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Review

Sustainability and innovation in 3D printing: Outlook and trends

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Abstract: The convergence of additive manufacturing (AM), sustainability, and innovation holds significant importance within the framework of Industry 4.0. This article examines the environmentally friendly and sustainable aspects of AM, more commonly referred to as 3D printing, a cutting-edge technology. It describes the fundamentals of AM in addition to its diverse materials, processes, and applications. This paper demonstrates how several 3D printing techniques can revolutionize sustainable production by examining their environmental impacts. The properties, applications, and challenges of sustainable materials, such as biodegradable polymers and recyclable plastics, are thoroughly examined. Additionally, the research explores the implications of 3D printing in domains including renewable energy component fabrication, water and wastewater treatment, and environmental monitoring. In addition, potential pitfalls and challenges associated with sustainable 3D printing are examined, underscoring the criticality of continuous research and advancement in this domain. To effectively align sustainability goals with functional performance requirements, it is imperative to address complexities within fused deposition modeling (FDM) printing processes, including suboptimal bonding and uneven fiber distribution, which can compromise the structural integrity and durability of biodegradable materials. Ongoing research and innovation are essential to overcome these challenges and enhance the viability of biodegradable FDM 3D printing materials for broader applications.

Keywords: additive manufacturing; 3D printing; Industry 4.0; sustainability; environmental implications; sustainable materials; alternative energy sources

1. Introduction

Additive manufacturing (AM) is driven by the primary goal of reducing both the time and steps required in the manufacturing process. This objective is achieved through the utilization of rapid prototyping technologies, which leverage 3D modelling software, such as computer-aided design (CAD), to expedite product design [1–3]. AM realizes the creation of products by adding successive layers of material, utilizing data derived from design software [4–7]. AM can be broadly categorized into two distinct types: single step manufacturing, which involves material fusion [7] to attain the fundamental geometry, and multistep manufacturing, which employs an adhesion principle, executed through a series of sequential processes [8]. A 3D-printed part and the layered manufacturing process are depicted in Figure 1. Selective laser sintering (SLS), stereo lithography (SLA), fused deposition modelling (FDM), laminated object manufacturing (LOM), and other AM techniques demonstrate how technology is evolving to achieve product geometry and optimize manufacturing [9]. With the least amount of material needed, AM is renowned for printing polymers, alloys, metals, and biomedical materials [10]. To combine materials for consolidated mechanical, optical, and physical properties, researchers took advantage of AM's interdisciplinary potential [11–13]. It has shortened lead times for crucial replacement parts and optimized supply chains [14].

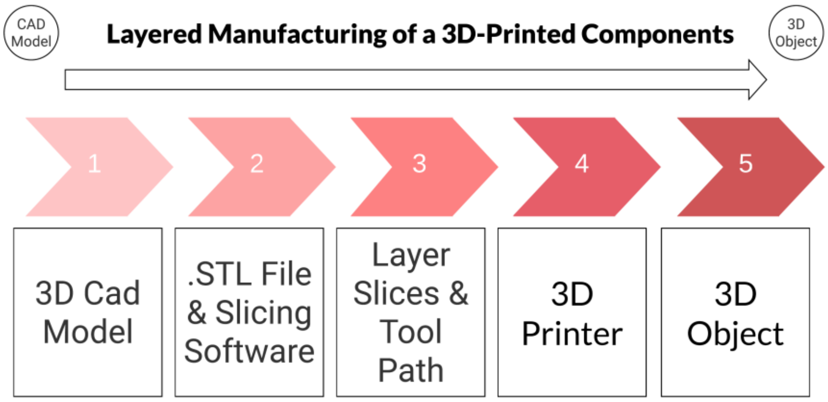

Figure 1. Layered manufacturing of a 3D-printed component.

AM stands as a transformative technology, significantly reducing the need for human intervention and reliance on service providers, particularly in remote areas. Its capability to enable users to 3D print machine repair parts bring forth a new era of self-sufficiency. The open-access nature of 3D printing design software fosters user adoption while concurrently saving resources. One of the most distinctive features of AM is its ability to facilitate fast mass customization, a realm in which conventional manufacturing methods often fall short [15]. Moreover, AM has effectively curbed labor and transportation costs by enabling on-demand production of products and parts. Unlike subtractive manufacturing, AM minimizes material waste by adding material only where needed, thus optimizing resource utilization [16,17].

