature (Despeisse et al., 2017; Garmulewicz et al., 2018). Using life cycle assessment tools, it was evidenced the environmental gains of the use of distributed approach (Kreiger et al., 2013; Wittbrodt et al., 2013). Moreover, recent research on the design of a closed-loop approach (Zhao et al., 2018), including the definition of supply chain network for plastic recycling based on AM technologies was identified (Pavlo et al., 2018). Nevertheless, more research is needed to evaluate and measure the global impact of the supply chain to collect waste materials in terms of social and political dimensions. In this stage it is fundamental to create logistical indicators in order to clarify the actors and to define under which conditions a closed-loop model could be applicable at a local level.

4.2. Recycling phase II: preparation

The preparation phase deals with processes to adequate waste materials in order to be useable recycled feedstock including identification, sorting and size reduction processes. Concerning the identification, Hunt et al. (2015) proposed a recycling code framework taking as example the resin identification developed in China. One key element of this proposal is the code expansion ability as more complex 3-D printing materials are introduced, which enables more flexibility regarding the current identification of plastic codes (1–7). An open source script was developed in order to be included in the printed part for recycling purposes. The widespread

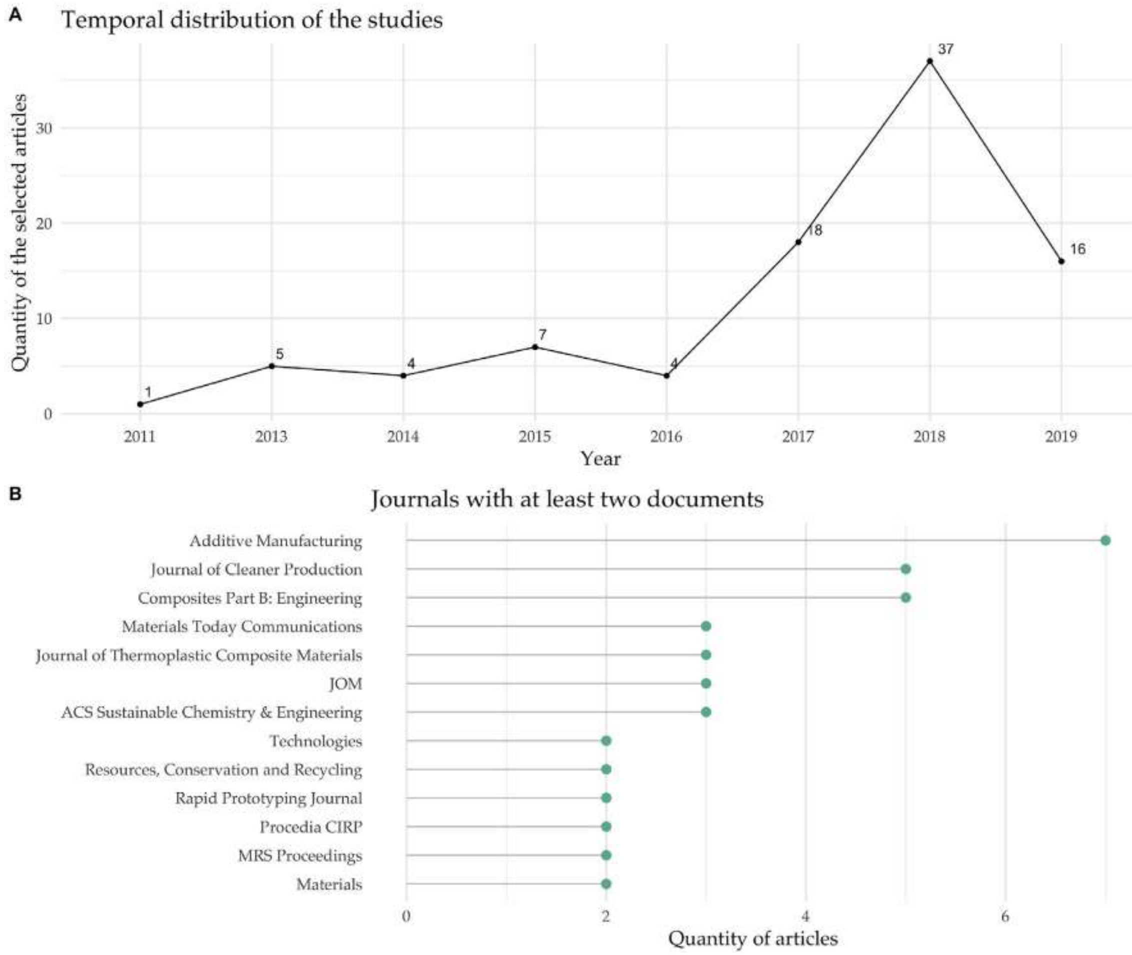

Fig. 6. Temporal distribution. Note: data only to June 2019.

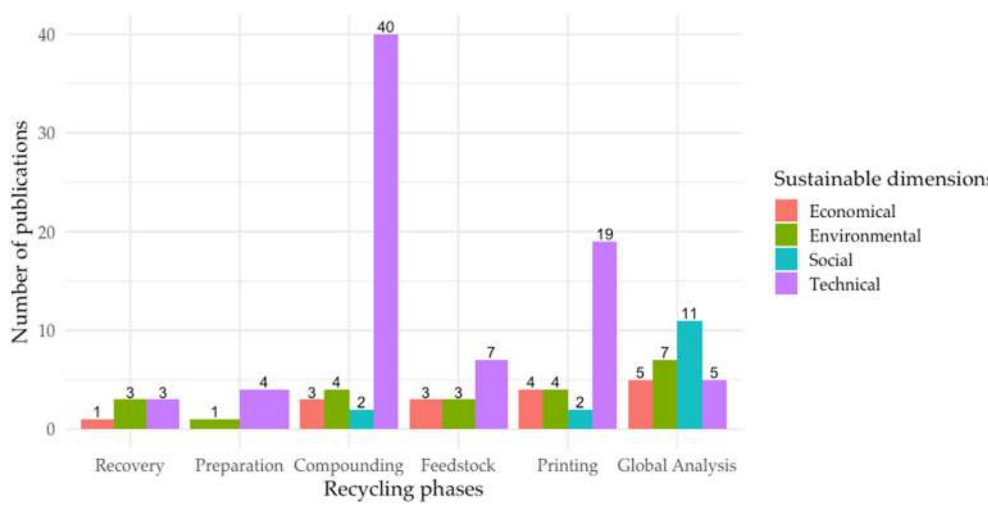

Fig. 7. Global results of the literature review.

adoption of plastic identification during the printing process could foster environmental consciousness about the recycling option. Further work is necessary to integrate such a concept into the wide array of open source slicing and CAD software.

