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Review

3D Printing as a Disruptive Technology for the Circular Economy of Plastic Components of End-of-Life Vehicles: A Systematic Review

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Abstract: The automotive industry is frequently associated with high polluting manufacturing systems, which raise concern owing to the current environmental frame. For this reason, new alternative manufacturing technologies with lower environmental impact have been proposed and tested, such as additive manufacturing (AM). Since AM technologies produce almost no waste, they can represent a huge opportunity for the automotive industry to become greener. In this sense, the object of the present review is to explore the challenges and strategies of 3D printing, recycling, and circular economy in the automotive industry. Therefore, to achieve the aim of the study, a systematic review methodology was used in five stages: (1) defining the targets; (2) extraction of papers from Scopus; (3) text mining and corpora text analysis of relevant documents from the platform; (4) identification of the dominant categories of the research topics; and (5) discussion and control of obtained results and provision of recommendations for future studies. The analysis of 14 relevant articles revealed that 3D printing technology represents an opportunity to empower small-scale producers of polymers, recycle ELV materials, and decentralize the supply chains of plastic articles. The possibility to include plastic parts produced by AM technology has been pointed out as an innovative option for car manufacturers. Unfortunately, till the present day, poor information was found in this regard. Findings highlighted the need for strategies to turn polymeric automotive components into more eco-friendly and safer materials, improve the supply chain of polymers, perform sustainability assessments, and reformulate waste policies for ELVs.

Keywords: circular economy; 3D printing; ELV; recycling; vehicles

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1. Introduction

In the actual scenario of scarcity and increasing prices of raw materials, the automotive industry has been one of the most affected sectors after the COVID-19 pandemic and the beginning of military interventions in East Europe [1].

To overcome the supply constraints of materials, organizations and stakeholders of the automotive industry must be more aware of the opportunities of implementing a circular economy (CE) of plastic components, integrating emergent technologies from Industry 4.0 [2,3]. In this regard, 3D printing [4,5], blockchain [6–8], the Internet of Things (IoT) [9], smart contracts [7], and Big data [10], among others, surge as promising technologies for CE.

Three-dimensional printing could be applied to extend the life cycle of different components of cars and integrate recycled materials to create customized pieces for vehicles [11], closing the loops in the production chains. In the context of the circular economy, 3D printing offers an option to reprocess recycled materials in a very clean and effective way [12].

For the stated reasons, this review, which follows the PRISMA guidelines, aims at giving an overview of the current tendencies of circular economy applied to the automotive industry and how 3D printing could improve the reprocessing of polymers for cars through a systematic review of the literature.

1.1. Circular Economy in the Automotive Industry

In the late years, the term circular economy has been extensively used in different contexts and with distinct definitions which vary according to the base concept of economy. Nonetheless, all of them are focused on a way that allows an organization to take full advantage of materials and resources, thinking about waste as raw materials with intrinsic value [13]. In this sense, the purpose of the circular economy is to delimit a "safe operating space for humanity" [14] that allows industry to overcome the scarcity of natural resources and reduce the impact on the environment while meeting the needs and demands of the global population, which, by 2030, is estimated to be ca. 8 billion people [15].

Economic stakeholders, such as companies, consumers, authorities at all levels, and non-governmental organizations (NGOs), have been crucial for the conversion process from the actual economic models into more sustainable systems. Initiatives such as Horizon Europe, the United Nations Sustainable Development Goals, the G7 Alliance on Resource Efficiency, and the Ellen Macarthur Foundation, for instance, play a fundamental role in supporting different ambitious projects of investment, development, and implementation of circular economy around the world. Furthermore, new legislative initiatives have been created to implement new directives concerning waste management, and landfill reduction, while encouraging recycling. From a strategic point of view, the comprehension of circular economy business models will guide organizations on the path to creating new business opportunities, which will help them to find new solutions to avoid raw materials' scarcity and be more resilient to raw materials' scarcity [14] and overcome price inflation of several commodities [16].

When referring to sustainability, one of the industries that arises concern is the automotive industry not only due to the pollution that results from the manufacturing processes and daily use of cars but, also, owing to the waste generated from car destruction by the end of their use. Indeed, every year, more than 6 million tons of materials and components from end-of-life vehicles (ELVs) are generated by the European Union (EU) [17]. Such fact raised generalized interest among governments which became more aware of how vehicles impact the environment throughout their life cycle. At the beginning of the 2000s, around 25% of the materials from end-of-life vehicles (ELVs) were still landfilled or incinerated for energy production, due to the lack of available and sustainable options to recycle some of their components [18]. For that reason, in 2000, the European Council published the directive 2000/53/EC where the EU required the reduction of ELV waste while recommending the use of an increasing number of recycled materials for the fabrication of new vehicles [18,19]. Fortunately, such efforts lead to significant advances, as reported by the European Statistical Office (Eurostat), which shows that the percentage of weight resulting from ELV components that are recycled and reused has been sustainably increasing since 2009 (Figure 1) [17].

Unfortunately, the Eurostat source does not currently provide the percentage data of only recycled materials as not all countries provide the required information. In addition, no further information from 2020 to the present day could be found in the database. Nevertheless, recent studies estimate that it will be possible to recycle around 89% of the materials derived from ELVs by 2030 [20]. To the present day, most of the efforts operated by the automotive industry are still focused on the production of lighter cars and electric vehicles, to reduce part of the greenhouse emissions derived from transport [21]. However, since the implementation of effective models concerning the recovery of materials from ELVs has been proposed as the path to follow in the coming years [22], some automotive firms are already making efforts to determine the environmental impact of their products during their life cycle. Furthermore, special attention has been paid to the incorporation of more recycled materials in their upcoming models.