Despite the high initial setup costs associated with 3D printing machines, AM-produced goods remain less expensive than those manufactured through traditional processes. The essentiality of AM in Industry 4.0 is evident, especially in the realm of mass customization [18]. The convergence of AM with technologies like AI, and cloud computing has given rise to the concept of digital twins, capable of addressing printing issues through monitoring, control, and real-time corrections [19].

Sustainable development, a critical global imperative, necessitates a delicate balance between social, environmental, technological, and economic facets. Extensive literature on additive manufacturing underscores the diversity in research methodologies, emphasizing the need to evaluate new sustainable technologies. Some studies compare qualitative and quantitative methods [20], while others delve into the integration of sustainability into firm strategies [21,22]. The energy-efficient nature of AM, along with its capacity to minimize material waste and inventory, positions it as a sustainable manufacturing solution [23–25]. Nonetheless, challenges such as hazardous powder emissions [26] and non-recyclable waste [27] persist, complicating assessments of AM's overall environmental impact [20,28].

A product's environmental impact is measured over the course of its life cycle through life cycle assessment (LCA) [29]. Goal definition, scoping, inventory analysis, impact assessment, and interpretation are among the LCA phases [30]. Numerous studies have been conducted on LCA techniques and applications [31–35]. Environmental benefits and cost-effectiveness are key considerations in product design. Decision-makers can compare the cost-effectiveness of investments and business decisions with the aid of the economic life cycle assessment (LCC) [36]. LCC analysis uses goal definition, scoping, and life cycle inventory analysis to identify the most economical course of action. LCC has a wealth of theoretical and practical documentation and is being used more and more in industry and government [37–41].

In the context of industry-specific applications, AM has demonstrated profound implications across various sectors including construction, medical, and manufacturing. Recent studies have explored emerging additive manufacturing technologies in 3D printing of cementitious materials within the construction industry [42]. Additionally, investigations into binder jetting 3D printing and large-scale construction applications provide valuable insights into the diverse applications of AM in construction [43,44].

2. Problem statement and objectives

The use of AM, particularly 3D printing, in industrial settings opens up a plethora of opportunities for sustainable production in the context of Industry 4.0. Nonetheless, despite promising developments, incorporating environmentally friendly practices and materials into 3D printing poses challenges. There is a critical knowledge gap regarding the full scope of environmental consequences, material limitations, and overall sustainability of various 3D printing techniques. Furthermore, the translation of sustainable practices, such as the use of recyclable and biodegradable materials, from theoretical frameworks to practical applications in 3D printing has largely gone unexplored. Existing literature emphasizes the importance of conducting extensive research into the environmental impact, material properties, and practicality of sustainable 3D printing.

This research aims to fill the gaps mentioned above and contribute to the long-term evolution of additive manufacturing by achieving the following goals:

- Investigate the environmental implications of various 3D printing techniques, such as energy efficiency, material efficiency, and waste generation, to gain a thorough understanding of their sustainability profiles.
- Evaluate the properties and limitations of sustainable materials used in extrusion-based 3D

printing, such as recyclable plastics, biodegradable polymers, and modified filaments, providing insights into their applicability and potential challenges.
- To understand the potential impact of 3D printing on sustainable development, investigate its role in specific domains such as renewable energy component fabrication, water and wastewater treatment, and environmental monitoring.
- Identify and analyze the limitations and challenges of using sustainable materials in 3D printing, with a focus on issues such as material translation accuracy, print quality, and structural integrity.

