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Systematic overview of nanocomposites obtained by VAT photopolymerization techniques: A cost and life cycle assessment approach

Revisión sistemática de nanocompuestos obtenidos por técnicas de fotopolimerización VAT: un enfoque de evaluación de costos y ciclo de vida térmicos

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Abstract

Additive manufacturing has shown advantages for nanocomposite fabrication. Despite VAT-photopolymerization being one of the first developed 3D printing technologies, high device costs made it a technology that was difficult to access. The massive production of these devices in recent years has opened this technology to everyone. Stereolithography and Digital light processing are the most prominent technologies used in this field. This systematic review studied 217 articles regarding SLA and DLP for additive manufacture of nanocomposites. The main finding of this systematic review shows that further research on circular economy and life cycle assessment of the SLA and DLP technologies is urgently needed. Also, a deeper discussion on the technology and material costs is recommended in order to give a more detailed insight on the final cost of these 3D-printed nanocomposites.

Keywords: nanocomposite; 3D-printing; additive manufacture; stereolithography; DLP; costs; LCA.

Resumen

La manufactura aditiva ha demostrado poseer ventajas en la fabricación de nanocompuestos. A pesar de que la fotopolimerización-VAT es una de las primeras tecnologías desarrolladas de impresión 3D, el alto costo de los dispositivos la hizo una tecnología de difícil acceso. La producción masiva de estos dispositivos en los últimos años ha abierto esta tecnología a todo el mundo. La estereolitografía (SLA) y el procesamiento digital de luz (DLP) son las tecnologías más prominentes usadas en este campo. En esta revisión sistemática se estudiaron 217 artículos relacionados con las técnicas SLA y DLP para la manufactura aditiva de nanocompuestos. El principal hallazgo de

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esta revisión sistemática es la necesidad futura de investigación en economía circular y evaluación del ciclo de vida de los procesos SLA y DLP. De igual manera, se recomienda una discusión más profunda respecto al costo de los dispositivos y los materiales para poder tener una visión más detallada del costo final de los nanocompuestos obtenidos por fotopolimerización.

Palabras clave: nanocompuesto; impresión 3D; manufactura aditiva; estereolitografía; DLP; costos; LCA.

1. Introduction

Additive manufacturing (AM), most known as three-dimensional printing (3DP), is the process of creating parts with the addition of material layer by layer [1] to create a 3D model, opposed to conventional manufacturing where such material is removed to create the desired part. Therefore, 3DP reduces the consumption of raw material which in turn can decrease the manufacturing costs [2]. AM can be used for printing the most complex materials such as ceramic-polymer composites [3], fiber-reinforced polymer composites [4], food [5], nanocomposites, and cementitious materials [6], [7].

AM is divided into seven categories by the ASTM standard, which are: vat photopolymerization, binder jetting, directed energy deposition, material extrusion, material jetting, powder bed fusion, and sheet lamination [8]. 3D-printed parts are usually used for rapid prototyping and the number of end-use 3D-printed parts has been increasing lately, however, a study [9] from more than 100 industries in the United States showed that there is a small group of manufacturers using AM to produce their final products. However, due to the new COVID pandemic, AM has been one the most used technologies in supporting the fabrication of medical protective equipment, mechanical ventilator accessories, and other parts [10].

The vat photopolymerization (VP) ASTM category consists of several manufacturing techniques using light as a stimulus to start a focused polymerization reaction. One of the most representative features of vat photopolymerization techniques is that it possesses the highest resolution and surface finish of all AM processes [2]. The main drawback of VP resides on the feedstock materials, as the polymer to be used must be a resin that can start its cross-linking process by means of light, known as photo-curable resins, which constraints the application of this technology. There are two exposure techniques in VP: serial scanning and flood exposure. Serial scanning works by running a laser over the resin to selectively polymerize the resin, while flood exposure selectively casts light on the layer according to the cross section of the part to polymerize the resin [2]. Stereolithography (SLA) being a Serial scanning technique and Digital light processing (DLP) is a flood exposure technique.