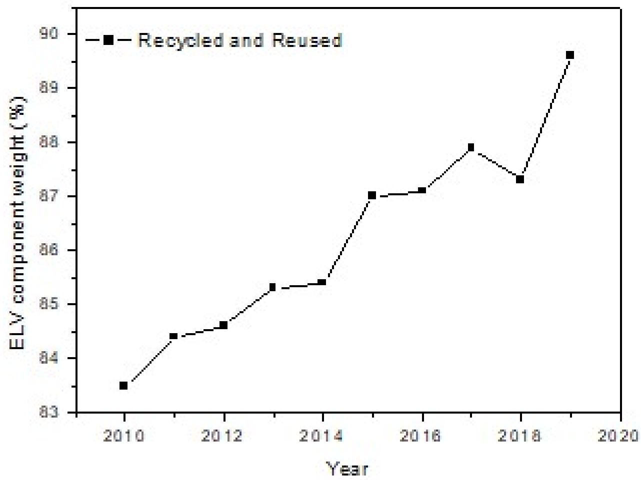

Figure 1. The weight percentage of ELV materials that are recycled and reused (adapted) [17].

For instance, Ford Europe is already determining the sustainability index of their components using indicators based on ISO 14040 (life cycle assessment) and increased the incorporation of sustainable materials in their vehicles by around 15%. The model Ford S-MAX 2.0 L gasoline integrates approximately 18 Kg of non-metallic recyclates and natural fibers [5].

Renault Group, in turn, has integrated the concept of the circular economy into its value chain since 2005. In addition, it is one of the founding members of the Ellen MacArthur Foundation, which is dedicated to the acceleration of the transition into a circular economy. Renault actively collaborates with subsidiaries, businesses, and startups to recover and recycle materials from ELVs [23]. Some of these collaborations were established with institutions such as GAIA, INDRA, and Boone Comenor Metalimpex, which are responsible for recycling metallic and non-metallic materials of reformed vehicles, operating short loops of secondary materials, and reconditioning electric vehicle batteries for a second life [23–25].

In the case of BMW, the group strategy relies on the reuse of carbon fibers from ELVs treated by pyrolysis, transforming them into recycled carbon fiber mats. These composites are then used to manufacture structural and non-structural automotive components in roofing panels, supporting shells of the rear seats, C-pillars, and upper trunk partition walls of different car models [26].

Tesla Inc. is currently recovering more than 99% of the metals contained in scrap and end-of-life batteries. The group is also using Blockchain Technologies to enable the tracking of the entire supply chain of materials used in the batteries [27].

Although recycling of materials may represent an opportunity for the automotive industry, it is crucial to standardize parameters to guide industrial stakeholders in what concerns the limitation of the generated carbon footprint, and how to reintegrate and recycle materials used in the cars [28,29]. In addition, it was reported by Hallack et al. that there exist important limitations such as hazardous and toxic materials, lack of material identification, incompatibility of materials for recycling, disassembly difficulties, and recycling inhibitors, among others, which can significantly limit the rate of recycled polymers from ELVs [30].

1.2. Three-Dimensional Printing

Three-dimensional printing, commonly known as additive manufacturing (AM), is a technology that enables the production of 3D parts from previously prepared CAD designs processed by slicing software. After the slicing step, where the 3D design is divided into multiple layers according to the desired printing specifications, the STL file is converted into a gcode for 3D printers to process. For this reason, it is possible to produce intricate shapes with high accuracy and detail. Owing to their processing requirements, polymeric materials are often suitable for 3D printing.

Besides creating customizable geometries, 3D printing of polymers is an attractive alternative to produce prototypes owing to the short processing time and almost no waste generation. Therefore, 3D printing offers an opportunity to digitalize the manufacturing of components and pieces, playing an important role in the Industry 4.0 scenario [31].

The use of 3D printing has increased since the expiration of key patents related to processes such as material extrusion, vat photopolymerization, and powder bed fusion. Indeed, the prices of 3D printers based on fused filament fabrication (FFF) tremendously dropped after the 2000s [32,33].

In the context of circular economy, AM offers the possibility to reprocess, reuse and remanufacture materials in a very clean, efficient, and effective way [12,34–36]. Moreover, the decentralization and versatility of the production systems allowed individuals, small businesses, and startups to contribute to the development of a regenerative economic system. Companies such as Filastruder (Snelville, GA, USA), FialabotProtoCycler (Barre, VT, USA), 3D Brooklyn (Brooklyn, NY, USA), Protoprint (Plav, Czech Republic), or Local Motors (Phoeninx, AZ, USA) are, in fact, already producing new components with different applications using waste as raw material [33].

In the opinion of some authors, the circular economy could be one of the most important technologies to ensure sustainable models of manufacturing since it favors the reorganization of production facilities, allowing the assembly of smaller supply chains and more rational use of resources [34,37].

For the automotive industry, 3D printing brings a new opportunity window to manufacture intricate components and car parts, which usually require specific molds and facilities that are not easily replicable worldwide, hindering the circular economy, and are associated with significant operating costs. As previously discussed, concerning circular economy, some quite known car brands are already exploring 3D printing and incorporating it into their operating system. In this regard, Ford Europe is already using 3D printers to produce vehicle parts from sand and nylon powder [5]. However, one of the most explicit examples of the adoption of 3D printing into the production system of the automotive industry is the case of Local motors. This American company, which was founded in 2007, relies on 3D printing to produce around 90% of the parts used for the assembly of their automobiles [33].

Considering the state of the art currently available, the present manuscript aims to present a systematic review concerning 3D printing and the automotive industry, with a special focus on the literature published from the year 2000, that discusses the concepts of 3D printing, recycling, circular economy, and car manufacturing. In addition, the geographic distribution of each search topic is provided. The numeric indicators and selected works were then analyzed in an attempt to answer the following questions:

- Question 1: Is the growth of scientific production in the field of 3D printing for application in the vehicle industry comparable to the growth of 3D printing research between 2000 and 2021?
- Question 2: Is the application of 3D printing for circular economy and recovery of plastic materials from ELVs feasible?
- Question 3: Is the term "circular economy" more used by European researchers?