3. Research methodology

A thorough and comprehensive systematic literature review (SLR) technique was used in this study to examine the complex interactions among innovation, sustainability, and additive manufacturing. The first stage was a laborious search that produced a large number of papers that were carefully selected based on inclusion criteria that guaranteed relevancy, with a focus on peer-reviewed sources and recent publications within the previous ten years. We have arranged the literature into major theme categories, including the foundations of additive manufacturing, sustainable materials, environmental implications, technique analysis, applications, and limits, in order to present an ordered study. Using a qualitative methodology, a comprehensive thematic analysis was conducted on the chosen literature to extract important conclusions and insights, promoting a nuanced comprehension of the condition of the field's study at the moment. The information was then carefully organized into parts that made sense and covered diverse aspects of innovation, sustainability, and additive manufacturing. Relationships between the various concepts were then identified and clarified. For every article that was chosen, a critical quality evaluation was carried out, analyzing factors including the article's relevance to the study subject, the technique used, and the reliability of the sources. To ensure the authenticity of the results, a thorough validation procedure was used, which included cross-referencing data from several sources, depending on credible journals and conference proceedings, and carefully examining and addressing any differences. Adhering to ethical guidelines, appropriate reference and recognition were upheld throughout the work, underscoring a dedication to scholarly honesty.

Despite possible gaps in the developing subject, this study attempted to include a variety of viewpoints and acknowledged its limits by concentrating only on material published up until the deadline. The positionality of the researchers was openly acknowledged, taking into account their prior knowledge in pertinent domains while scrupulously preserving neutrality throughout the thorough investigation of innovation, sustainability, and additive manufacturing. With the use of this SLR approach, significant insights and important patterns might be extracted, advancing our understanding of this dynamic and ever-evolving field of study.

4. Discussion on findings

4.1. Material choice analysis

4.1.1. Recyclable plastics for extrusion-based 3DP

FDM plastics must be recycled to extend their life cycle and enable sustainable and eco-friendly

AM. Their linear molecular chain structure allows thermoplastics to soften when heated and harden when cooled, making them recyclable [42]. Thermoset plastics cure irreversibly. Reusability depends on this fundamental difference. Table 1 lists common 3D printing thermoplastics like ABS and PLA. Tensile strength and Young's modulus, which measure tensile elasticity, are crucial. ABS is ideal for high-stress tooling parts, while PLA is better for healthcare and prosthetics [43,44].

Table 1. Common 3D printing thermoplastics and their applications.

Abbreviation	Full name	Applications	References
ABS	Acrylonitrile butadiene styrene	Industry, Health care	[45–47]
PLA	Polylactic acid	Health care, Industry	[46,47]
PC	Polycarbonate	Health care	[48]
PET	Polyethylene terephthalate	Industry	[49]
HIPS	High-impact polystyrene	Industry	[50]
PHA	Polyhydroxyalkanoates	Health care, Industry	[51]
PVA	Polyvinyl alcohol	Health care	[52]
PCL	Polycaprolactone	General application, Health care	[53]

Mechanical or chemical recycling can recycle thermoplastics. Mechanical recycling melts shredded plastic into 3D printer feedstock filament. While economically beneficial, each recycling cycle degrades material properties due to chain-scission reactions caused by impurities, lowering molecular weight by 46% and viscosity by 80% as examined by P. Jagadeesh et al, also an observed lower tensile strength for recycled part as compared to its virgin counterpart [54,55] this is also exemplified in Table 2 with ABS. Material properties can also contribute in varying other parameters such as natural frequencies [56]. Conversely, chemical recycling depolymerizes plastic through a chemical reaction to reproduce it [57]. The open-source Recyclebot recycles plastic waste into 3D printing filament, reducing embodied energy and environmental impact compared to standard filament manufacturing [57,58]. The melt-extrude cycle degrades physical properties. Regenerating and purifying nylon-6 waste does better at maintaining FDM filament material properties [59,60].

Table 2. Material properties of extruded and recycled plastics (ABS, PLA, Nylon-6).

Material	Yield tensile strength [MPa]	Young's modulus [GPa]	Melting temperature [°C]	Source
ABS, extruded	13.0–65.0	1.00–2.65	177–320	[61–64]
ABS, recycled	32	2.125	177–320	[65]
PLA, extruded	30	2.3	205	[65,66]
Nylon-6, extruded	35.0–186	0.450–3.50	205	[65,66]
Nylon-6, recycled	55.79–86.91	1.64	205	[65, 66]

4.1.2. Biodegradable plastics for extrusion-based 3DP

Biodegradable plastics degrade naturally due to their composition. Photodegradation, thermal-oxidative degradation, and microorganism metabolization of polymer chains are enabled by the sun's UV light [67]. Degradation depends on material structure, chemical composition, and environment [68]. AM made from biodegradable materials reduces waste and avoids landfills. Composting these materials reduces landfill volumes [69].