SLA uses a laser to cure selectively the resin through the action of scanning mirrors, sometimes lenses are used to help focus the laser light. This process can achieve a final print resolution of 20 µm [11], this resolution is related to the laser beam size. A common set up of SLA technology is depicted in Figure 1. On the other hand, DLP relies on a digital micro-mirror device used in order to project different light geometries of the part cross section, to polymerize a complete layer of resin, making this process faster (but sacrificing resolution), as the minimal measure of the final printed part is limited by the pixel size of the projector screen. A common set up of DLP technology is shown in Figure 1. As a result of the differences in the operating conditions and apparatus set up, SLA technology offers a more accurate impression, although it takes longer than DLP, as DLP can print complete layers at a time considerably shorter. The pixelated effect on the DLP technology is due to the light being projected from a light projector, the pixel size determines the accuracy of each printing. Such pixel size is usually referred to as a 'voxel' in 3D printing [12], which is considered short for 'Volumetric picture element' or 'volumetric pixel'.

Meanwhile, circular economy models are now being implemented elsewhere due to the significant challenges and large-scale problems we are facing such as the worldwide pollution, the increasing energy needs, overpopulation, and adverse policies and economic models that became a threat for the planet sustainability [13]. AM is not the exception with this need [14], [15], and therefore important efforts need be made for the technology to become a real green solution. Nanocomposites have shown to be an excellent way to capture contaminants [16] and provide solutions to complex environmental issues [17]. With the combination of AM, innovative solutions become possibilities. The purpose of creating composite materials is to take advantage of useful properties of different materials while trying to overcome their drawbacks.

The use of nano particles and nanomaterials has been increasing over the years, achieving areas of impact from fuels and propellants [18] to super capacitors [19]. Nano scale reinforcements are widely used to increase the mechanical or chemical properties of a matrix. Using nano metric materials as reinforcement for the resin matrix in SLA and DLP manufacturing processes can significantly increase the properties of the final nanocomposite [20]. This mixing of nanocomposites with the VP techniques has led to a new research field which has involved multiple kinds of applications such as radar absorbing materials [21], piezo electric materials [22], biomedical [23], printable elastic conductors [24], hydrogels [25], among others. A proper dispersion of the reinforcements in the resin also increases the final properties of the nanocomposite material, this is achieved by different techniques with ultra-sonication being one of the most widespread [26].

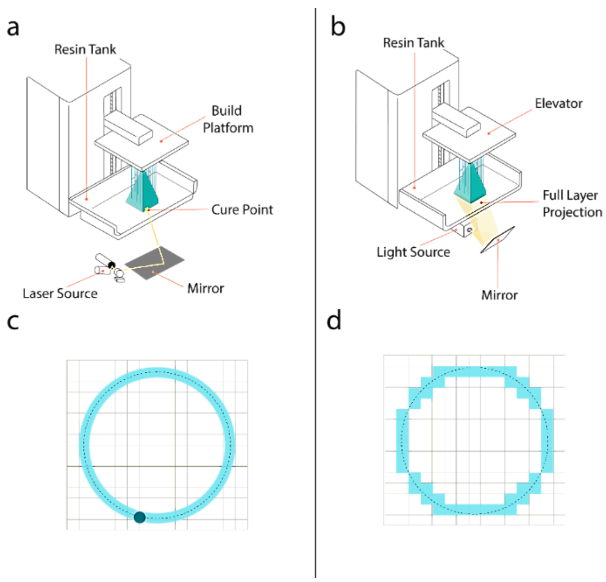

Figure 1. SLA vs DLP technologies. a) SLA apparatus set up. b) DLP apparatus set up. c) Laser beam sized resolution from SLA, in which a single point gets cured at a time without a pixelated effect. d) Display pixelated resolution from DLP, in which a complete projected geometry (layer) gets cured. Source: Author.

This systematic literature review analyses the recent increase on nanocomposite materials obtained by VP techniques such as SLA and DLP, by studying a total of 217 research papers in the field while keeping track of the economic and environmental perspectives involved in 3DP – SLA – DLP, with the aim of unfolding research opportunities in this growing VP manufacture field. The review is organized as follows. First, we present the information on nanocomposites obtained by VP covering the SLA and DLP technologies, the materials used in the selected articles, and the pre and post processing of these nanomaterials. Then, the articles that had cost related terms in their studies are introduced. Finally, the articles that mentioned terms related to environment and life cycle assessment (LCA) are presented. Analysis and results are discussed, as well as the suggested research opportunities.