Finally, the obtained results are discussed considering the current economic context and the 3D printing technology available, highlighting research limitations and future research potential.

2. Materials and Methods

A systematic literature review was carried out to identify and critically evaluate the findings of relevant peer-reviewed studies.

2.1. Eligibility Criteria

The inclusion and exclusion criteria were applied freely and independently by 4 experienced reviewers and experts about innovation, 3D printing, and polymer engineering, who judged the studies.

2.2. Search Strategy and Information Resources

Scientific papers published between 2000 and 2021 were analyzed in April 2022, employing the Scopus platform as the search engine and the following keywords: "Recycling", "3D printing", "vehicles", and "circular economy". Then, three inclusion criteria were imposed to filter the results. The first was the selection of the search field "Article Title, Abstract, Keywords", while the second was the interval of analysis from 1 January 2000 to 31 December 2021. Finally, the third inclusion criterion was related to the type of documents considered, which, in the case of the present work, was applied to only consider research papers. Table 1 demonstrates the Boolean operators used for the searches in the Scopus platform.

Table 1. Boolean operators applied in Scopus.

Search Term
TITLE-ABS-KEY ("recycling") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("3D printing") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("vehicles" AND "recycling") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("3D printing" AND "vehicles") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("circular economy" AND "vehicles") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("3D printing" AND "recycling") AND PUBYEAR > 1999 AND PUBYEAR < 2022
TITLE-ABS-KEY ("3D printing" AND "circular economy") AND PUBYEAR > 1999 AND PUBYEAR < 2022

The limitation of the time interval was chosen to match the publication of the European directive for the reduction of waste from end-of-life vehicles [19]. In addition, it includes the expiration date of many of the existing patents of 3D printing technology, which was between 2000 and 2014.

Then, the choice of keywords relied on the growth of scientific production of each of the related terms during the interval of analysis.

2.3. Selection and Data Collection Process

The data collected from the research papers were identified, the duplicated records were excluded, and then mapped and linked between the topics under analysis, considering the year of publication and country.

To filter the results presented by Scopus, the papers were ordered by relevance in the search engine, and the abstracts of the first 60 articles of each search were downloaded in plain text, grouped in a txt file, and then uploaded to the Voyant Tools platform (version 2.6.1).

The correlation and significance of terms in the corpus of the texts were analyzed using the software. Then, concepts such as "reuse", "remanufacture", "pollution", "recovery", "wastage", "sustainability", or "green" were signalized to choose the papers for subsequent analysis by the experts. Each of the reviewers worked independently and was not involved in the pre-selection phase or the bibliometric analysis to warrant impartiality in the selection of studies.

3. Results

As illustrated by Figure 2, after inputting the Boolean operators in the search engine, imposing the inclusion criteria, and further examination as described in the methodology section, 14 publications were selected for analysis.

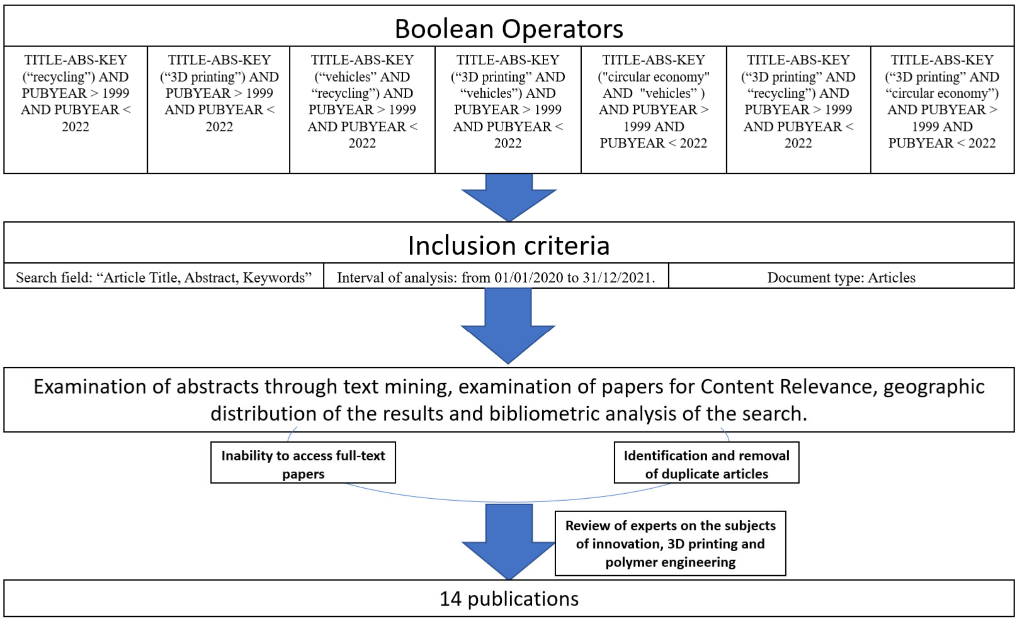

Figure 2. Review collection process.

The summary of the number of results of each search is presented in Table 2. The considered research papers were characterized in the subsequent sections according to their geographic and temporal distribution.

Table 2. The number of articles and reviews resulting from the search string.

Search Term	Number of Articles Found in Scopus
"recycling"	171.005
"3D printing"	47.385
"vehicles" AND "recycling"	3.719
"3D printing" AND "vehicles	509
"circular economy" AND "vehicles"	340
"3D printing" AND "recycling"	342
"3D printing" AND "circular economy"	79

3.1. Temporal Distribution of the Studies

The temporal distribution of the publications is shown in Figure 3.