Regarding the sorting process, it is found that this stage was the least considered in our set of studies because the studies reported the use of a material identified from a specific waste (i.e PLA from fablabs) or it is put as initial insight in the methodology without more details on how the material was sorted or cleaned. Concerning the size reduction, there have been different attempts to design and build prototypes for shredding recycled material (Lee et al., 2019; Reddy and Raju, 2018; Romero-Alva et al., 2018). It is reported from manual operations (e.g. hardware scissors - Granulometry: > 5 mm) (Chong et al., 2017), use of industrial rotor beater mill (Granulometry: 0.2–5 mm) (Jaksic, 2016) and cryogenic grinding process (Granulometry: 450–750 μmm) (Boparai et al., 2016; Singh et al., 2016). Regarding the cleaning process, the use of using mild soap and water to remove particles from plastic wastes containers was stated (Woern et al., 2018b; Zander et al., 2018). However, a definition of a 'cleaned material' was not found in the reviewed studies.

4.3. Recycling phase III: compounding

Compounding phase step is related to the development of mono- and composite-materials for DRAM purposes. Concerning mono recycled materials, different studies have been made to show the technical feasibility to recycle mono-plastics. They include, polyethylene terephthalate (PET) (Zander et al., 2018), high-density polyethylene (HDPE) (Baechler et al., 2013; Kreiger and Pearce, 2013), linear low density polyethylene (LLDPE) and low density polyethylene (LDPE) (Hart et al., 2018; Kumar et al., 2019), polypropylene (PP) (Pepi et al., 2018; Stoof and Pickering, 2018; Zander et al., 2019), polystyrene (PS), polylactic acid (PLA) (Anderson, 2017; Cruz et al., 2015; Cruz Sanchez et al., 2017), acrylonitrile butadiene styrene (ABS) (Cunico et al., 2019; Czyżewski et al., 2018; Lanzotti et al., 2019; Mohammed et al., 2019, 2018a; 2018b, 2017; R. Singh et al., 2019d), polycarbonate (PC) (Reich et al., 2019), thermoplastic elastomer (TPE) (Woern and Pearce, 2017) and biomass-derived poly(ethylene-2,5-furandicarboxylate) (PEF) (Kucherov et al., 2017).

One of the main conclusions of these studies is the positive technical feasibility to use recycled mono-materials for printing purposes through a variety of pathways (Dertinger et al., 2020). However, not all thermoplastics are in the same maturity level for DRAM purposes. For instance, recycled HDPE has been proved from a technical (Kumar et al., 2019; Singh et al., 2018a,b,c) and life cycle analysis perspective (Kreiger and Pearce, 2013). For PLA material, tensile (Cruz Sanchez et al., 2017) and flexural (Lanzotti et al., 2019) properties have been studied. Using recycled PET, Zander et al. (2018) argued that the printing process was challenging in part due to its high fusion temperature, crystallinity, water absorption to weak interfacial welding between layers. The presence of low compounds and contaminants in the recycled PET structure potentially leads to an accelerated degradation (Zander et al., 2019). On the other hand, recycled ABS, PLA, HDPE are well consolidated as materials for DRAM. Efforts need to be made in order to improve the printability of PP, and PET due to bed adhesion, deformation and weak interfacial welding between printed layers. The printability is a function of the cooling process and the diffusion of polymer chains between layers, and thus, failures in the printing process commonly occurs at these interfaces (Turner et al., 2014). Concerning the recycling for conventional thermosets for AM is limited. However, new development materials on reprocessable thermosets (3DPRTs) is a major research axis to explore (Cicala et al., 2018; Zhang et al., 2018).

On the other hand, there have been several literature reviews about the technical aspect of composite materials in the AM context (Brenken et al., 2018; Hofstätter et al., 2017; Mohan et al., 2017; S. Singh et al., 2017b). Special attention has been paid on the production of polymer/composite feed stock filament as it is economical, environmentally friendly and adaptable to flexible filament materials (S. Singh et al., 2017b). Details about mechanical properties of composite materials for printing using virgin materials are well documented elsewhere (Brenken et al., 2018; Mohan et al., 2017). However, in our case, the main goal is to present studies related to composite that uses recycled materials in their approach. It is noticed that the studies consider strategies to include recycled material in terms of composites plastic/plastic, plastic/metal, plastic/ceramics and plastic/fibers.

Blending virgin/recycled material at various ratios via extrusion process can be a cost-effective way to increase re-use of recycled materials. Advances in this regard were found using PP/PET/PS (Zander et al., 2019), ABS/PLA/HIP (R. Singh et al., 2019a), PP/Tires Wastes (Domingues et al., 2017). Additionally, R. Singh et al. (2019a) investigated a multi-material printing to superpose recycled layers using a multi-nozzle in order to evaluate structural applications. This approach might be useful for the creation of meta-materials contained using local deposition of specific layers (soft, hard and mix) in the printed object for custom functional prototypes. These approaches to print locally recycled materials within the printed part can enable experimental studies to determine optimal quantities of mixed material (virgin + recycled) in different locations of the printed part. This technical aspect can contribute to the establishment of quality standards for AM composite materials containing recycled plastic.

Metal composites using recycled polymer were explored using iron powder (Kumar et al., 2019; Xu et al., 2018), tungsten carbide (Kumar and Czekanski, 2018), iron/silicon/chromium/aluminum (Pan et al., 2018). For instance, Pan et al. (2018) evaluated the effects of adding Fe,Si,Cr,Al nano-crystalline powders into the recycled PP/HDPE for filament extrusion. Physical and mechanical analysis tests revealed that recycled PE/PP filaments with 1% Fe–Si–Cr or Fe–Si–Al resulted in improved thermal stability, yield strength and elastic modulus compared with the original recycled filaments, thanks to the enhancement of inter-facial adhesion between the nano-metal powders and the polymer reducing crack formation. Xu et al. (2018) developed a reusable metallic ink from biodegradable polymer and highly alloyed steel. The obtained results envision applications where the porosity and comparable electrical and mechanical performances that are required using a cost-effective alternative. The development of plastic/metal composite material would be for DRAM applications that use built-in functionalities such as electrical conductivity. The use of iron powder in the recycled polymer matrix could lead to non-destructive testing applications in civil engineering (Kumar et al., 2019).