2. Methodology

The methodology used in this article was adapted from Tranfield and Denyer [27], which mainly set the aim of the review and accomplishing with a series of systematic filters to ensure the relevance of the final documents to be analyzed. Therefore, after the aim of the review was defined, a systematic search of information was performed in the Scopus database in order to conduct three different studies, corresponding to three stages. The first stage focuses on the VAT photopolymerization techniques involving nanocomposite materials. The second one focuses on the costs involving this type of process; and the third one focuses on the life cycle assessment (LCA) that can be or has already been implemented.

As the aim of this study is to analyze those articles relating nanocomposite materials and the VP technologies, an initial search in the database was performed involving the ‘nanocomposite’ and ‘additive’ topics. Searches were narrowed by excluding publications before 2015 which were surprisingly very few [28], [29], [30], [31]. Also, books and book chapters, as well as conference papers, were excluded from the search as this review will only analyze research articles. The search was conducted using the search strings and keywords listed in Table 1.

The Scopus report (Figure 2) shows the number of articles by country (the 10 most relevant countries) in the study of the 137 initial results of the search string 1, with the United States and China taking participation in over 30 documents each, followed by India and the United Kingdom with nearly half the participation from that of the United States and China individually.

Each search string was filtered two times in order to narrow the number of articles in each search by relevance in the field of study.

Table 2 shows the number of articles per search and its subsequent filtering stages. The first filter applied in all the searches was a Scopus database automatic filter of the publish year, the search was narrowed down to articles excluding articles before 2005, in this initial filter stage only research articles were used.

Table 1. Search strings, keywords, terms, and combined terms of the systematic search.

Item	Description
Terms	Nanocomposites, 3Dprinting, AM, SLA, DLP, costs, LCA
Combined terms	VAT photopolymerization, circular economy, life cycle assessment
Search String 1	ALL (nanocomposites)) AND (((additive)) AND (sla)
Search string 2	ALL (nanocomposites)) AND (((additive)) AND (sla) AND (cost)
Search string 3	ALL ((nanocomposites) AND ((sla) OR (stereolithography)) AND ("life cycle"))

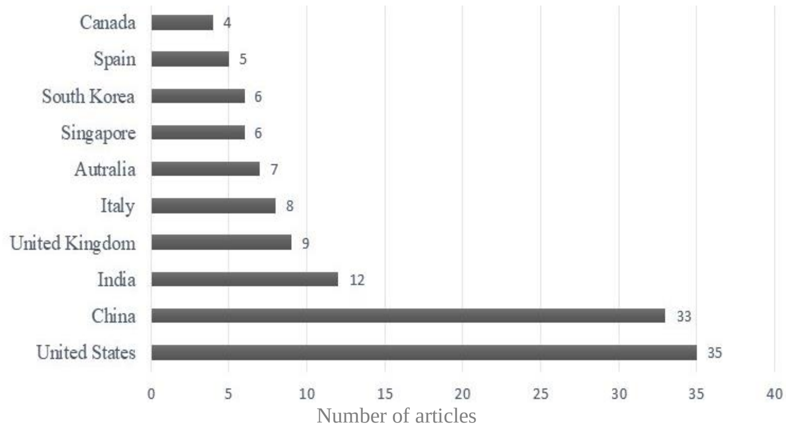

Figure 2. Number of articles in the VAT-photopolymerization techniques by country. Source: Author.

Table 2. Number of results in the Scopus database for each search string and their subsequent filtering stages.

Search string	N° of results	Filter 1	Filter 2
ALL (nanocomposites)) AND ((additive) AND ("sla")	137	122	16
ALL ("stereolithography")) AND ("nanocomposite") AND (cost)	45	41	4
ALL ((nanocomposites) AND ((sla) OR (stereolithography)) AND ("life cycle"))	35	24	5

The second filtering stage was an extensive look up at the title, abstract and keywords of each paper so articles not referring to nanocomposites obtained by VAT photopolymerization were excluded to ensure the relevance of the final documents.

After a detailed analysis of the results obtained in the second filter of search string 1, the number of articles selected for the first part of the study on the nanocomposites obtained by VAT-photopolymerization techniques was narrowed down to a total of 10 documents.