PET, HIPS, PLA, PHA, and PVA are biodegradable polymers used in FDM. While PET is recyclable, some bacteria can biodegrade it [70]. Due to its high impact resistance, HIPS may warp when printed and be degraded by certain bacteria [71]. PLA is biodegradable and made from plant starch. Another bioplastic, PHA, is produced by microorganisms and has petroleum-like properties. Water-soluble, petroleum-based PVA is biodegradable and recyclable [72]. Table 3 lists the tensile strengths and melting temperatures of the mentioned materials.

Table 3. Material properties of biodegradable polymers (PET, HIPS, PLA, PHA, PVA) for FDM.

Material	Yield tensile strength [MPa]	Young's modulus [GPa]	Melting temperature [°C]	Source
PET	45.0–90.0	0.107–5.20	120–295	[73,74]
HIPS	26		140–295	[75]
PLA	8.00–103	1.97	220–240	[74]
PLA, recycled once	51	0.050–13.8	-	[75]
PLA, recycled five times	48.8	3.093 plus/minus 0.194	-	[76]
PHA	15–40	3.491 plus/minus 0.098	1.0–2.0	[76,77]

Extrusion-based 3D printing uses thermoplastics, but recycling them requires energy and degrades their properties. Some plastics take at least 50 years to biodegrade, depending on conditions (aerobic or anaerobic). Aerobic bacteria decompose plastic into carbon dioxide and water using oxygen [78–80]. Respiration and fermentation can occur anaerobically [78,80].

4.1.3. Modified plastic filaments

To make greener FDM feedstock, companies are developing filaments from biodegradable plastics and biomass-based fillers (Table 4). To mimic wood, these bio composite filaments contain up to 40% biomass-based fillers like bamboo, pine, birch, or olive wood fibers [81]. This innovation could lead to more sustainable AM materials.

Table 4. Biodegradable and biomass-based filament compositions for greener FDM feedstock.

Material composition	Filament diameter [mm]	Extrusion temperature [°C]	Source
PLA/lignin (5–15 wt%)	1.78 plus/minus 0.04	205	[82]
PLA/PHA/recycled wood fibers (10–20 wt%)	2.85 plus/minus 0.1	210	[83]
PLA/wood flour (5 wt%)	1.75	210	[81]
PLA/cellulose fiber (0–20%)	2.85	210	[84]
PVA/cellulose nanocrystals (2–10 wt%)	1.7		[85]
PCL/cocoa shell waste (0–50%)	1.75	120	[86]

4.1.4. Cellulose materials for extrusion-based 3DP

Extrusion-based 3D printing (3DP) materials' environmental impacts are crucial to the sustainability of this additive manufacturing (AM) process. Cellulose materials are a cost-effective and eco-sustainable alternative. Cellulose, the most abundant renewable biopolymer in plant cell walls and a structural component, has promise. Due to their tendency to decompose at high temperatures and swell in narrow-diameter nozzles, unmodified cellulose materials are not suitable for extrusion-based 3DP [87,88]. Table 5 lists feedstock cellulose-based materials. Tenhunen et al. investigated rigid cellulose acetate and flexible acetoxypropyl with acetic acid and acetone for textile applications. The branched structure of acetoxypropyl cellulose reduced adhesive properties, making it a promising material for textile customization and functionalization [89]. Henke and Treml tested spruce chips, similar to those used in particle boards, with various binders. Their 3DP process involved depositing a dry mixture of bulk and binder, then adding water as an activator for material solidification [90]. Kariz et al. used a piston to extrude two beech wood powder feedstocks with different adhesives (polyvinyl acetate and urea formaldehyde). This process took 2 hours to solidify on a heated bed at 80 °C and then another 2 weeks to cure, longer than conventional AM methods [91]. Rosenthal et al. also studied the liquid deposition of a paste-like suspension of ground beech sawdust and methyl cellulose, a lubricant and binding agent. Despite poor mechanical properties, the authors created an extrudable feedstock of 89% sawdust [92].