Plastic/ceramic composites have been explored for rapid tooling applications (N. Singh et al., 2018a) using polymer waste as matrix material and SiC/Al2O3 from the filament development to the use on investment casting (Singh et al., 2016). Recycled nylon (Boparai et al., 2016; Singh et al., 2016), HDPE (A. K. Singh et al., 2018c; N. Singh et al., 2019e, 2018a), LDPE (N. Singh et al., 2018b), ABS (R. Singh et al., 2019c) and syntactic foams (A. K. Singh et al., 2018c) have been successfully tested. Rheological and thermal behaviour (Boparai et al., 2016) confirmed the suitability of plastic/ceramic filaments. The melt flow index (MFI) value has been highlighted as a quality indicator for the composite material, prioritizing obtaining a value equivalent to commercial filaments to avoid changes in the default printing process. The results of this recycling route are encouraging to further develop applications with much more added value in DRAM.

Finally, the creation of composite feedstock for AM using natural recycled fibers is a means to improve material properties, but also, to add value to waste organic materials. The inclusion of reinforcing fibres offers the potential to reduce shrinkage, better mechanical properties, add value to the recycled polymer and recycled fibers. Fibers such as harakeke, hemp and recycled gypsum (Stoof and Pickering, 2018), biochar (Idrees et al., 2018), banana (R. Singh et al., 2019b), wood residues (Horta et al., 2018; Pringle et al., 2017) and macadamia nutshells (Girdis et al., 2017) were converted into a viable composite filament filament for 3D printing applications. Nevertheless, a maximum fiber content needs to be considered in the process. Above from there, filaments and printing defects appear affecting the mechanical and geometrical stability (Stoof and Pickering, 2018). This recycling route for different types of agricultural wastes reinforced with the recycled polymers could improve sustainability options for both materials (R. Singh et al., 2019b).

Other types of fibers include the use of glass (Rahimizadeh et al., 2019; Veer et al., 2017), and recycling of continuous carbon fiber reinforced thermoplastic composites (CFRTPCs) (Tian et al., 2017). Recycling of printed CFRTPCs is an axis of development given the superior mechanical properties of these compounds to create lightweight structures. This approach represents a cleaner production model for future compounds. However, recycling efficiency is an opportunity to improve in order to meet the requirements of industrial production. In the same way, the work developed by (Rahimizadeh et al., 2019) proved the feasibility of using recycled glass fibers from wind turbine blades with comparable mechanical properties to virgin filament.

4.4. Recycling phase IV: feedstock

The main goal of this phase is to obtain an adequate recycled material in order to be used in the printing. The open source hardware approach (free, self-replicating, modular) of this design is noteworthy, as it reduces costs, facilitates manufacturing and assembly, while ensuring the reproducibility of the process. For instance, Woern et al. (2018b) provided the designs for a waste plastic extruder (recyclebot) capable of making commercial-quality 3-D printing filament. The filament fabrication conditions reported were 0.4 kg/h using 0.24 kWh/kg with a diameter precision ±4.6%. In this line, Zhong et al. (2017) evaluated the recyclebot extruder prototype in terms of the energy payback time using the embodied energy of the PLA and ABS materials. The use of the recycler to create a printing filament from post-consumer plastics has proven to be an effective way to save energy. Indeed, the coupling of solar energy and waste recycling is an important opportunity for rural and humanitarian applications as noted by (King et al., 2014; Mohammed et al., 2018a).

Similarly, Woern and Pearce (2018) presented an open-source 3-D printable pelletizer chopper system for providing compounding for filament making or feed stocks for direct particle printing purposes.

An interesting approach is the identification of specific plastic waste in order to validate secondary raw materials. For instance, using packaging waste (meals-ready-to-eat) from the military sector, Hart et al. (2018) recycled proved the chemical resistance, minimal permeability, and flexibility, and toughness for non-load bearing applications where barrier properties are required. Supply material is difficult to obtain in army operations because of its remote location, reducing the supply dependence will not only increase the operational readiness and self-sufficiency but will also improve the security of combatants (Pepi et al., 2018). Therefore, local recycling is a structural advantage in this type of context. Other specific recycling source were PET bottles (Idrees et al., 2018; Mosaddek et al., 2018), e-waste (Czyżewski et al., 2018; Gaikwad et al., 2018; Zhong and Pearce, 2018), tire rubber (Alkadi et al., 2019; Domingues et al., 2017). Indeed, Zhong and Pearce (2018) showed that e-waste plastic from computer labs could be directly recycled into products with AM for cost savings over 300X compared to equivalent commercial products.

An interesting approach is the use of leftover material in selective laser sintering (SLS) to be used in FFF (Kumar and Czekanski, 2018, 2017; Mägi et al., 2016, 2015). In SLS, powders that have not been sintered in the printing process become unusable (after a certain number of reuse cycles) and eventually become waste. Since high energy consumption is required for the production of powders, the generation of these wastes has an impact on the global sustainability of the process. The production of filaments from SLS waste to be used in the FFF technique was successfully demonstrated and mechanical properties and economic advantages are reported in (Kumar and Czekanski, 2018, 2017). If these two processes are connected, they could contribute to overall environmental sustainability by tightening the loop in the material life cycle. Other types of synergies among industrial processes can be possible identifying monomaterial specific waste niches to be reused in distributed recycling. However, it is necessary to define the requirements of the plastic waste. This concept is normally referred to as industrial ecology (Clift and Druckman, 2016). Significantly more work is needed to map the lessons of industrial ecology to the distributed manufacturing and recycling proposition described here.

4.5. Recycling phase V: printing

The fused filament fabrication is well established in the additive manufacturing context. Nonetheless, the technical development of fused granular fabrication (FGF) could be an important path to prove the recyclability of plastic wastes (Canessa et al., 2017; Reich et al., 2019; Woern et al., 2018a). FGF is able to print from pellet material eliminating the need to manufacture filament. These FGF systems have successfully recycled a number of virgin polymers as well as post consumer waste in a “green fablab” context (Byard et al., 2019). For instance, Woern et al. (2018a) tested the open source Gigabot X to evaluate virgin PLA and four recycled PLA, ABS, PET and PP particles. Experimental work was made to optimize the print speed and extrusion conditions in order to find optimal printing set-ups for each polymer. Printing time was reduced (6.5x to 13x) with respect to conventional printers depending on the material, with no significant reduction in the mechanical properties. Indeed, using plastic/plastic composite of recyclable polypropylene (PP) blended with tire wastes was proved by Domingues et al. (2017) using a robotized equipment. These examples open extraordinary new possibilities to enhance the DRAM. This approach takes away the filament fabrication, which is a time-, cost-consuming process. An important research path is to evaluate the printability for a wide range of recycled polymers with minimal post-processing via FGF. Exploring new recycled polymers from specific niches could lead to new recycling loops.