3. VAT photopolymerization

This first stage of the study focused on the analysis of the results obtained in the first search string after the filtering stages. The final 10 documents selected for this first stage will be discussed and the results were classified into 5 different areas (graphite Nanocomposites, biomedical, Nano cellulose, Nano-particles, and Nano-structures using the VAT photopolymerization 3D printing techniques. Table 3 presents the journals in which the selected articles appeared as well as their main area of impact and year of publication. The number of articles per publication year is represented in Figure 4, and the number of selected articles by area of application with its corresponding percentage of participation is represented in Figure 3.

All the 10 articles selected in this first stage had a deep insight of the VAT photopolymerization technique which consists of a layer-by-layer additive manufacturing process in which a light stimulus initiates a focused polymerization reaction on a photo sensitive resin. The articles were grouped according to relevant technique, materials, pre-processing and post-processing applied.

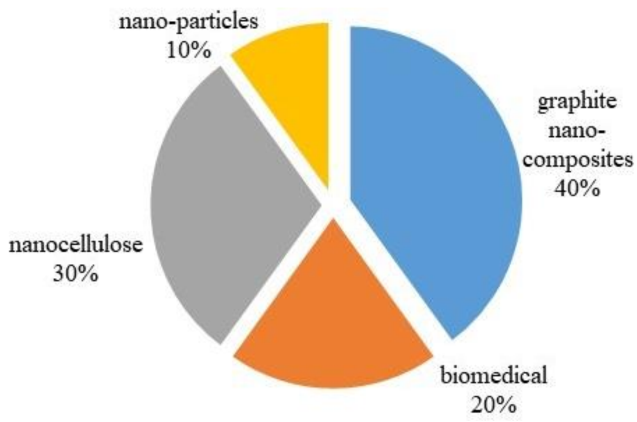

Figure 2. Participation in the Stage 1 of the study by area of application. Source: Author.

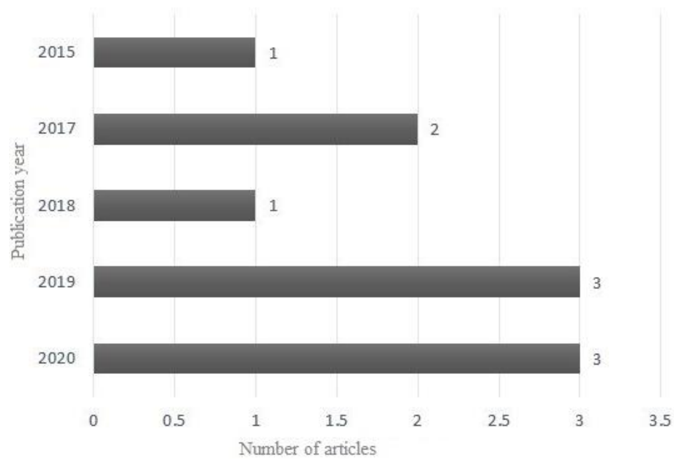

Figure 4. Number of articles per publication year. Source: Author.

Table 3. List of selected articles for the VAT-photopolymerization stage of the systematic review with their corresponding publication year, journal, and main area of impact

Ref	year	Journal	Area
[32]	2020	Polymers MDPI	graphite Nano-composites
[33]	2020	Materials Science and Engineering R: Reports	biomedical
[34]	2020	Journal of Applied Polymer Science	Nano cellulose
[35]	2019	ACS Applied Materials and Interfaces	graphite Nano-composites
[36]	2019	Nanomaterials MDPI	Nano cellulose
[37]	2019	Composites Part B: Engineering	graphite Nano-composites
[38]	2018	Polymers MDPI	Nano-particles
[39]	2017	ACS Applied Materials and Interfaces	graphite Nano-composites
[40]	2017	ACS Applied Materials and Interfaces	Nano cellulose
[41]	2015	Polymers for Advanced Technologies	Biomedical

3.1. Stereolithography (SLA)

The stereolithography 3D printing technique (usually referred to as SLA) consists of the curing of a specific point of a layer of the part to be printed, this is usually obtained by means of a focused laser beam, thus the final resolution of the printed part is the size of the beam itself. Figure 1 shows a schematic set up of an SLA device. Table 4 shows the studies in which an SLA apparatus was used, along with the kind of printer used and the main improved feature with the addition of the nano-filler.