Table 5. Cellulose-based feedstock materials and solidification methods for 3DP applications.

Material composition	Method of solidification	Printer used	Source
Cellulose acetate/acetic acid (30/70)	Solvent Evaporation	3DN-300, 20–41 psi pressure	[89]
Acetoxypropyl cellulose/acetone (80/20)	Solvent Evaporation	3DN-300, 20–41 psi pressure	[89]
Spruce wooden chips/binding agents	Aerosolized water as an activator	Homemade Delta 3D printer	[91]
(methyl cellulose, gypsum, sodium silicate, cement)	-	-	-
Beech wood powder/PVAc (17.5/82.5, 20/80)	Drying (80 °C, 2 h)	Homemade Delta 3D printer	[91]
Beech wood powder/UF (15/85, 17.5/82.5)	Drying (80 °C, 2 h)	Homemade Delta 3D printer	[91]
Ground beech sawdust/ methyl cellulose (90/10)	Drying (60 °C, 5 days)	Cartesian 3D printer	[92]

4.2. Material choice analysis

Below is a flowchart depicting the names of the nine sustainable 3D printing techniques. Each node in the flowchart in Figure 2 represents one of these techniques, providing a quick visual reference.

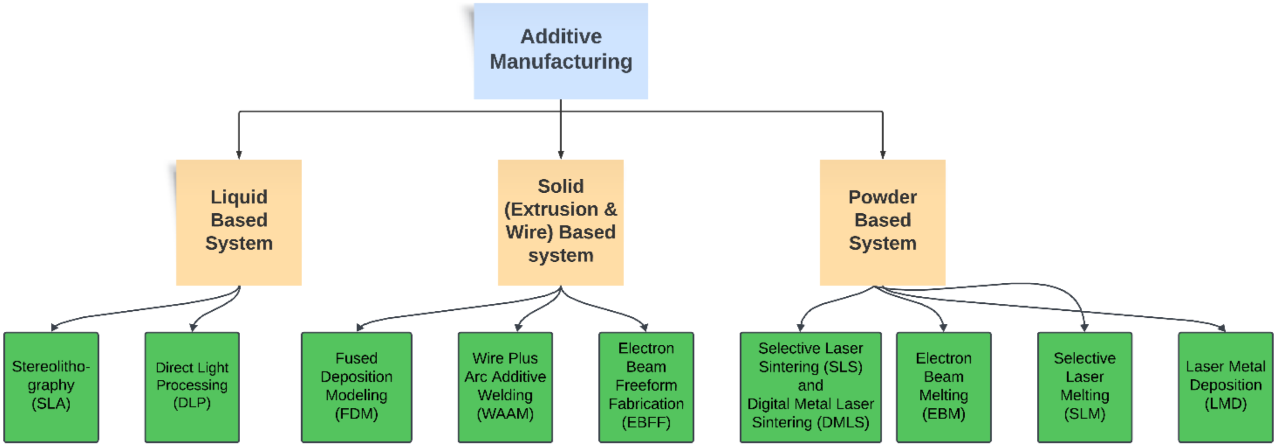

Figure 2. Common sustainable additive manufacturing techniques.

Following the flowchart, a detailed Table 6 presents a comprehensive comparison of these methods based on material efficiency, energy efficiency, and waste generation. This data will help readers gain a deeper understanding of the sustainability aspects associated with each 3D printing technique.

Table 6. Comprehensive comparison of material efficiency, energy efficiency, and waste generation for 3D printing techniques.