Other types of direct extrusion include a piston-drive head (Volpato et al., 2015) and screw-based (Canessa et al., 2017) extrusion approaches. However, more research is needed to evaluate degradation profiles, the stability of the cross-sectional area affecting the dimensional and surface finish, the influence of granulometry in the printing process. Determination of optimal configuration parameters for specific materials and a real estimation of their performance in terms of relative flow rate, printing speed, and global energy consumption are required (Canessa et al., 2017). The direct extrusion systems could facilitate the use of recycled materials in DRAM, and the research needed to make these systems widespread has just begun.

4.6. Recycling phase VI: quality

In the transition from waste-to-product, it distinguished the material quality evaluation in three distinct moments: (1) raw material, (2) 3DP feed stock, and (3) printed part. Fig. 8 shows the percentage of the registered studies that declare a technical characterization of plastic waste based on the type of test (y-axis) and the moment that is performed (x-axis).

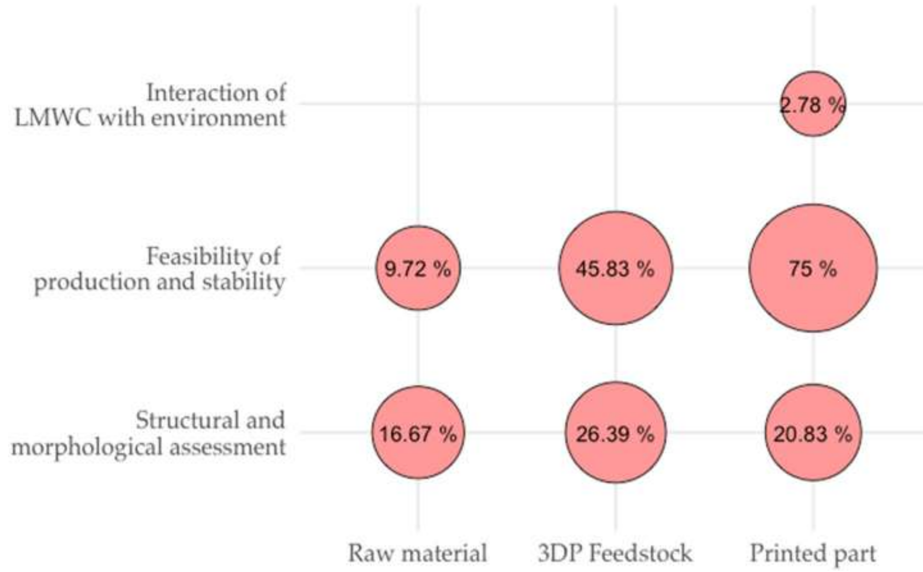

Fig. 8. Percentage of technical characterization by type and moment, reported in the retrieved studies.

Among the technical studies, 75% reported a characterization test to the recycled final part, about 46% for the 3DP feed stock filament, yet only 9% tested the raw recycle waste. The technical assessment of raw material properties allows users to estimate the quality of the initial recycled material. Key properties such as flowability and thermal characteristics. For instance, Kumar and Czekanski (2017) evaluated the melt flow index (MFI) of three different proportions of recycled HDPE reinforced with SiC/Al_2O_3 with the aim to have comparable rheological behavior as a commercial filament.

Concerning the 3DP feed stock, it refers to the evaluation of the filament properties in the case of fused filament fabrication. For FFF technique, diameter and linear density of the filament are considered as the most important quality parameters. Mechanical properties such as tensile modulus and elastic modulus of the filament are evaluated as they are important for estimating the degradation caused by the extrusion process. In the case of composite filaments, morphological analyses are performed to validate the distribution of the matrix and filler within the filament structure (Pan et al., 2018). For FGF, size particle distribution is generally explored as a quality input.

Finally, the last case is the evaluation of the properties of the printed object. Printability is one of the first tests performed on waste material, which refers to the capacity of the material to be extruded preserving the dimensional geometry after extrusion and having a minimum of strength. Mechanical properties were the most used test for the validation of the recycled material for DRAM counting tensile (Cruz Sanchez et al., 2017), flexural (Lanzotti et al., 2019), fatigue (Letcher and Waytashek, 2014). Different printing issues can be found such as warping, deformation or buckling. Also, specific elements such as barrier properties of the printed model (Hart et al., 2018).

Moreover, the creation and validation of methodologies that improve DRAM could help support the ambition of zero-waste. Concerning the FFF technique, different methodologies have been found in the literature (Chong et al., 2015; Cruz Sanchez et al., 2017; Cunico et al., 2019; Feeley et al., 2014; Gaikwad et al., 2018; Singh et al., 2016; Tian et al., 2017). In terms of technical recyclability, Cruz Sanchez et al. (2017) reported a general methodology to evaluate the degradation curves of thermoplastics using PLA as a case study. For composite materials, Singh et al. (2016) presented a methodology to reuse nylon-6 waste for the casting process. From a modeling perspective, Clemon and Zohdi (2018) proposed a mathematical framework that identifies the distribution of stress contributions from the micro- and macro-scale based on mixed recycled content for the printing process. The development of methodological approaches allows researchers to reduce the development time and cost of mixed material optimizing experimental sets. In summary, the Table 2 summarizes the advances in the plastic recycling in the context of additive manufacturing.

5. Discussion of the results

The purpose of this research is to make a systematic review of the literature on thermoplastic recycling within the context of additive manufacturing. Figs. 6 and 7 summarize the obtained results, from these it appears clearly that:

- There is a growing interest for DRAM initiatives, as 92 papers were registered in the last decade coming from a diverse variety of research teams (Fig. 6).
- Although significant advances have been achieved on the Compounding and Printing stages, in order to develop DRAM initiatives, more efforts should be devoted by the research community to the Recovery and Preparation stages.
- Technical aspects are the most addressed, as 71 papers out of 92 treat the technical dimension. At the same time, Environmental (22), Economical (16) and social (13), are sustainability dimensions that are still to be further developed.
- In order to achieve this, there is a need for a holistic view and multiple competencies and points of view are needed. 28 papers were registered having a global vision of the DRAM initiative.

In that follows, the current advances in the field for each stage within the recycling process from Fig. 4 and the deep analysis of the papers reported in appendix A. To make easy this analysis will be divided into three main aspects: 1) preparation of the recycled

Table 2
Advances in Distributed Recycling for additive manufacturing.