Table 4. Articles that used an SLA apparatus

Ref	Device	Technique	Improved features
[32], [39]	Form 1+	SLA	stiffness, tensile strength, thermal conductivity
[33]	NR	SLA	Continuous printing
[34]	Autocera	SLA	Tensile strength, modulus
[35], [38], [40]	Form 2	SLA	Tensile strength, ductility

3.2. Digital light processing (DLP)

The digital light processing 3D printing technique (usually referred to as DLP) consists of the curing of an entire layer of the part to be printed. This is usually achieved by using either a UV display or a UV light projector, which projects the geometry of a complete layer at the same time, thus achieving faster printing but reducing the resolution of the print, as such resolution is now the pixel size of the screen or projector. Figure 1 shows a schematic set up of a DLP device. Table 5 shows the studies in which a DLP apparatus was used, along with the kind of printer used and the main improved feature with the addition of the Nano reinforcement.

Table 5. Articles that used a DLP printing technology

Ref	Device	Technique	Improved features
[36]	Duplicator D7 +	DLP	Tensile strength
[41]	Envisiontec Perfactory3	DLP	Tensile strength, E Modulus, toughness
[37]	Autodesk 3ds Max	DLP	compression stress

3.3. Materials

In this section, different materials used throughout the 10 articles will be listed (Table 6), as well as enhancements in properties achieved by both Vat photopolymerization techniques. The materials used were classified into matrix materials and Nano-reinforcements. Figure 5 shows different types of Nano-reinforcements used in the studies with its corresponding participation.

All the studies used nano-sized particles to reinforce the polymeric matrixes. Most of the studies used an acrylic or methacrylic acid resin [33], [35], [36], [37], [38], [39], while only 3 of the studies used a custom mixture of resins to achieve their final nanocomposite matrix [32], [40], [41].

J. O. Palaganas et al. [35] and J. Z. Manapat et al. [39] did not purchase a commercial nano-reinforcement, instead, they both synthetized graphene oxide (GO) and obtained these nanoparticles through laboratory-controlled chemical reactions and then freezing and grinding the resulting GO material to obtain the end-use nano GO.

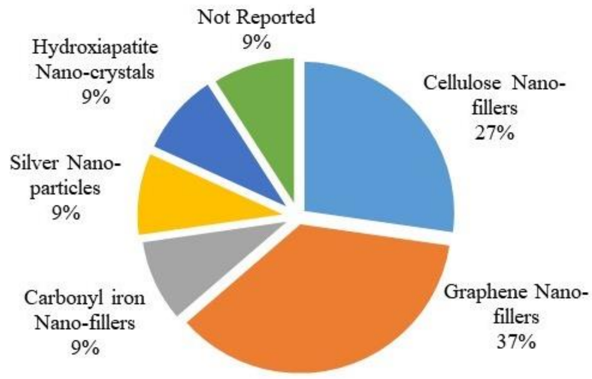

Figure 3. Nano-fillers used with its corresponding percentage participation in the articles. Source: Author.

3.4. Pre-processing

In the field of nanocomposites obtained by Vat-photopolymerization, a wide range of preprocessing techniques is usually required to ensure the dispersion of the reinforcements within the resin. This can be reflected on the selected documents as all of them required a sort of preprocessing technique, from simple mechanical stirring to complex surface abrasion of the Nano-fillers. Mixing the resin and the Nano-fillers is a crucial preprocessing step to homogeneously disperse the reinforcement into the resin and to avoid agglomeration of fillers [2], as this will result in uncured or partially cured spots. Three of the studied articles used sonication as mixing method [34], [39], [40], some others focused on performing a surface abrasion or treatment of the nanoparticles to assure a proper matrix-reinforcement bonding [36], [37], [39], [41], as some particles showed hydrophobic properties which decreased the successful addition of the Nano fillers. All of the different pre-processing strategies used in the analyzed articles are shown in Table 6.

