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Sustainable design approaches for thermoplastics in additive manufacturing

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ABSTRACT: Additive manufacturing is enabling on-demand fabrication of desirable polymer designs. Due to the technology's widespread use, there is a need to ensure sustainable design approaches are practiced. Here, thermoplastics for fused deposition modeling is reviewed for life-cycle stages, mechanical properties, and design strategies. Life-cycle stages assessed include formulation, processing, applications, and end-of-life as well as recycling processes. Mechanical properties are considered for recyclable thermoplastics, with fillers to enhance functionality. Finally, design methods are considered to create mechanically efficient designs, such as metamaterials, that reduce material usage and processing time. The review highlights the great potential for creating sustainable designs with additively manufactured polymers, and their mechanical capabilities for broad applications.

KEYWORDS: additive manufacturing, sustainability, 3D printing, life-cycle, polymers

1. Introduction

As product design techniques continue to expand, so must the design for sustainability of materials. Design for sustainability of plastics in additive manufacturing is critical, given their widespread use and environmental impact. Here, we investigate the potential of using recycled plastics in additively manufactured parts while maintaining or increasing mechanical properties. Plastics are widely recognized for their versatility in manufacturing everyday items such as water bottles, product packaging, trash cans, dinnerware, and many others (Evode, Qamar et al. 2021). Given their multiple applications, there are also many different types of plastics, including acrylic, polyethylene, and acrylonitrile-butadiene-styrene (Group 2019). However, when examining the life cycle of plastics, there are numerous opportunities for improving their sustainability. Without recycling, many plastic products end up as waste in landfills, contributing to further environmental waste. Although efforts have been made to reduce this impact—such as the adoption of paper straws, reusable plastic grocery bags, and separate waste bins for metal, paper, and plastic—these actions merely slow the accumulation of plastic waste. A more effective solution to extend the life of plastics is to integrate them into products and prototypes repeatedly, which could be achieved through additive manufacturing.

Additive manufacturing, also commonly known as 3D printing, is revolutionizing the materials and fabrication industry. As the name suggests, additive manufacturing involves creating 3D objects through a layer-by-layer process, slowly building each designed part with capabilities for high accuracy and complex geometries. There are various types of 3D printing, with fused deposition modeling (FDM) being among the most prominent for its capabilities for printing polymers through melt extrusion processes, such as recyclable thermoplastics. Thermoplastics are polymers with a simple molecular structure with chemically independent macromolecules that do not permanently crosslink. These traits allow for ease of melting and reforming several times without sacrificing mechanical/chemical strengths, making them a strong candidate for FDM printing (Biron 2018). In FDM printing, the polymer filament is heated until it melts, and then, using computer-aided design (CAD) modeling, the nozzle is directed to deposit the liquid polymer layer by layer onto a print bed as it recreates the digital design model layer by layer (McCarthy and Brabazon 2021). FDM printers deposit materials according to different structures and infill patterns to form mechanically functional parts.

Mechanical parts often wear out and need replacements, therefore when designing mechanical parts, it is essential to consider their sustainable impact. Sustainability can refer to environmental, economic, and social impacts all of which FDM printing can influence through its materials lifecycle, low cost, and availability of non-toxic materials for users. Environmental sustainability is a key focus area since it uses polymer materials that, when discarded after use, can have negative impacts. However, recycling these materials can create a more circular economy for materials use. The cost-effectiveness of recycling is a challenge to ensure sustainable materials remain competitive—if recycling processes are not efficient, consumers may not adopt the process. These factors can be considered through the context of design to determine approaches to improve sustainability and mechanics of polymers to increase their adoption through additive manufacturing, with a focus on FDM as an initial feasible technology. Key considerations for these design factors are summarized in Figure 1.