Phases	Subcategory	Research	Focus	Reference
I	Collection	Supply chain	Closed loop, mathematical optimization	Pavlo et al., (2018)
II	Identification	Recycling codes	Recycling codes, distributed manufacturing	Hunt et al., (2015)
	Size reduction	Shredding equipment, pelletizer	Size distribution	(Reddy and Raju, 2018; Romero-Alva et al., 2018; Woern and Pearce, 2018)
III	Mono-Plastics	ABS	Tensile properties	(Czyżewski et al., 2018; Gaikwad et al., 2018)
		PLA	Tensile properties	(Anderson, 2017; Cruz et al., 2015; Cruz Sanchez et al., 2017)
		HDPE	Tensile, thermal, filament extrusion	(Baechler et al., 2013; Chong et al., 2017; Kreiger et al., 2013)
		PET	Tensile, DMA, DSC	Zander et al., (2018)
		TPE	Thermoplastic elastomer, thermoplastic polyurethane	Woern and Pearce, (2017)
		PEF	Green polymer	Kucherov et al., (2017)
		Epoxy	3DPRT, epoxy, tesind infusion	(Cicala et al., 2018; Zhang et al., 2018)
	Composites	Plastic/Plastic	Multi Material printing	(Alkadi et al., 2019; Dunnigan et al., 2018; He et al., 2020; Hu et al., 2017; R. Singh et al., 2019a; Zander et al., 2019)
		Plastic/Metals	LDPE, HDPE, PA2200, Fe powder, tungsten carbide, metallic ink	(Kumar and Czekanski, 2018; Kumar et al., 2019; Pan et al., 2018; Xu et al., 2018)
		Plastic/ Ceramics	HDPE, nylon, bakelite, SiC/Al2O3, syntactic foams, aluminum matrix composite, thermal properties	(Boparai et al., 2016; A. K. Singh et al., 2018c; N. Singh et al., 2019e, 2018a; 2018b; R. Singh et al., 2019c; Singh et al., 2016)
		Plastic/Fibers	Carbon fiber reinforced thermoplastic composites (CFRTPCs), fiberglass, Biochar, Liquid Crystal Polymer (LCP), banana fiber, natural fibres, Macadamia nutshell	(Gantenbein et al., 2018; Girdis et al., 2017; Idrees et al., 2018; Rahimizadeh et al., 2019; R. Singh et al., 2019b; Stoof and Pickering, 2018; Tian et al., 2017; Veer et al., 2017)
IV	Extrusion	Open hardware	recyclebot, energy payback time, pelletizer	(Baechler et al., 2013; Woern and Pearce, 2018; Woern et al., 2018b; Zhong et al., 2017)
	Secondary raw materials	Powder bed fusion to FFF	SLS, FDM, polyamide composite	(Kumar and Czekanski, 2018, 2017; Mägi et al., 2016, 2015)
		Niche recycling	packaging, fiber recovery, wind turbine blades, mussel shell, military meal-ready-to-eat	(Rahimizadeh et al., 2019; Sauerwein and Doubrovski, 2018; Zander et al., 2018; Czyżewski et al., 2018; Gaikwad et al., 2018; Hart et al., 2018)
V	Fused granular fabrication (FGF)	Material properties	gigabot X, moineau pump, PC, ABS, PLA, PET, PP	(Canessa et al., 2017; Reich et al., 2019; Whyman et al., 2018; Woern et al., 2018a)
		Large scale	HDPE, wood fibers, composites, tires wastes, economical life cycle	(Byard et al., 2019; Domingues et al., 2017; Horta et al., 2018; Keating and Oxman, 2013; Volpato et al., 2015)
	Printed part	Quality improvement	mechanical properties, surface finishing, melt flow index	(Cunico et al., 2019; Lanzotti et al., 2019; Sa'ude et al., 2015)
		Modelling	phase averages, integrity, composite strength	Clemon and Zohdi, (2018)
	Driven applications	Case studies	energy storage devices, dry cells, Humanitarian aid, eco-printing, solar, Space, In-space manufacturing (ISM), Drones, Educational, wood furniture waste-based	(Fateri et al., 2018; Jaksic, 2016; Mohammed et al., 2018a, 2018b; Mosaddek et al., 2018; Pringle et al., 2017; R. Singh et al., 2019d; Zhong and Pearce, 2018)
VI	Environmental	Life cycles assessment tools	LCA, distributed recycling &	(Gaikwad et al., 2018; Kreiger et al., 2013, 2014; Kreiger and Pearce, 2013; Zhao et al., 2018)
		Recycling methodologies	cradle to cradle, thermo-mechanical recycling	(Chong et al., 2015; Cruz Sanchez et al., 2017)
	Economical	Life-cycle economic	costs, ROI	(Byard et al., 2019; Petersen et al., 2017; Wittbrodt et al., 2013)
		Entrepreneurial	Business Model, circular economy, industry 4.0, service design	(Nascimento et al., 2019; Petruzzi et al., 2017; Wittbrodt et al., 2013)
	Social	Barriers and opportunities	disruptive technology, technological innovation	(Garmulewicz et al., 2018; Peeters et al., 2019)
		Material	intellectual property, open source materials	(Pearce, 2015; Ramakrishna et al., 2019)
		Faire trade	ethical product, fair trade standards &	Feeley et al., (2014)
		Recycling demonstrators	Solar Energy, green manufacturing, educational, mini-factory	(Heyer et al., 2014; King et al., 2014; Lee et al., 2019; Mohammed, Wilson, Gomez-Kervin et al., 2018; Muschard and Seliger, 2015; Radharamanan, 2011)

material at local level, (2) the printing process chain and use, and finally (3) the opportunities of open source to foster distributed recycling in the circular economy context.