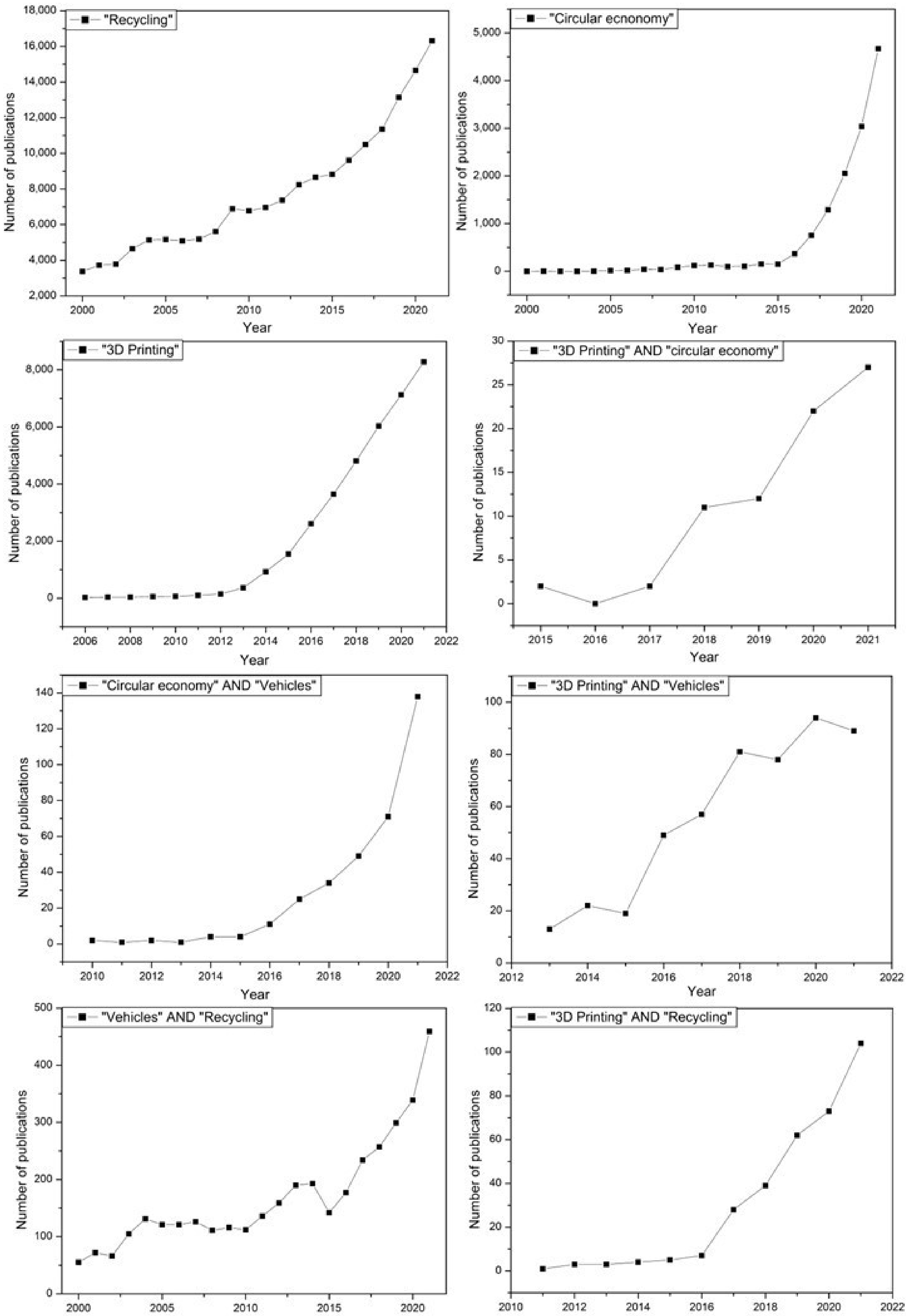

Figure 3. Temporal distribution of the studies. Source: Scopus.

It should be noted that, although there is a difference in the number of articles, the temporal growth of the referred topics was exponential from 2000, and there are no records of results of the term "circular economy" before 2001.

From the plots presented, it can be noted that topics such as the reuse of materials, ELV, and 3D printing are becoming widely studied by the international scientific community with exponential growth since 2000.

3.2. Geographic Distribution of the Results

The results obtained from the search by region show that the countries with the highest scientific production in all the topics addressed are the United States of America and China, representing 37.7% of the publications. However, despite this discrepancy among other countries, it was detected that the incidence of the term circular economy is present more regularly in publications from countries in the European space with an incidence of 70%, followed by Asian countries with an incidence of 17% (Figures 4 and 5).