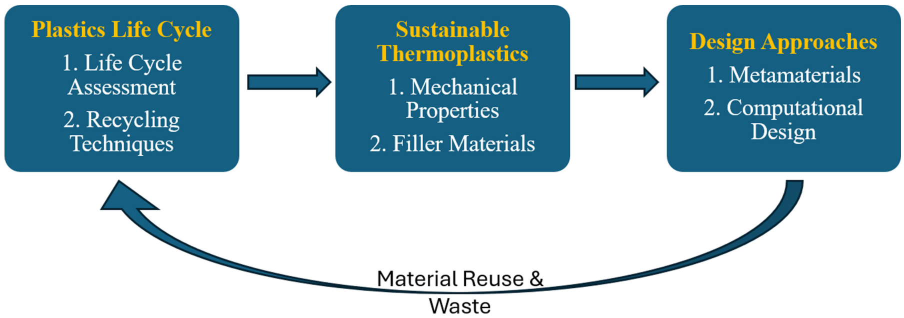

Figure 1. Key areas considered for sustainable additive manufacturing for mechanical design

The three areas in Figure 1 are all connected through the sustainability approach for design. When deciding which parts to discuss regarding thermoplastic use in FDM printing, specific topics informed by the literature review were targeted to address knowledge gaps. With regards to motivation, the issue of plastic waste in landfills globally is reviewed that leads to a need to consider both life cycle assessment and recycling techniques. For development, design specifications need to be analyzed and met so that the recycling methods are not a waste, thus leading to determining plastic material properties and how they might alter mechanics with the integration of filler materials (Cash, Daalhuizen, & Hekkert, 2023). The need to enhance the mechanics of designs extends further to the use of metamaterials. Metamaterial design enhances the mechanical efficiency of polymer materials by engineering repeating patterns of unit cells to lattices that are further improved through computational design.

Figure 1 highlights the plastics lifecycle, sustainable thermoplastic material properties, and design approaches as key areas affecting the adoption and use of FDM printed sustainable polymers, which will guide this paper's review and discussion of the current state of the art. Firstly, the plastic material life cycle is covered, starting with the polymer life cycle assessment. When considering material life cycle, a birth to grave approach is reviewed in the context of polymers for additive manufacturing. Afterwards, recycling techniques are discussed in detail, including mechanical, chemical, and biological processes. Then, the strategy of integrating recycled plastics and other materials into the original monomers, called fillers, are considered to enhance the mechanics and usability of materials in new material cycles. Next, the mechanical properties of polymers are examined to ensure design requirements are met and to determine the purpose of using polymers for additive manufacturing. These mechanical properties are discussed by highlighting the advantages of filler materials to enhance functionality. Finally, design approaches of the polymers are considered by forming polymers in mechanically efficient metamaterial structures, and considering computational design approaches to optimize the use of materials within those structures. Metamaterials enhance design sustainability by decreasing production time and material usage through a product's lifecycle.

This review uses Figure 1 areas to highlight key research considerations for designers to beneficially use sustainable polymers with additive manufacturing technologies to reduce environmental impacts. Contributions from the paper are a highlight of relevant literature to reveal design approaches, mechanical properties of materials, and promising research areas. Practically, research in this area can reduce the impact of polymers on the environment as they are recycled with emerging design tools to ensure they maintain functionality and mechanics. Upon completion of the review, key findings will highlight areas for design researchers to pursue to better leverage emerging additive manufacturing technologies while sustainably solving mechanical design problems across application areas. The literature gathered for this paper was conducted by considering sustainable methods to determine design specifications and recycling techniques to ensure a circular economy for thermoplastics.

2. Material life cycle

2.1. Life cycle assessment

A lifecycle assessment informs designers of key stages in the formation, use, and end of service for materials that can affect environmental impact. Assessing the sustainability for materials at each stage can aid designers in effectively fabricating and specifying the use for products. For polymers in additive manufacturing using FDM, a cradle to grave assessment is reviewed with an emphasis on recycling the material, as highlighted in Figure 2. The cradle to grave assessment includes the main steps of: Polymer Design & Formulation, Processing of Polymers, Applications in Products, and End-of-life of Products. During the End-of-life of Products, recycling techniques are examined to enhance sustainability (Guarda, Caseiro et al. 2024).