5.1. Pre-treatment of the recycled material at local level

The distributed recycling via additive manufacturing activity could emerge mainly as local user-driven initiatives (Feeley et al., 2014) and the recycling network is not necessarily as a formal structured industrial supply chain sector (Santander et al., 2020). Therefore, the recovery stage and the definition of pre-treatment conditions (discarting, identification, separation, sorting, cleaning, size reduction and drying) remains an important point to improve the readiness and effectiveness of the technical conditions required at a local level. The adequation process is more efficient when processed in small volumes from sectors which produce homogeneous waste streams (Karlsson, 2004), reducing the costs associated with sorting and cleaning (Hopewell et al., 2009) given the complexities when the waste is mixed with other materials (Signoret et al., 2019). Nascimento et al. (2019) stated that the technologies of the industry 4.0 can help to identify and collect waste in the frame of a circular smart production system model. Indeed, the role materials informatics can play an important role in order to achieve high-speed and robust acquisition, management, multi-factor analyses, and dissemination of diverse recycled materials data (Ramakrishna et al., 2019), and to assist in the development and protection from 'intellectual property tragedy' of the public domain materials for low-cost open source 3D printers (Pearce, 2015). In the reviewed literature, several studies choose a particular waste source or type of plastic waste in the recyclability analysis. The remaining question is how to evaluate a particular waste source or niche, defining qualitative indicators (Horta Arduin et al., 2020) that allows practitioners to choose materials that can be printable. A systematic analysis to qualify possible mono-stream waste sources is unclear from the evidence of the reviewed studies. For example, in the case of recycling of waste electrical and electronic equipment, the "Internet + WEEE collection" platforms are strategies to collect that are receiving attention from business ecosystems (Jian et al., 2019; Sun et al., 2020). Also, data-driven frameworks (Jiang et al., 2020) with internet of things and data mining technologies could be explorative approaches to implement for distributed recycling. There are research opportunities to develop optical sensors at both industrial and small-scales to improve the sorting of wastes (Signoret et al., 2019). The development of ex-ante methodologies and tools of analysis to clarify the potential of the landfill reduction is a research path to further improve the distributed recycling process.

The other critical point concerns the sorting and cleaning process to promote distributed recycling. From the selected literature, it is not clear how the cleaning process should be made at local level and under which conditions is technical and economically feasible. The appropriate decontamination is important because of the toxic pollutants present in the plastic wastes (Picuno et al., 2020; Verma et al., 2016). The decontamination step needs to be framed in terms of occupational safety, health risks and testing protocols that could reduce harmful fumes in the feedstock fabrication (filament or pellets) testing procedures is required in distributed recycling (Feeley et al., 2014). Also, the development of small sorting technologies (Rani et al., 2019) are needed to be integrated in the recycling chain for DRAM. If the recycling process is developed as community-based initiatives (Diehl et al., 2018; Mohammed et al., 2018a), the technological development should be focused on the characterisation of separated and commingled plastic fractions using quick, reliable and relatively cheap methods (Karlsson, 2004).

On the other hand, the use of life cycle assessment tools demonstrated the environmental advantage of distributed recycling network to process post-consumer goods into 3D printing feedstock because of lower embodied energy than both virgin and conventionally recycled materials (Baechler et al., 2013; Kreiger et al., 2013, 2014; Kreiger and Pearce, 2013; Pavlo et al., 2018). It was argued that the trend reversal from large-scale and centralized approaches towards local manufacturing and recycling was economically advantageous (Gwamuri et al., 2014). Nevertheless, more work is needed in the definition of the local scale (e.g. house, building, neighborhood), the structural facilities required (Pavlo et al., 2018), and the stakeholders to involve clarifying the conditions to implement recycling networks. For instance, innovation spaces such as fablabs were identified as possible actors to participate as recycling hubs for a community (Byard et al., 2019; Peeters et al., 2019). However, due to the economical and quality issues in the preparation phase, it remains uncertain the economical advantages (Peeters et al., 2019). The modeling of closed-loop approaches might also contribute to identify the required infrastructural and organizacionales elements to viabilize a sustainable recycling operation (Santander et al., 2020).

5.2. *Printing process chain and use of the recycled parts*

The technical validation of the use of recycled material in the printing process chain has been the main research focus from the reviewed papers. The thermo-mechanical simulation to create recycled filament (virgin or composite) is until now the common place that studies have characterized the recyclability process. Both mono- and composite-materials prove the advances in this area. A technical path to complete the recycling evaluation is to detail at molecular level the degradative mechanisms through the thermo-oxidation recycling process (Tröger et al., 2008). Modelling the oxidative degradation under different environmental conditions enables determinate polymer thermal aging, the sensitivity to the attacking environment and consequently the lifetime of the recycled printed object (Karlsson, 2004; Vilaplana and Karlsson, 2008).

However, the question that remains unclear is about the willingness by users to use recycled 3D objects and eventually to become 'prosumers' in the recycling process (Kreiger et al., 2014). Educational courses on distributed recycling are perceived as a means to encourage students to think about the access to the digital manufacturing capabilities and their sustainability-related issues (Jaksic, 2016; Schelly and Pearce, 2019). Moreover, the examples of consumer objets as furniture (Pringle et al., 2017), drones (Mosaddek et al., 2018), or local manufacturing and recycling demonstrators (Heyer et al., 2014; Muschard and Seliger, 2015) could improve the lack of awareness of the value of recycled materials (Garmulewicz et al., 2018). There are economic advantages of using recycled printed products. For instance, Petersen et al. (2017) proved that the cost to fabricate a Lego block could be reduced from 6 cents/block to about 0.5 cents per block. In the toy market, the reduction for final users can range between 75% and 90% under the condition that open source design files remain available. For larger products, the use of FGF proved large high-value sporting goods products (e.g. snowshoes) only in the extreme case of producing only 1 per week was not economic. The ROI for all other capacity factors ranged from 10 to 240% without including labor (Byard et al., 2019).

The drivers for adoption of recycled printed products relies on the domain of technology and cost of usage, including the decrease in the cost of open source 3D printers and its feedstock along with the increase in the number and quality of free designs (Rayna and Striukova, 2016). Nevertheless, beyond the pure technical aspects of the 3D printing domain, the deepest barrier for the use of recycled products relies on societal consumption (linear economy) and the high quality demand from consumers (Peeters et al., 2019). From a systemic perspective, the plastic waste issue is beyond the consumer side and the responsibility needs to include the extraction and production stakeholders (Conlon, 2020). Thus, one key element to redefine the definition of waste in a global sense (Ewijk and Stegemann, 2020). The legal framework is a missing aspect that was not found in the reviewed literature. Therefore research on the creation of minimal standards that need to be met to validate a recycled product.

5.3. *Open source as a driver to foster distributed recycling for circular economy purposes*

Open source is one factor that has contributed to foster the adoption of additive manufacturing for a larger public than industrial and research laboratories (Beltagui et al., 2019, 2020; Raasch et al., 2009). In that sense, it is suggested that the open source could be a driver to foster also for the recycling process, reducing the costs to create technology for the pre-treatment stage, which at the end will be a driver for the circular economy. The development of open hardware scientific equipment is getting attention thanks to the high profit/cost ratio guaranteeing a technical performance equal or superior to traditionally manufactured equipment (Pearce, 2017b). The integration of open source hardware development within traditional education systems opens up possibilities in both pedagogical and research aspects (Irwin et al., 2014). The development of digital manufacturing capabilities, electronics and free software, creates a whole ecosystem that allows designers to move from conceptual prototypes to functional prototypes at a reduced cost (Pearce, 2014).