Table 6. Matrix and Nano-reinforcement materials used in the studied articles, as well as the pre and post processing used

Ref	Matrix	Filler	Enhancements	Pre-processing	Post-processing
[32]	Form Clear v2 (acrylic monomers and oligomers)	GNP (avanGRP-40)	Young's Modulus	high-shear mixing, degasification	IPA wash, 60°C heating, UV post-cure
[33]	Highly hydrated polymer	NR	continuous printing	oxygen-permeable build window	NR
[34]	Methacrylic acid (MA) resin	Cellulose Nano-crystals	strength, thermal stability	ultra-sonication, freeze drying, grinding	160°C heating, UV post-cure
[35]	Methacrylic acid (MA) resin	Graphene Oxide	Tensile strength, ductility	synthetized Graphene oxide, grinding	IPA wash, 60°C heating, UV post-cure
[36]	Polyurethane acrylate-based resin	Cellulose Nano-fibrils	Tensile strength	cellulose surface PEG treatment	IPA wash, UV post-cure
[37]	Polymethyl-methacrylic resin (Tethon 3D)	graphene, carbonyl iron	Tensile strength, thermal conductivity	electro-chemical exfoliation	EtOH 99% wash, UV post-cure
[38]	Acrylic resin (Ebecryl 7100)	silver salt (AgNP's)	Tensile strength, ductility	overnight mixing of resin and Ag-Salt	IPA wash, thermal post-cure @90°C
[39]	Acrylic resin (FLGPGRO2)	Graphene Oxide	Stiffness, Tensile strength	acetone-sonication, mixture ltrasonication	IPA wash, mild annealing @50°C & 100°C
[40]	Poly(ethylene glycol) diacrylate (PEGDA575) based hydrogel	Cellulose Nano-crystals	Tensile strength, ductility	mixture ultrasonication	phosphate-buffered saline (PBS) wash
[41]	PTMC-MA resin and PTMC-MA/nHA resins (custom mix)	hydroxyapatite Nano-crystals	Tensile strength, E modulus	Cold-Methanol precipitation, stirring	propylene carbonate/ethanol wash

3.5. Post-processing

Both Vat-photopolymerization techniques studied in this review produce a semi green part, which means that there is no complete reaction of the cross-linked photopolymerization thus generating a mandatory post-processing, requiring both a cleaning wash for uncured resin leftovers [42] and a post curing process to ensure the full reaction in the end nanocomposite. All the articles analyzed in this study used either of the aforementioned post treatments, some of them even used a heating process during or after the post curing process. All the post cured parts in the articles used either thermal [43] or UV [44] in the final cure of the nanocomposite.

Five of the ten articles reported the use of isopropyl alcohol (IPA) to wash out the remains of uncured resin [32], [35], [36], [38], [39]. At the same time, most of them used a thermal curing, as heat is known to emit light in the non-visible spectrum. Ovens were used to finish the curing process in 5 of the studies [32], [34], [35], [38], [39]. In addition, there were several documents that reported the use of UV post curing machines [32], [34], [35], [37] to ensure the complete curing of the end parts.

Two of the studies reported the use of ethanol to wash out the uncured resin [37], [41] instead of the usual IPA wash.

4. Cost Analysis

The search string 2, which was a refined search of the Table 7 shows these documents with their corresponding publication year, journal and country. The search string 2, which was a refined search of the articles related to the VAT-photopolymerization techniques with the word 'costs', initially returned 45 results. However, most of the results did not actually state cost related information. Most of them just mentioned the word 'cost' in terms like 'low cost', 'high costs', and alike. Thus, this second stage study will only focus on 4 articles considered the relevance to the cost Analysis.

Table 7. Cost related articles with their corresponding country, journal and publication year

Ref	Pub year	Journal	Country
[45]	2020	Nanomaterials NDPI	China
[46]	2020	Progress in Materials Science	United States
[47]	2019	Journal of Nanomaterials	China
[48]	2018	Additive Manufacturing	United States

In this section of the systematic review, 2 important topics were identified to be analyzed, which were both the device and Material costs.

4.1. Device cost

Table 8 shows a list of the printing devices used in the documents from search string 1, 2 and 3 with the corresponding used VP technique, device purchase cost range, and their main features of dimensions and power.