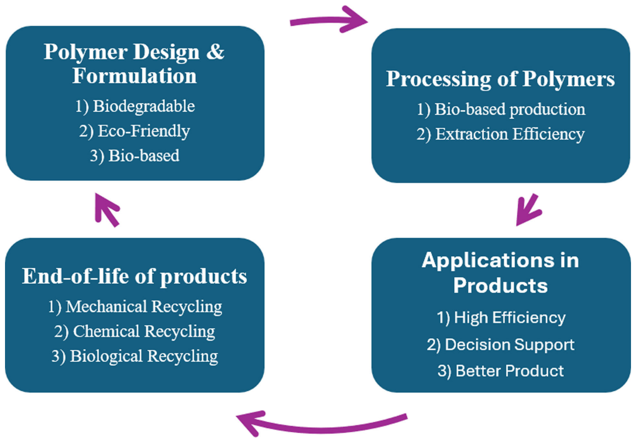

Figure 2. Sustainable polymer life-cycle

The first important part of developing a sustainable life cycle for polymers is the creation or formulation of the original monomers. These monomers may be selected from materials by considering the following qualities: Biodegradable, Eco-Friendly, and Bio-based (Guarda, Caseiro et al. 2024). Biodegradable refers to materials that are decomposed by bacteria or other living organisms (Gadhave, Das et al. 2018). Examples include polylactic acid (PLA), polymers based on polyhydroxyalkanoates (PHA's), and polymers based on starch, such as high glucose units mixed with common polymers (i.e. PLA and PHAs) (Sharma 2021). Polymers that are eco-friendly are those that produce the least number of emissions during development and are, as previously mentioned, typically biodegradable as well. Biodegradable polymers are possible to compost or decompose without harming the environment. Bio-based polymers are constructed from partial or complete organic materials. These first steps are crucial to consider to ensure that designs made through additive manufacturing are capable of being recycled, as products made from organic materials are often recyclable.

The next step of the life cycle is the processing of polymers with polymerization. The two main aspects of this step include the bio-based production and extraction efficiency of the processed polymers. Bio-based production can form bioplastics. Bioplastics provide an eco-friendly approach for manufacturing when compared to conventional manufacturing of plastics using fossil fuels. Bioplastic are favorable because they can reduce greenhouse gas emissions throughout processing steps (Islam, Xayachak et al. 2024). Along with bio-based production, there needs to be high extraction efficiency. Extraction efficiency for polymers refers to the percentage of the additive material that is successfully removed from a polymer sample using a solvent extraction technique. To successfully extract a high percentage of the polymers from a solvent, temperature and pressure are vital. Temperature must increase to decrease the solvent viscosity and surface tension, allowing for easier flow into the polymer matrix design. However, at elevated temperatures, the solute will begin to boil and evaporate. To counter this effect, pressure is increased and, simultaneously, the boiling temperature is increased (Kettle 2008). An example of this extraction technique for starch-based PLA is a hybrid technique of dry and wet milling. This process, which involves first the grinding down the bio-based materials into much smaller sizes and then soaking them in water and diluted sulfuric acid, allows the user to extract the starch from the raw materials to integrate into the PLA materials and create the final polymer. The more starch that can be extracted, the higher the extraction efficiency becomes, creating a more bio-based product in the design process (Singh, Pandey et al. 2024), which overall increases the sustainability of the material.

The third part of the life cycle is the distribution of polymer-based product designs to consumers. High efficiency in this step ensures the product is transported to distribution centers seamlessly and that each product performs as intended. Since the polymer-based products are fabricated using additive manufacturing processes, on-site fabrication can reduce the need for transportation as each product is produced locally without the need of transport from fabrication centers to distribution centers. On-site manufacturing decreases not only time required, but also energy and carbon emissions for transportation, ultimately saving money. Product applications can also have their own loop when considering decision support and better products. This is accomplished by using data and other statistics regarding the public's and designer's view of the new product, allowing the manufacturing company to make informed decisions on how to make the products in question better with each iteration of the prototypes. The data collected, however, can be complex since it can come from several different sources including market demand, designers' preferences, design alternatives, and even uncertainties (Besharati, Azarm et al. 2006). Therefore, it is vital for designers to isolate each step in the life-cycle assessment process to optimize stages to create an overall more sustainable product.