There have been several studies in the scientific literature about the definition (Korhonen et al., 2018a, 2018b), key elements (Ghisellini et al., 2016) and the scope (Geissdoerfer et al., 2017) of the circular economy concept in the scientific and business literature. Cramer (2018) identified that four conditions need to be met in order to use high grade recycling in the circular economy framework: 1) an adequate collection system and logistics; 2) guaranteed volumes of supply; 3) market demand for recycled materials; and 4) quality guarantee of recycled materials. Based on the definition of the circular economy concept proposed by (Kirchherr et al., 2017), the potential research opportunities for DRAM driving the circular economy at the:

5.3.1. Micro level

- Development of low-cost, free and open source, digitally manufactured (ideally from recycled waste) tools to enable distributed DRAM including: scientific tools to enable grading and typing recycled waste plastic, tools for separating materials, shredding them, and improvements on the existing tools to either produce waste plastic filament or directly 3D print waste plastic.
- Development of novel waste based composites that involve material characterization, as well as life cycle economic and environmental assessments of DRAM.
- Develop applications of these new DRAM waste material composites and markets for these applications.

5.3.2. Meso level

- Finalize complete closed loop DRAM case studies based on material and location to demonstrate technical, ecological and economic feasibility.
- Develop business models that can fabricate and sell these DRAM tools, their kits or components as well as services around calibrating, using and maintaining them.
- Develop paths to enable existing recycling organizations and businesses to convert to these new DRAM-focused business models.

5.3.3. Macro level

- Develop policies to provide incentives for the open source development (Heikkinen et al., 2020) for these paths for DRAM.
- Development of educational materials, curricula, public service announcements, and school programs to implement DRAM in public and private schools, community centers, maker/hackerspaces and fablabs, and religious communities.
- Develop means to disrupt fossil-fuel based plastic markets by offsetting materials with DRAM based products.

6. Conclusions and perspectives

In this article, a systematic literature review was performed in order to map the advances in the plastic recycling for additive manufacturing. A framework using 6 main stages (recovery, preparation, compounding, feedstock, printing, quality) was proposed in order to identify the global value chain of the distributed recycling via additive manufacturing approach.

Based on the results, it is concluded that the recovery and preparation stages are less studied. Research efforts need to be taken in the pre-treatement of the recycled material, including efficient models to collect waste material, technology and methodologies to develop quality indicators of the waste material. Then, based on these indicators, strategies of local cleaning and sorting process could be potential opportunities to promote. Thus, a systematic definition of the process to perform for cleaning, sorting and size reduction including quality indicators for each of them is a major research path. In addition, it is important to identify sectors which produce homogeneous waste streams and that are feasible to collect are important with the purpose to connect particular niche waste with potential applications with add value thanks to the 3D printing advantages.

On the other hand, it was observed that a big amount of work has already been done in the scientific community in order to validate the technical feasibility at compounding, feedstock and printing stages for numerous mono and composites- materials based on recycled assets. This is explained by the fact that the structural and feasibility of production assessment levels are well documented in the literature. Nevertheless, to maximise the potential of distributing recycling, attention should be focused on the willingness to use recycled 3D objects. Several driven applications of waste material were found including furniture, toys. The validation of DRAM needs to continue to show the usefulness of recycled printed parts. However, the research on the creation of minimal standards and legal framework are major elements to validate.

Finally, we have proposed different future research paths at the micro, meso and macro level to better understand the connections between circular economy and distributing recycling to reach the full potential. The establishment of such links can aid in the development of technical, social and economical aspects fostering waste management policies to improve the closed and open loop recycling. Moreover, it is relevant to the development of each stage proposed in this review in order to scale the acceptability of DRAM to reach the full technical potential as a masterpiece of the circular economy. Research focused on the recyclability of conventional thermoset plastics is a future perspective in order to increase the scope of the DRAM approach for CE.

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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Appendix A

Table A.1
Primary studies considered in the literature review

Author	Year	Category	Recycled.Material	Closing the loop			Raw			Feedstock			Printed part			Sust. dimensions			
				Source	Feedstock quality	Application	SM	FP	LMWC	SM	FP	LMWC	SM	FP	LMWC	Tech	Eco	Soc	Env
Recovery																			
Pavlo et al. (2018)	2018	I																	X
Hart et al. (2018)	2018	I	MRE meal bags	Military (Meal Ready to Eat)	Diameter	Military	X			X			X	X	X	X	X		X
Czyżewski et al. (2018)	2018	I, III	ABS	E-waste				X			X			X		X			
Gaikwad et al. (2018)	2018	I, III, VI	E-Waste,ABS	E-waste			X				X		X	X		X			X
Preparation																			
Hunt et al. (2015)	2015	II														X			X
Woern and Pearce (2018)	2018	II			Size Distribution											X			
Reddy and Raju (2018)	2018	II														X			
Romero-Alva et al., (2018)	2018	II														X			
Compounding																			
Cruz et al. (2015)	2015	III	PLA				X	X		X	X			X		X			
Singh et al. (2016)	2016	III	Nylon-6			Investment casting					X			X		X			
Boparai et al. (2016)	2016	III	Nylon6							X	X					X			
Mohammed et al. (2017)	2017	III	ABS,HDPE		Diameter									X		X			
Woern and Pearce (2017)	2017	III				Printability (3D models)											X	X	
Anderson (2017)	2017	III	PLA											X		X			
Chong et al. (2017)	2017	III	HDPE		Diameter, Extrusion rate					X	X					X			
Cruz Sanchez et al. (2017)	2017	III	PLA					X			X			X		X			
Hu et al. (2017)	2017	III	PLBSI,PLA							X	X			X	X	X			X
Girdis et al. (2017)	2017	III	Macadamia nutshell			Wood-plastic composites replacement					X			X		X			
Veer et al. (2017)	2017	III	PP											X		X			
Kucherov et al. (2017)	2017	III												X		X			
A. K. Singh et al. (2018)c	2018	III	HDPE								X					X			
Dunnigan et al. (2018)	2018	III	PolyliteÂ®,Nylon										X	X		X			
Xu et al. (2018)	2018	III	Chitosan											X		X			
Cicala et al. (2018)	2018	III	SuperSap epoxy monomers CLX(S)								X			X		X			
N. Singh et al. (2018b)	2018	III	LDPE			Investment casting, Rapid tooling					X		X	X		X			
Zander et al. (2018)	2018	III	PET	Bottles and Packaging		Military	X	X		X	X		X	X		X		X	
Tian et al. (2017)	2018	III	PLA,carbon fiber								X		X	X		X	X		X
N. Singh et al. (2018a)	2018	III	HDPE			Printability (Pins)				X	X			X		X			
Zhang et al. (2018)	2018	III	2-hydroxy-3-phenoxypropyl acrylate				X				X			X		X			
R. Singh et al. (2019b)	2018	III	ABS,PA6				X			X	X			X		X			
Stoof and Pickering (2018)	2018	III	PP								X			X		X			