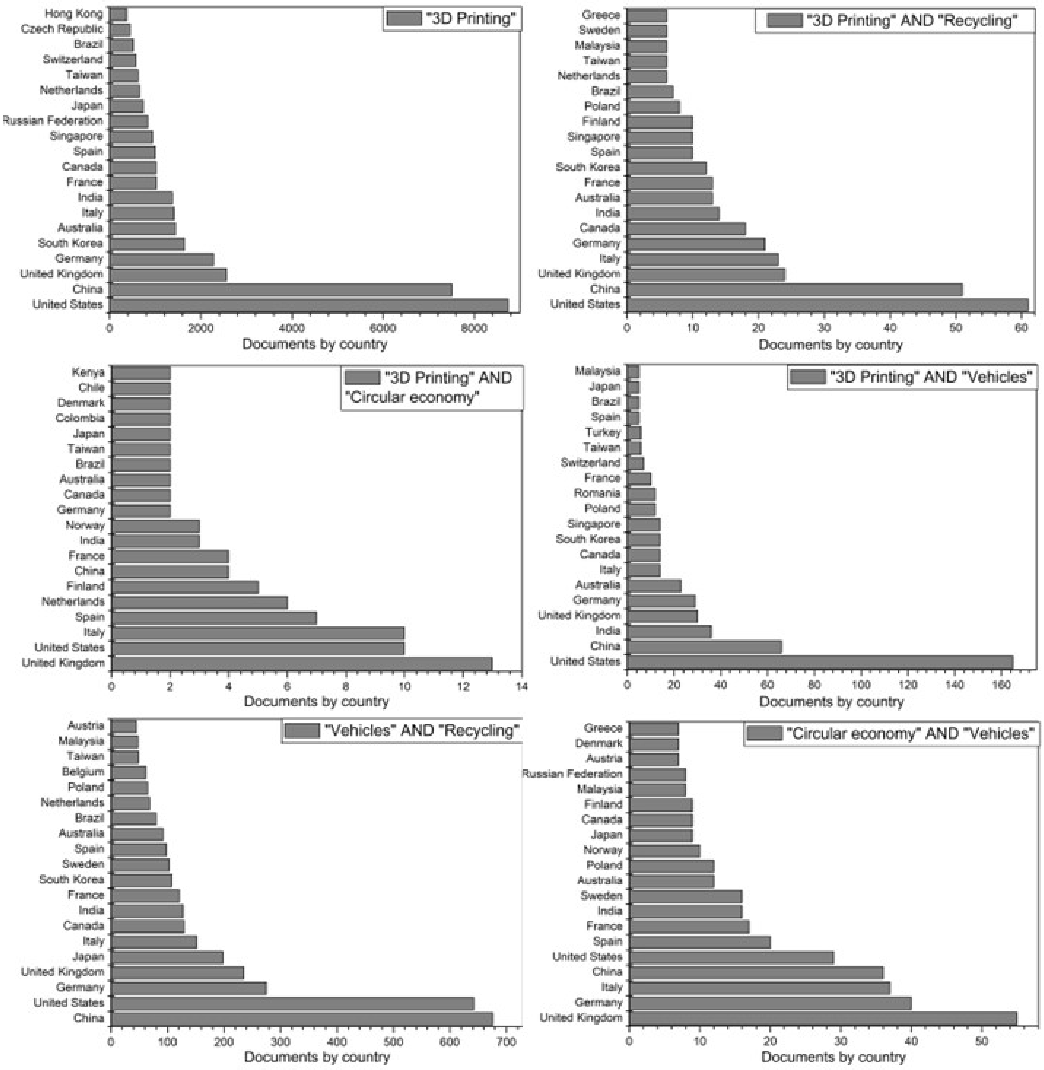

Figure 4. Publications by country or territory between 2000 and 2021. Source: Scopus.

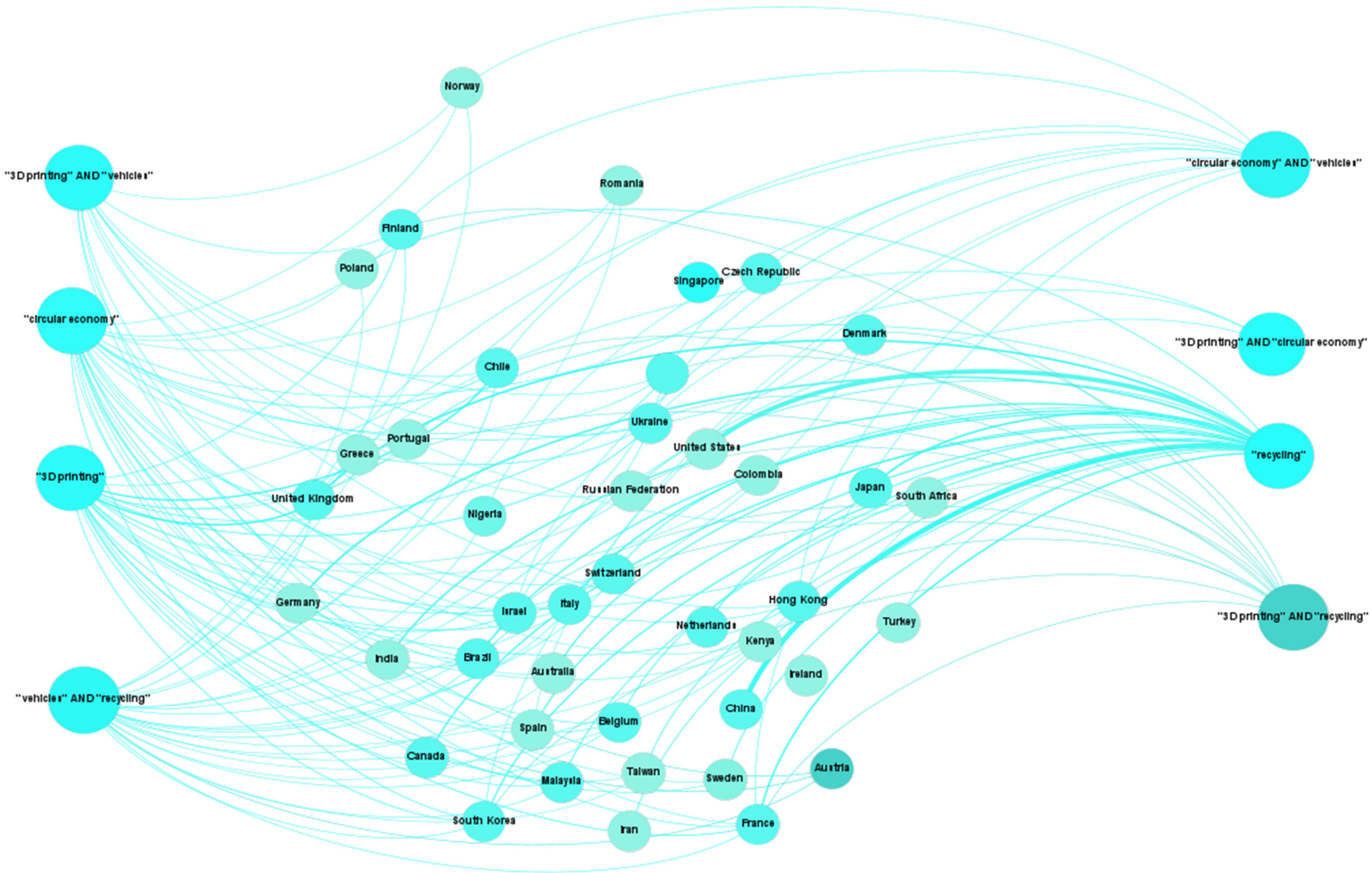

Figure 5. Interaction between the different topics by country.