The last step of life-cycle assessment deals directly with the end of life for bio-based polymer waste, with recycling being an environmentally friendly option. Three different recycling techniques are commonly used for polymeric materials. These techniques include mechanical, chemical, and biological, and are used to depolymerize the polymeric materials back into their respective monomers. After depolymerization, the monomers are examined closely and purified to remove any contaminants or byproducts that may have developed in the waste material that could hinder the polymerization of the recycled monomers. All of these techniques are critical for designers to consider when finding the best environmental strategy for using polymer materials in additive manufacturing.

2.2. Recycling techniques

The three different recycling techniques, mechanical, chemical, and biological, all require consideration for how they influence the sustainability and functionality of materials for additive manufacturing. The following techniques have been adopted for bio-based polymeric waste (Briassoulis, Pikasi et al. 2021). Mechanical recycling involves the retrieving of polymeric waste, both contaminants and plastics. Then, mechanical separation, typically completed through written programs in machines, is completed, removing the non-recyclable foreign bodies from the recyclable plastics. After this separation, the remaining plastics are shredded down to fine flakes, which are washed and dried to further remove any remaining contaminants. Then, the flakes are sorted again to ensure that flakes of different densities are not mixed together as this can cause an issue down the line when repolymerization takes place. All of these types of separation methods are assisted using techniques such as color differences, near-infrared, fine sieving, etc. The flakes are then melted down to form pellets of the recycled plastic, ready for repolymerization. Using mechanical recycling, a plastic's mechanical properties can increase. For example, a study shows the results of a tensile test using blended waste thermoplastic polyurethane (T) and polypropylene (P). With these materials blended at a ratio of 90T:10P and extruded into a dog bone shape, the mixture provided an increase in tensile strain at break to 144.1% from 4.3% compared to homogenous polypropylene (Lin, Lin, & Bao, 2020). In this sense, mechanical recycling operates by physically altering polymeric materials, allowing for further refinement in the creation of materials.

Chemical recycling is the process of transforming bio-based plastic waste products into lower molecular weight products via chemical reactions, which can be referred to as waste-to-chemical techniques. Some examples of this process are hydrolysis and glycolysis. Glycolysis is a string of reactions to degrade polyester by glycol by hydrolysis. Hydrolysis is a reaction of functional groups of ester, PLA, and PET conducted in an acidic, alkaline, or neutral medium at a high temperature and pressure. Overall, chemical

recycling is an efficient alternative for recycling plastic waste and reducing greenhouse gases, thus promoting a circular economy (Siddiqui, Redhwi et al. 2021). Using dissolution, a special type of hydrolysis, the impurities and additives are removed from the waste polymer leaving behind the remaining polymer to reuse as needed. One study has shown that some plastics are recovered up to almost 98% using dissolution. (Meyer zu Reckendorf, Sahki, Perrin, Lacoste, Bergeret, Ohayon, & Morand, 2022). The main approach of chemical recycling is to alter the material by means of adding and removing chemicals to breakdown polymers and enable the construction of new materials.
Biological recycling focuses mainly on degrading polymers through enzymatic action of microorganisms (e.g. Myxomatosis genus bacillaceae and Pseudomonadaceae) with the integration of UV radiation to quicken the process. The microbial consumption of the waste plastics leaves behind chain fragmentation of the polymer into monomers, followed by mineralization through aerobic or anaerobic degradation (Kumar, Sadeghi et al. 2023). Biological recycling largely deals with organic matter and processes which is highly sustainable, but is difficult for designers to setup to efficiently process materials at scale. Overall, selecting recycling processes relies on considering trade-offs in accessibility of resources, how much energy is required to transform materials from one state to another, and how the process affects the final mechanics of polymer parts.