(*continued on next page*)

Table A.1 (*continued*)

Author	Year	Category	Recycled.Material	Closing the loop			Raw			Feedstock			Printed part			Sust. dimensions			
				Source	Feedstock quality	Application	SM	FP	LMWC	SM	FP	LMWC	SM	FP	LMWC	Tech	Eco	Soc	Env
Pan et al. (2018)	2018	III	HDPE,PP		Diameter			X		X	X					X			
Gantenbein et al. (2018)	2018	III	Liquid-Crystal-Polymer							X	X			X		X			
Idrees et al. (2018)	2018	III	PET	PET bottles			X			X			X	X		X			
Pepi et al. (2018)	2018	III	PET,HDPE,PP	Milk juges, Soda bottles, Yogourt containers, Cups		Military							X	X		X			
Alkadi et al. (2019)	2019	III	Ground Tire Rubber	Tire Rubber										X		X			
Mohammed et al. (2019)	2019	III	ABS		Diameter, Extrusion flow rate								X	X		X			
R. Singh et al. (2019c)	2019	III	ABS,Bakelite										X	X		X			
He et al. (2020)	2019	III	ABS,PBT Resin				X				X					X			
R. Singh et al. (2019a)	2019	III	ABS,PLA,HIPS			Load-bearing structures	X				X			X		X			
Kumar et al. (2019)	2019	III	HDPE, LDPE			Nondestructive testing (civil engineerig)					X			X		X			
Zander et al. (2019)	2019	III	PET,PS,PP	Soda bottles, Yogurt containers						X	X			X		X			
Rahimizadeh et al. (2019)	2019	III	PLA,Fiber glass	Wind turbines	Size distribution					X	X			X		X			
N. Singh et al., (2019d	2019	III	HDPE			Rapid tooling				X	X			X		X			
Kumar and Czekanski (2018)	2018	III, IV	Polyamide 12 (PA2200)							X	X					X	X		
Zhao et al. (2018)	2018	III, VI	PLA										X	X		X			X
Feed stock																			
Baechler et al. (2013)	2013	IV	HDPE		Diameter, Lineal density						X					X			X
Mägi et al. (2015)	2015	IV	PA 12								X			X		X			
Mägi et al. (2016)	2016	IV	PA 12			Hand prostheses		X						X		X			
Kumar and Czekanski (2017)	2017	IV	PA 12	SLS wastes						X	X			X		X	X		X
Zhong et al. (2017)	2017	IV															X		X
Petruzzi et al. (2017)	2017	IV				Hospital of Objects												X	
Sauerwein and Doubrovski (2018)	2018	IV	Mussel shells											X		X			
Woern et al. (2018b)	2018	IV	PLA		Diameter											X			
Printing																			
Keating and Oxman (2013)	2013	V	ABS,HDPE, Urethane											X		X			
Volpato et al. (2015)	2015	V	PP							X	X					X			
Jaksic (2016)	2016	V				Educational											X	X	
Domingues et al. (2017)	2017	V	PP,Tires Wastes	Tires Wastes									X	X		X			
Sa'ude et al. (2015)	2017	V	ABS		MFI						X					X			X
Canessa et al. (2017)	2017	V	PLA		Diameter									X		X			
Pringle et al. (2017)	2017	V	PLA,Wood		Diameter									X		X			
Whyman et al. (2018)	2018	V					X							X		X			
	2018	V	PET	PET bottles		Unmanned Aerial Vehicules (Drones)					X			X		X	X		

Mosaddek et al. (2018)															
Mohammed et al. (2018a)	2018	V	ABS,HDPE	e-waste, Jerry can	Diameter, Electrical consumption	Humanitarian aid					X	X		X	
Fateri et al. (2018)	2018	V	PVA			Space	X	X	X	X	X	X			
Woern et al. (2018a)	2018	V	ABS,PLA,PET,PP		Size distribution						X	X			
Horta et al. (2018)	2018	V	HDPE								X	X			
Clemon and Zohdi (2018)	2018	V										X			X
Mohammed et al. (2018b)	2018	V	ABS		Size distribution, Energy consumption	Humanitarian				X		X			
Zhong and Pearce (2018)	2018	V	ABS		Diameter							X	X		X
Lanzotti et al. (2019)	2019	V	ABS								X	X			
Cunico et al. (2019)	2019	V	ABS			Chemical plastic welding					X	X			X
Reich et al. (2019)	2019	V	PC		Size distribution	High-strength Applications, High-temperature Applications, Rapid molding					X	X	X		
R. Singh et al. (2019)a	2019	V	ABS			Electrical (Energy storage devices), Voltage Measurement	X			X	X	X			
Conceptual															
Radharamanan (2011)	2011	VII									X	X			
Kreiger et al. (2013)	2013	VII	HDPE												X
Kreiger and Pearce (2013)	2013	VII												X	X
Wittbrodt et al. (2013)	2013	VII	PLA												X
Heyer et al. (2014)	2014	VII												X	
Feeley et al. (2014)	2014	VII												X	
Kreiger et al. (2014)	2014	VII	HDPE										X		X
King et al. (2014)	2014	VII												X	
Pearce (2015)	2015	VII												X	
Chong et al. (2015)	2015	VII										X			X
Muschard and Seliger (2015)	2015	VII												X	
Petersen et al. (2017)	2017	VII				Toy market							X	X	
Ramakrishna et al. (2019)	2017	VII									X			X	
Lee et al. (2019)	2018	VII	ABS,PLA						X		X	X			
Garmulewicz et al. (2018)	2018	VII											X	X	
Peeters et al. (2019)	2019	VII												X	
Nascimento et al. (2019)	2019	VII											X	X	
Byard et al. (2019)	2019	VII	ABS,PP		Size distribution								X		

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