3.3. Review Collection Process

To determine the relevance, the categories were classified by the experts into four groups of interest (Table 3) as follows: (1) Business Strategy, which refers to signalized opportunities for automotive industry resilience; (2) Innovation, which includes modernization and digitalization studies for 3D printing and other emergent technologies for the automotive industry; (3) Material Science, which includes applied methods, experimental approaches, and processes for the circular economy of plastics; and (4) Policy and Planning, which refers to the articles focused on the management of production systems that contribute to a circular economy, environmentally friendly production and minimization of raw material consumption. It is worth mentioning that studies can be classified into more than one category.

Table 3. Description and categorization of the core themes of articles selected from Scopus.

Ref	**The Study Deals with**	**Topics of the Article**				**Accept? (Yes/No)**
		Business Strategy	**Innovation**	**Material Science**	**Policy and Planning**	
[16]	Circular economy and business strategies for the implementation of CE in the manufacturing industry.	X	X		X	Yes
[14]	Study the interrelation of circular economy with academia, industry, and policymakers, pointing out the gaps between them.	X	X		X	Yes
[38]	This study highlights the potential uses of AM in a sustainable industry.	X	X		X	Yes
[18]	An overview of recycling in the European Union since the implementation of the European directives for waste management of ELVs.	X	X		X	Yes
[31]	Three-dimensional printing process development for the future of the industry and the strategic framework of this technology for materials.	X	X	X	X	Yes
[39]	The framework of additive manufacturing to perform a closed recycling global chain.	X	X		X	Yes
[40]	A qualitative study to explore the opportunities of 3D printing for sustainable design and circular economy of polymers.	X	X		X	Yes
[41]	Analyzes the opportunity of design using 3D printing technology for next-generation low-weight components.	X	X	X		Yes
[42]	Compares mechanical properties between 3D printed and injection molding samples from recycled ABS.	X	X	X		Yes
[43]	This paper is a comparative mechanical performance analysis between particle material extrusion and filament printing using recycled polycarbonate and virgin polycarbonate.	X	X	X		Yes
[44]	Performs the reprocessing of carbon fiber composites, characterizes the mechanical properties of the recycled pieces, and analyzes the energetic consumption of reprocessing.	X	X	X		Yes
[35]	Conducts a mechanical performance analysis of PLA after successive recycling.	X	X	X		Yes
[45]	Explores the economic feasibility of a distributed closed-loop supply chain network using OS 3D printing technologies.	X	X		X	Yes
[22]	Develop an interactive algorithm to investigate an effective strategy for recycling ELVs.	X	X		X	Yes
[46]	Analyses the financial situation of the vehicle scraping and recycling industry in Poland.	X			X	No

To characterize the sample, it is worth saying that every analyzed article falls into the "Innovation" and "Business Strategy" topics, 42.86% of the articles fit into the "Material Science", and 50% into "Policy and planning". This reflects that innovation in manufacturing is strongly linked with the resilience of businesses and organizations.

3.4. Text Corpora Analysis

Three-dimensional printing has been gathering attention among the scientific community, indeed some of the authors suggest that this technology may play an important role in sustainable production through recycling and lean manufacturing.

> *"The sustainable aspects of 3D Printing such as less material wastage, less post processing and very less cost even for manufacturing complex parts makes 3D Printing a technology of the future. The other sustainable aspects include the potential of 3D printing to reuse plastics, recycle and reduce emissions"*

(Jandyal et al. [31], p. 33)

> *"The use of 3D Printing helps to produce designs which are sustainable"*

(Jandyal et al. [31], p. 34)

> *"3D printing being a sustainable technology has a potential to replace conventional technologies"*

(Jandyal et al. [31], p. 41)

> *"3D Printing apart from being cost effective is also environment friendly, hence can help to mitigate the adverse effects of industrialization on the environment"*

(Jandyal et al. [31], p. 41)

> *"AM gives a high degree of freedom to the design and production process"*

(Sauerwein et al. [40], p. 1137)

> *"The analysis of the design projects showed that AM creates opportunities to enable circular design strategies like upgrades and repair which extend a product's lifespan, even if these were not considered in the original product design"*

(Sauerwein et al. [40], p. 1138)

> *"Based on the recycling and remanufacturing process of 3D printed CFRTPCs, a cleaner production pattern of composites for the future can be conceived"*

(Tian et al. [44], p. 1617)

> *"3D printing process itself is a clean manufacturing method without any waste of raw material"*

(Tian et al. [44], p. 1617)

> *"3D printing may offer a simple way of instant robotic fabrication and ready-to-use functional systems"*

(Ugur et al. [38], p. 548)

> *"AM may play a significant role in diminishing waste resources and reducing energy consumption by employing just-in-time production"*

(Ugur et al. [38], p. 552)

"In recent years, there has been an increasing amount of interest in the scientific community and entrepreneurial initiatives to propose solutions to tackle the issue, including the use of plastic recycling for 3D printing purposes"

(Santander et al. [45], p. 10)

The possibility to include additive manufacturing technology has been pointed out as an innovative option for companies in the context of Industry 4.0, through design and process improvement.