3. Polymer mechanics

3.1. Material properties

For design applications, material properties are a critical initial step for determining mechanical functionality and processing details. Properties such as density, tensile strength, elongation at yield, elastic modulus, melting point, and acceptable printing speed are considered when choosing materials for additive manufacturing. Density of parts is highly coupled to weight and mechanical performance of final parts. Yield tensile strength, elongation at yield, and elastic modulus dictate how a material reacts to load and fails. Melting point determines how high the nozzle temperature is required to properly liquify the polymer. Finally, printing speed changes can alter mechanical strengths after printing as a material is processed. For additive manufacturing purposes for polymers, polylactic acid (PLA), polyethylene terephthalate (PET), polyethylene terephthalate glycol (PETG), polyamide/nylon 12, high-density polyethylene (HDPE), and acrylonitrile butadiene styrene (ABS) are all common materials used for mechanical design applications. The materials listed are all thermoplastics for FDM printing, recyclable, and can have filler materials integrated into the extrusion process to enhance their properties and are summarized in Table 1 (MatWeb 2024).

Table 1. Mechanical and printing properties of commonly extruded thermoplastics

Polymer	Density ($\frac{g}{cm^3}$)	Tensile Strength (MPa)	Elongation at Yield (%)	Elastic Modulus (GPa)	Melting Point (°C)	Printing Speed ($\frac{mm}{s}$)	Source
PLA	1.00-3.41	8.00-103	1.00-4.00	1.00-13.8	64-220	40-50	(Ansari and Kamil 2021)
PET	1.12-1.47	34.0-108	2.00-86.0	1.16-7.65	220-280	50-100	(McClements 2024)
PETG	1.18-1.37	28.3-101	2.70-575	1.10-20.3	160-293	20-60	(Loskot, Jezbera et al. 2023)
PA12 (Nylon 12)	1.00-1.12	20.0-76.0	50.0-400	0.332-2.23	171-180	20-30	(Myshechkin and Lim 2023)
HDPE	0.93-1.27	2.69-60.7	5.00-14.0	0.483-1.75	26-135	25-150	(Schirmeister, Hees et al. 2019)
ABS	1.01-1.20	13.0-65.0	2.00-30.0	1.00-2.65	170-320	30-70	(Rezaeian, Ayatollahi et al. 2022)

The property that ties material properties to processing is the range of valid printing speeds for the material that can alter the values of mechanical strengths. The tensile strength, in particular, is affected as the printing speed and extrusion temperature changes (Ansari and Kamil 2021). Print speeds of 40 mm/s and 50 mm/s were tested with extrusion temperatures of 190, 210, and 230 degrees Celsius. Results showed that, as both print speed and extrusion temperature increase, so does the tensile strength of PLA materials. A similar study with ABS material showed effects on elongation, ductility, and tensile strength by changing solely the printing speed (Rezaeian, Ayatollahi et al. 2022). Results showed that the elongation and ductility increased with the printing speed while the maximum ultimate tensile strength was inversely related to the printing speed. These findings demonstrate that the processing of materials, in addition to their molecular makeup affect mechanical properties. Thereby the recycling process and manufacturing process require careful consideration to ensure recycled materials function as intended in their end products.

3.2. Filler materials

Design optimization relies heavily on reducing material costs while maximizing material strengths during fabrication processes. Strategies such as adding fillers to recyclable thermoplastics can maintain or increase mechanical properties through processes such as melt intercalation, solution blending, and in-situ polymerization (Arora, Dua, Singh, Singh, & Senthilkumar, 2024). By using filler materials, the lifetime of thermoplastics can significantly increase. Filler materials are a cost-effective way of integrating waste thermoplastics with either natural resources or other waste products (Mazzanti, Malagutti, & Mollica, 2019). Specifically, for FDM printing, when returning previously used polymers back into their original monomers, filler materials can be mixed into monomers after extracting contaminants. There are numerous studies that demonstrate the benefits of fillers, for instance when extruded into the polymer and mechanically tested, fillers can improve mechanical properties such as elastic modulus, tensile strength, and elongation (Müller, Šleger et al. 2022; Al Rashid & Koç, 2023; Seno Flores et al., 2024; Vidakis et al., 2021; Veley, Ugwumadu, Trembly, Drabold, & Al-Majali, 2023; Abdelhaleem, Abdellah, Fathi, & Dewidar, 2016). By using fillers strategically, designers can fine-tune materials for specified mechanical properties while mitigating environmental impact.