3D printing process	Material efficiency	Energy efficiency	Waste generation	Comments	Source
FDM	Moderate, depends on material	Energy-efficient, heats material during printing	Low	Sustainability depends on material choice.	[93]
Wire plus arc additive manufacturing (WAAM)	Moderate, improved with recycled wire feedstock	Energy-efficient, relies on arc welding technology	Moderate	Recycled wire feedstock can enhance sustainability.	[94]
Electron beam freeform fabrication (EBFF)	High, used in aerospace applications	Energy-efficient with electron beams	Low	Highly material-efficient, especially for aerospace applications.	[95,96]
Stereolithography (SLA)	Low, improvements with resin recycling	Energy-efficient, uses UV light for photopolymerization	Moderate	Sustainability can be enhanced through resin recycling.	[97]
Direct light processing (DLP)	Low, sustainability through material selection	Energy-efficient, utilizes UV light for curing	Moderate	Material choice and waste reduction are critical for sustainability.	[97]

Continued on next page

3D printing process	Material efficiency	Energy efficiency	Waste generation	Comments	Source
Selective laser sintering (SLS) and digital metal laser sintering (DMLS)	High, highly sustainable for metal parts	Energy-efficient, laser selectively fuses metal powder	Low	Highly sustainable for metal components.	[97]
Electron beam melting (EBM)	High, suitable for aerospace and medical applications	Energy-efficient, electron beams consume less energy	Low	Sustainable for aerospace and medical applications.	[98,99]
Selective laser melting (SLM)	High, sustainable for metal parts	Energy-efficient, uses laser to selectively melt metal powder	Low	Sustainable for metal parts with high material efficiency.	[100]
Laser metal deposition (LMD)	Moderate, sustainable for repair and feature addition	Energy efficiency depends on application and power settings	Low	Suitable for repair and feature addition applications.	[101]

4.3. Applications

Figure 3 depicts how 3D printing transforms manufacturing, changing its environmental impact throughout the product life cycle and promoting sustainability. Since additive manufacturing builds products layer by layer without cutting or reshaping, it uses fewer resources and produces less waste. Support structures are usually removed after production and reused in most 3D printing methods, causing few material losses [102]. The manufacturing process is shorter and more direct with 3D printing, reducing energy consumption and CO_2 emissions [102]. Technology that allows on-site production could reduce shipping-related carbon emissions. 3D printing has the potential to reduce industrial net CO_2 emissions and energy use, but it must be implemented in mass production, production speed improved, and printable materials made more accessible. Considering a ‘rebound effect' where efficiency increases activity is also important [102,103]. Some 3D printing methods such as laser metal deposition, are better for material reuse than others, like FDM, which uses less energy but produces emissions [104–107].

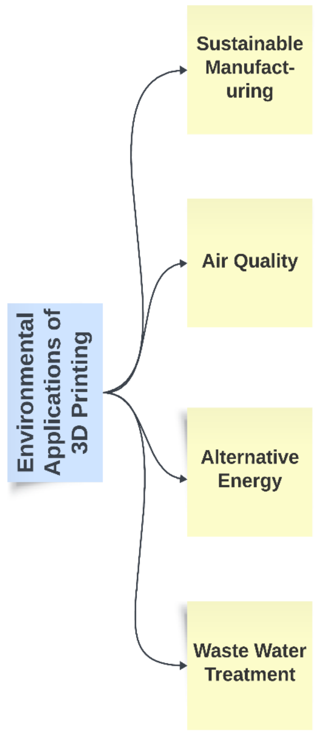

Figure 3. 3D printing applications for sustainable environment.

4.3.1. Air quality monitoring

3D printing is used to make air quality monitors. Salamone et al. 3D-printed nEMoS, a nano environmental monitoring system that measures indoor air quality. Cheap and reliable, nEMoS reports CO_2 concentration and other environmental parameters [108]. The customization capabilities of 3D printing have helped create casings for other air quality monitors like iAir for indoor air quality and HOPE for outdoor air quality [109,110]. Wang et al. created a small, portable wearable particulate matter monitor using 3D printing, advancing miniaturized sensors [111]. Pollutant filters and scrubbers are 3D printed. A flexible air filter with a photocatalyst by Xu et al. removes NO from the air [112]. Additionally, 3D printing has enabled unique geometry in scrubber components like the Vortecone scrubber's circular channel [113].

4.3.2. Water and wastewater treatment

Advanced 3D printing technology has enabled new water and wastewater treatment methods. The customization capabilities of 3D printing could lead to cheaper membranes, a cost-effective and efficient alternative to conventional methods [114,115]. 3D printing is ideal for ceramic membrane-based treatment materials [116], but it struggles to print structures below submicron resolution and material compatibility [115,117]. 3D-printed ceramic water filters and oil-water separation meshes have been studied [118,119]. Super hydrophilic membranes and air filters can be 3D printed to improve pollutant removal [120].