"The mode of manufacturing is gradually shifting from traditional to non-conventional processes. It requires intensive knowledge of materials and their respective properties. With the current knowledge of materials and processes, some modifications have been done in the traditional techniques using 3D printing"

(Jandyal et al. [31], p. 38)

"Recent advances in 3D-printing have enabled more accurate control of material placement than ever before, making multi-material 3D-printing a new tool for manufacturing bioinspired composites"

(Gu et al. [16], p. 318)

"Cyber-physical integration facilitates smart factories with high efficiency that are capable of fabricating high-quality customized products"

(Ugur et al. [38], p. 553)

"The current barrier of mass production on location will be overcome with personal- and customized fabrication"

(Ugur et al. [38], p. 553)

Some authors state that limitations regarding the operability of 3D printing in a circular economy could be overcome by future regulations and logistic strategies. In addition, the market growth will benefit the recycling of plastics using this technology.

"As the global shift because of the superior economics of distributed recycling and manufacturing, the prosumer community will benefit from regulations that stipulate that manufacturers identify the materials in their products"

(Reich et al. [43], pp. 12–13)

"The economic and environmental feasibility of the local plastic recycling network will be possible at decreasing prices of virgin plastic filament. From a market perspective, this implies that as the 3D printing market grows and the price of virgin plastic filament decrease"

(Santander et al. [45], p. 10)

"Efforts need to be taken in the pre-treatment 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"

(Cruz et al. [39], p. 14)

"However, the research on the creation of minimal standards and legal framework are major elements to validate"

(Cruz et al. [39], p. 14)

"It is easy to see that recycling the ELVs depends on establishment of an efficient ELV recycling network, which not only can reduce the impact on the environment during the recycling process, but also can facilitate the effective reuse of recycled resource"

(Zhang et al. [22], p. 2)

The findings related to materials science and transportation logistics also showed promising experimental results about the recycling of plastics and composites through 3D printing.

"This study clearly shows that a combination of 3D-printing, droptower impact testing, and finite element simulation is vital to gain a fundamental understanding of the key material attributes critical for the design of next-generation impact resistant materials"

(Gu et al. [16], p. 322)

"The tests confirm the possibility of secondary processing of used electronic equipment housings into an extrudate used as a filament in the FFF additive manufacturing technology. The mechanical properties of testing structural elements depend on manufacturing technology and process parameters, mainly temperature and pressure"

(Czyzewski et al. [42], p. 1452)

"In the industry, [3D printed components] will have a positive impact on the possible applications of re-using ABS waste like a structural secondary material to apply in additive manufacturing"

(Czyzewski et al. [42], p. 1453)

"The results of this study found that sifted recycled PC shards could be effectively used as feedstock for PME/FPF additive manufacturing"

(Reich et al. [43], p. 13)

"The viability of recycled PC particles offers a wide range of uses that can replace more expensive solutions for prosumers and industry alike"

(Reich et al. [43], p. 13)

"In the present research, a recycling and remanufacturing process for 3D printed CFRT-PCs has been put forward, which provided a fully recyclable composite materials with mechanical properties even higher than the original ones"

(Tian et al. [44], p. 1615)

"A better interface and mechanical performance have been obtained due to the [3D printing] recycling process"

(Tian et al. [44], p. 1617)

"The developed PLA filaments are very practical and provide the greatest application potential in the AM industry since the PLA filaments can be employed to print physical models with high tensile strength economically"

(Kuo et al. [35], p. 16)

> *"It is interesting to note that the barrel temperature is the most significant control factor affecting the diameter of PLA filament followed by recycling material addition ratio, extrusion speed, and cooling distance"*
>
> (Kuo et al. [35], p. 10)

> *"According to the above findings, the developed PLA filaments are very practical and provide the greatest application potential in the industry because the PLA filaments can be used to fabricate three-dimensional models with high tensile strength under the condition of low manufacturing cost."*
>
> (Kuo et al. [35], p. 15)

> *"A wide range of materials … can also be recycled to manufacturing new filament"*
>
> (Kuo et al. [35], p. 16)

> *"This work has demonstrated the economic and environmental feasibility of a distributed closed loop supply chain network for plastic recycling using OS 3D printing technologies"*
>
> (Santander et al. [45], p. 11)

> *"The proposed model and the developed algorithm in this paper have provided an efficient quantitative method to find a compromising (optimal) policy for the practical ELV recovery management problem in an uncertain environment"*
>
> (Zhang et al. [22], p. 22)

Moreover, limitations regarding the recycling and recovery of materials were discussed by researchers, and future perspectives were stated.

> *"To maximise the potential of distributing recycling, attention should be focused on the willingness to use recycled 3D objects"*
>
> (Cruz et al. [39], p. 14)

> *"It is essential that sustainable opportunities offered by AM support multiple product life cycles when designing for a circular economy"*
>
> (Sauerwein et al. [40], p. 1138)

> *"Reduction of the costs such as the processing costs and the transportation costs generate more significant impacts on the optimal recycling policy than the change of the component selling prices in the secondary markets"*
>
> (Zhang et al. [22], p. 23)

> *"It is suggested that adopting advanced processing technology and machinery equipment is the most important measure to improve the ELV recovery efficiency in this case"*
>
> (Zhang et al. [22], p. 23)

4. Three-Dimensional Printing as a Path to Improve the Circular Economy of ELV Polymers

Traditionally, the polymeric parts of cars are made by injection or thermoforming, which require specific molds and facilities that are not easily replicable worldwide, hindering circular economy. In addition, they are often associated with high operating costs.

Polymers are attractive raw materials, especially owing to their lighter weight compared with metals and ceramics. In addition, the so-called engineering polymers can present mechanical properties which fulfill the requirements of several components not only from your daily life but also from several industry types with higher demanding needs. However, the global high demand for plastics, and their inherent waste production and disposal problem, jeopardize their sustainable use. Indeed, only in Europe, it is estimated that in 2020 the demand for plastic components was 49.1 million tons, of which 8.8% refers to the automotive industry. Unfortunately, from the total production of plastics, only a small counterpart is recycled, and the higher part is simply incinerated for energy recovery [47].