Mubarak et al. [45], as well as Feng et al. [47] insisted that VP technologies were considered as low-cost AM techniques. In contrast, Dizon et al. [48] mentions SLA techniques as being high energy consuming due to the usage of lasers that results into high heat losses, which is indirectly converted into money loss. Wu et al. referred to VP produced parts as being 'cost-effective' and emphasized on the importance of this factor for hearing aids, orthopedics and prosthetics, and surgical guides and models [49].

4.2. Material cost

None of the 19 articles from this study presented any sort of material purchase costs, nor compared costs of either the resins or the reinforcements.

There are many technology suppliers involved in the process of AM of nanocomposites. The documents analyzed in this section did not present the purchase costs of their printing devices. Though all of them mentioned the word 'cost', none of them showed an interest in the economic aspects of the producing of their nanocomposite materials obtained by VP.

Table 8. Technology cost of various apparatuses used in the study

Ref	Device	Type	Reported Dimensions/Power	Cost range (USD)	Source
[36]	Duplicator D7 +	DLP	Build Volume: 120 x 68 x 180mm Power: 48 W	700 - 1,000	[55]
[41]	Envisiontec Perfactory 3	DLP	Size: 73 x 48 x 135 cm XY accuracy: 0,05 mm	50,000 -110,000	[56]
[17]	Form 1 +	SLA	Dimensions: 30 × 28 × 45 cm Power: 60 W	3,299 - 3,600	[57], [58]
[21], [24], [26]	form 2	SLA	Dimensions: 34.5 × 56 × 79 cm Power: 65 W	3,500 - 4,000	[59]
[47]	Photon	SLA	Printing volume: 115 x65x155 Power: 40W	230 - 300	[60]
[45]	Dream 3D-C200	SLA	NF	NF	NF

NF: Not Found

5. Life cycle assessment (LCA)

On this third stage of the study, articles that are related to VP technologies, nanocomposites and Life cycle assessment were of interest. 35 articles were initially scouted by the Scopus database, after their subsequent filtering and analysis of abstract, title, and keywords. Only 5 articles out of the initial 35 documents mentioned the compound term of 'life cycle assessment' or LCA. LCA is a technique used to evaluate the potential environmental impact of a product life cycle starting from the raw materials involved in its fabrication, to the final product and disposal [50].

Diagrams showing general LCA processes were shown in reference [51]. LCA of 4D printed parts with VP techniques was commented by Rastogi et al. [25]. In some studies, the term LCA was not used, and a LCA was not considered, however, they discussed the production of VP printed parts for environmental purposes [42], [43], which related the final printed parts directly to the life cycle of such technologies.

Khosravani et al. [54]. studied the LCA of various AM techniques, including SLA. They manifested their concerns about the environmental impact of SLA technology due to the high energy consumption from this technology compared to other more environmentally friendly AM techniques. Table 9 shows the articles studied in this third stage classified by their area of environmental impact.

Table 9. Environmental and LCA related articles

Ref	Year	Journal	Area of impact
[53]	2017	Advanced Science	Energy
[25]	2019	Chemical Engineering Journal	Degradation
[52]	2019	Journal of Water Process Engineering	water quality
[51]	2020	Chemical Engineering Research and Design	air quality
[54]	2020	Applied Materials Today	waste, energy, air quality

6. Analysis and results

In the articles from stage 1, the procedures for material characterization and mechanical properties assessment are well known, as well as correctly applied because all of them material characterization and mechanical analysis of the materials were performed before and after the creation of the nanocomposite material.

Only one of the documents [33] did not report the used nano filler, this article was related to 3D printed hydrogels. Neither did Liet al. [33] reported any post-treatments that can be applied to these nanocomposite materials. Geven et al. [41] were the only reporting a compound post wash of propylene carbonate/ethanol for the removal of uncured resin leftovers. The reason was that the final nanocomposite material was intended to be used as an orbital implant, and the removal of such leftovers was of prime importance.