4.3.3. Alternative energy sources

3D-printed microbial fuel cells, wind turbine blades, and photovoltaic (PV) cells are being tested in renewable energy technologies. Microbial fuel cells, which generate power and oxidize organic pollutants in wastewater, benefit from 3D printed anodes that have better microbial adhesion and area [121,122]. Flexible solar cells are printed on metal foils and translucent plastics using 3D printing. This technology also creates ultra-thin microcell arrays with flexible front electrodes that perform similarly to solar cells [123]. Since their geometries can be optimized, 3D-printed photovoltaic cells have higher energy densities than flat, stationary panels [123,124]. Researchers have used 3D printing to create turbine blades that mimic plant leaves and self-heating mesh for blade de-icing [125,126]. Small, affordable residential wind turbines can be built using 3D printing, providing a sustainable power source [127–129].

5. Limitations

In the pursuit of sustainable manufacturing practices, the integration of biodegradable materials within FDM 3D printing processes presents several challenges that impact both structural integrity and environmental goals.

5.1. Fused filament fabrication parameter adjustments for sustainable 3D printing

- Achieving accurate printing with biodegradable materials necessitates meticulous parameter adjustments and printer configurations tailored to the specific characteristics of each material [130].
- The diverse melting points, moisture contents, and compositional variations inherent in biodegradable polymers complicate the standardization of printing parameters, demanding continuous calibration for optimal results.
- Factors such as extrusion temperature, printing speed, nozzle diameter, and filament quality significantly influence the printing outcome, adding complexity to the process and potentially reducing efficiency.

5.2. Void formation and mechanical weakness

- The layer-by-layer construction inherent in FDM 3D printing introduces voids and inconsistencies between layers, compromising the mechanical strength and durability of printed objects.
- These voids act as stress concentration points, diminishing fracture toughness and overall structural integrity [131].
- The challenges associated with void formation stem from suboptimal extrusion parameters, inaccurate temperature settings, filament quality issues, and inadequate bed adhesion, among others.
- Despite efforts to mitigate void formation through parameter adjustments, achieving uniform mechanical properties across different biodegradable materials remains elusive due to their varied material characteristics.

5.3. Brittleness and limited performance of biodegradable materials

- Biocomposite filaments composed of biodegradable materials exhibit increased brittleness and limited heat resistance compared to traditional non-biodegradable materials [132].
- Uneven fiber distribution within the polymer matrix exacerbates microvoid formation, further compromising material strength and longevity.
- These limitations, coupled with accelerated moisture deterioration and high production costs, pose significant challenges to the widespread adoption of biodegradable materials in FDM 3D printing applications.
- The performance gap between biodegradable and non-biodegradable materials underscores the need for ongoing research and innovation to enhance the mechanical properties and processing capabilities of sustainable printing materials.

6. Conclusions

While the integration of biodegradable materials in FDM 3D printing holds promise for advancing sustainability objectives, inherent complexities pose significant hurdles to achieving desired structural quality and functional performance. Addressing these limitations requires a multifaceted approach, including the development of standardized printing parameters, advancements in material science, and continued innovation in additive manufacturing technologies. By acknowledging and addressing these challenges, researchers and industry stakeholders can pave the way for the widespread adoption of sustainable 3D printing practices in diverse application domains.

7. Future recommendations:

- Explore novel materials and formulations to improve mechanical properties and reduce brittleness.
- Develop standardized printing parameters and configurations for diverse biodegradable materials to enhance printing accuracy and efficiency.
- Investigate advanced bonding techniques and infill strategies to minimize void formation and enhance structural integrity.
- Foster collaborations between academia, industry, and regulatory bodies to drive innovation and address sustainability challenges in 3D printing technologies.

Use of AI tools declaration

The authors declare they have not used artificial intelligence (AI) tools in the creation of this article.

Conflict of interest

The authors declare no conflicts of interest.

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