Although energy is produced, several reports state that the incineration of plastics induces a higher impact on the environment than landfilling [48]. However, landfilling is not a reasonable solution.

The results of the present study suggest that 3D printing emerges as a technique that grants a delocalized, autonomous, customizable, and flexible production [39], which allows the manufacture of a wide variety of polymeric products, enabling the use of virtual reality, programming, and remote work [40]. These factors modify the role of suppliers in the production lines and may represent an important technology to transit to Industry 4.0 [38].

The reintegration and reuse of polymers commonly used by the automotive industry, such as acrylonitrile butadiene styrene (ABS) and polycarbonate (PC), is technically feasible. Indeed, it was demonstrated that is possible to extrude and produce parts from recycled ABS and PC through 3D printing [12,42,43]. Herein, the factors that have more influence on the mechanical properties of the samples were related to the manufacturing technology and process parameters [42,43]. The evaluation of the thermal stability, chemical composition, and mechanical properties allowed to conclude that there were no significant variations between recycled and virgin material [12]. Indeed, the mechanical performance was quite similar.

Fiber-reinforced materials printed in 3D made from recycled Polylactic acid (PLA) and carbon fiber have been studied by Tian et al. and the results demonstrated that 73% w/w of PLA and 100% w/w of carbon fiber were recovered, mechanical properties of remanufactured specimens exhibited a 25% higher bending strength and proved non-downgrade in the recycling process [44]. Kuo et al. also found recycled PLA could be used to produce filament using optimized parameters with a tensile strength 1.1 times the commercially available PLA filament and with low production costs [35]; PLA surges as an option for the fabrication of polymeric components as it is a biodegradable and compostable thermoplastic derived from renewable plant sources, such as starch and sugar [49].

On the other hand, biomimetic designs have also taken advantage of the progress of 3D printing, being able to generate complex patterns that resemble those existing in nature to improve the resistance and the mechanical properties of polymer parts. Gu et al. studied 3D printed parts using two base polymers with a nacre-like architecture demonstrating that it was possible to produce prototypes based on composite designs and create patterns that could prevent the perforation of a projectile upon impact [41]. This study provided an interesting example of how to reintegrate and remanufacture low-weight components with optimal impact-resistance properties for next-generation vehicles.

Kreiger et al. conducted a lifecycle analysis and found that a distributed model for producing filament from waste uses less energy than conventional manufacture, mostly because of transporting, and savings were found to extend over 80% [50].

Toxicological implications have to be overlooked since many of the plastic components of cars may contain hazardous substances [33,36]. The 3D printing community has already discussed alternative systems of codification and norms requiring polymer producers to indicate flame retardants, stabilizers, and filling materials included in their plastic materials, consequently facilitating the management of polymeric waste, and allowing 3D print producers to benefit from these regulations [43]. Overcoming these challenges and promoting the use of non-toxic additives can lead to a new generation of products that successfully operate in a circular economy.

One of the great tasks of regulatory entities is to guarantee that the treatment and waste separation are accurately executed, in order to be suitable to feed other production chains. Currently, there is no reliable data concerning the amount of ELV plastic that is recycled in the European Union. Indeed, there are many countries where incineration of such waste continues to be the preferred option [17]. Regulators must ensure that polymers are kept in the system to recycle.

However, in some authors' opinions, the environmental and economical effectiveness of additive manufacturing as a method of reprocessing materials still needs to be validated, due to inconsistency of the energy consumption outputs, greenhouse gas emissions, and difficulties related to logistics in supply chain management in a real scenario [39].

5. Conclusions

The present manuscript explored the opportunity that 3D printing offers for a circular economy of ELVs through a literature revision concerning 3D printing, circular economy, and recycling. Furthermore, it provides a guiding principle for stakeholders in the automotive industry concerning the challenges and strategies to integrate additive manufacturing into the circular economy of ELVs.

The results of the systematic literature review revealed that most of the papers included have empirically and conceptually proved the importance of 3D printing as a promising technology for circular economy and automotive applications. The wide range of variables that influence the relationship between the circular economy, 3D printing, and the automotive industry highlights the interdisciplinary nature and complexity of the covered issues. Therefore, researchers must consider a holistic approach that includes organizational, social, political, technological, and financial variables affecting innovation processes.

The literature review also showed that 3D printing technology represents an opportunity to empower small-scale producers and decentralize the supply chains of goods, creating a new market and facilitating eco-design, reuse, repair, and extending the life cycle of polymers [40].

The bibliometric data presented demonstrate that the term "circular economy" is frequently associated with research from European countries, which is seven times greater than the ones found in the rest of the sample. Topics such as the reuse of materials, ELVs, and 3D printing are becoming widely studied by the scientific community with exponential growth since 2000. Unfortunately, poor information was found in the automotive industry about the application of 3D printing in the manufacture of vehicles.

Some of the most outstanding problems addressed by the authors were the need to define strategies to turn polymeric automotive components into more eco-friendly and safer materials, improve the supply chain of polymers, perform sustainability assessments, and reformulate waste policies of ELVs.

6. Recommendations and Limitations

As this study was conducted based on the available open-access literature from Scopus from the years 2000 to 2021, it is recommended for future research to include press information and journals and to expand the sources of data, which will enrich the results of this study.

The current study aimed at building a comprehensive review of the relationship between the circular economy, automotive industry, and waste ELV managing activities based on a literature sample; therefore, the specifics of each topic may not be fully covered.

It can be suggested that future research efforts integrate qualitative studies such as focus groups or semi-structured interviews with managers from the automotive industry and the 3D printing community in order to give a more detailed perspective about how AM would fit in the market in the next years.

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