The use of heat post curing processes in ovens, instead of direct UV light post curing in most of the analyzed articles, shows a trend on the combination of post processes to ensure the proper achievement of desired mechanical, thermal and electrical properties of the nanocomposite materials. One of the studies [45] allegedly used a SLA apparatus that was not possible to find information of, presumably either an own-built device or the model name. A web search was performed trying to find information about it and the results showed that such a device has only been used in S. Mubarak et al. [45] work, and their study was the only one from the selected articles in this review to use TiO2 nanoparticles (TNPs) as reinforcement. Also, Zuo et al. [37] did not report the device used in their study; however, they did report the software used to create the CAD models to be printed, which was reported to be 'Autodesk 3D max'. Autodesk company has a single 3D VP printer, which is known under the name of 'EMBER 3D desktop printer' that the company stopped producing due to reasons that are not a concern of this review.

Y. Zuo et al. [37] study showed a remarkable feature of iron-polymethyl and graphene-carbonyl nanocomposites which were used for the successful absorption of microwaves. They advocate such increase in absorbing properties as being related to the magnetic loss of the carbonyl-iron powder (CIP) microspheres.

Referring to material properties obtained within the studied articles, De León et al. [32] showed an improvement in the electrical conductivity of the printed nanocomposite. Mohan et al. [36] managed to achieve up to a 37% enhancement in the tensile strength of PU-3%CNF/rGO by using surface-grated nanocellulose. All the documents reported an enhancement in the mechanical properties compared to the those of the resin without nanofillers.

Regarding the second stage of the study, which focused on the costs involved around SLA and DLP techniques, several findings can be discussed. Even though the purpose of most academic research is not to offer the reader an economic analysis involving the production, technologies and material costs, we consider this be of prime importance for the modern industrial world, which seeks a constant balance between investment and profits. Therefore, we proposed the creation of a report in which technologies around VAT photopolymerization and its corresponding purchase costs are reported.

With such parameters, the procedure that estimates the production costs of nanocomposite materials obtained by either SLA or DLP techniques can be easily attainable, for both retail and mass production of nanocomposite parts.

Although the articles did not comment, discuss or recommend any of the devices used for their studies, several reviews have been made of each of the used apparatuses. The Duplicator D7+ along with the Anycubic Photon are among the most affordable VP machines, they both have a decent print resolution and very similar print volumes, therefore making them a very decent option for the manufacture of nanocomposites for personal use. Form 1+ and Form 2 printers have a bigger printing volume, and their manufacturer offers a wide range of spare parts, customer service and extensive background of its technologies, which makes these 2 printers a little more suitable for commercial printing. For massive commercial production of cured resin parts, the Envisiontec Perfactory 3 is more suitable due to its printing volume; however, its purchase costs are very high and such high volume may not be entirely used in the production of nanocomposites.

For the LCA, no follow up of the life cycle of the raw materials, was performed, and only the end parts were related to environmentally friendly applications. Many materials and processes were recently developed with AM aiming sustainability [61] and circular economy [15], which can help in solutions to some of the major issues is facing now the humanity with global warming.

Concerns were manifested about the use of these technologies because of the type of electrical energy source, as none of the studies ran their machines with alternative energy produced electricity.

7. Conclusions

This systematic review shows that the application fields of composite materials can be extended towards the nano and micron scales mainly because of the feasibility of producing nanocomposite parts by using the SLA and DLP technologies, being able to produce materials with enhanced mechanical and electrical properties, with features in geometry and precision difficult to achieve in conventional manufacturing processes.

Several factors are involved in the end-product cost of each printed part. None of the analyzed papers presented a way to estimate the final printed nanocomposite cost, therefore, a research opportunity that considers the estimation of the full costs of manufacturing a nanocomposite material using these technologies emerges. We suggest including estimation factors such as: device purchase cost, matrix and reinforcement purchase cost, electric energy consumption of the device, printable volume and device up-times and maximum printable volume.

Regarding Life Cycle Assessment, a new research opportunity opens up with this study, as 3D printed parts with these technologies do not study an energy-cost balance and analyzing the production costs of these composite materials from renewable energy sources can be a trend in the field.

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Autor Contributions

L. D. Gil: Conceptualization, Data curation, Investigation, Writing – original draft, Writing – review & editing. I. L. de Camargo: Investigation, Validation, Writing – review & editing. E. I. Gutierrez-Velasquez: Investigation, Validation, Writing – review & editing. H. A. Colorado: Conceptualization, Methodology, Project administration, Supervision, Writing – original draft.

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Conflicts of Interest

The authors declare no conflict of interest.

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