PLA is one of the most cost-effective thermoplastic options and can often have natural fibers used as a filler material. PLA has a wide utility for medical uses due to its biodegradable and biocompatible characteristics. Different filler materials for PLA include cork and even further modified PLA (Arockiam et al., 2022; Müller et al., 2022). A 50:50 blend of virgin PLA (vPLA) material mixed with post-consumer (recycled) PLA (PC-PLA or rPLA) showed to have a tensile strength less than vPLA, but greater than rPLA. The increase in mechanical properties from the rPLA to the 50:50 blend was due to the 50:50 blend having a better interlayer adhesion. It was also determined that a higher nozzle temperature for the blend and a larger layer height during printing was the reason for a better interlayer adhesion (Al Rashid & Koç, 2023). vPLA can also be mixed with cork and shows about a 50% decrease in tensile strength, but a 45% increase in elongation at yield due to an increase in ductility (Müller et al., 2022), which demonstrates its versatility for design applications.

PET and PETG are both non-biodegradable thermoplastics. Since both of these are not bio-based polymers, a filler material can simply be made out of itself through recycling both thermoplastics, for instance by recycling face shields no longer used for protection. After three recycling cycles, the elasticity, tensile strength, and further mechanical properties may decrease rapidly (Seno Flores et al., 2024), which suggests further materials and recycling options should be considered if more cycles are desired for use.

PA12 is a tough, semi-crystalline polymers with low glass transition temperature. This allows for ease of processability, and strong impact strength. PA12 has been commonly used in the automobile parts as well as in the textile industry and fabrics due to its strong mechanical properties. Similar to PET/PETG, PA12 can often be recycled back into itself, by mixing different percentages of virgin PA12 (vPA12) and recycled PA12 (rPA12). In doing so, there is an increase in both elastic modulus and tensile strength reported through 4 cycles of thermomechanical recycling processes. After the 4th cycle, these properties decreased steadily (Vidakis et al., 2021), which also suggests a need for designers to take care when recycling to consider how mechanical attributes of products may change.

HDPE is a high density plastic desirable for everyday products such as milk jugs, shampoo bottles, bleach bottles, cutting boards, and piping (Plastics 2021). Unfortunately, due to its high density, warping during the FDM fabrication process is common, thus making FDM printing for this plastic rarer than others. However, when mixed with coal polymer composites, this warping issue is mitigated greatly, allowing for a viable avenue to additively manufacture HDPE parts (Veley et al., 2023). Even though coal does not provide a significant increase in strength, this process provides a better design overall.

ABS is one of the most common printing materials (Peterson, 2019). With its high impact strength, excellent dimensional stability, and good surface qualities, this thermoplastic can be fabricated through FDM printing for a wide use in many industries including trucks, kitchens, bathrooms, electronics, and medical areas (Khledj et al., 2024). Similar to PLA, ABS can be mixed and extruded with natural fillers such as basalt fiber fillers. With 100% ABS, the tensile strength was recorded as 40.32 MPa. As basalt fiber fillers were added, from 5% to 10% to 15%, the tensile strength of the mixture increased to 40.48 to 44.44 to and 56.67 Mpa (Abdelhaleem et al., 2016). The increase in mechanical properties demonstrates the positive effect of fillers and provides new approaches for designers in enhancing materials for applications through consideration of processing techniques and mechanical requirements.

4. Design approaches

4.1. Metamaterials

Design approaches can enhance the sustainability of manufactured systems, by creating mechanically efficient metamaterials that reduce the volume of material necessary and fabrication time. Metamaterials are engineered structures possessing aggregate material properties based on the organization of their repeating structure, such as lattices constructed from unit cells (Egan, Bauer, Shea, & Ferguson, 2019). Metamaterials offer higher mechanical efficiency, which allows for a reduction in materials usage, therefore improving sustainability. Computational design enables the design of more mechanically efficient metamaterials. Reduced material usage and increased performance for metamaterial structures are particularly beneficial for products that require shipment, where weight reduction leads to lower energy consumption and emissions (Abozied, Osman, & Elmahdy, 2016). Metamaterials exhibit unique mechanical characteristics, making them versatile across diverse engineering applications (Saunders 2020), especially when considering functional mechanisms such as stimuli-responsiveness with potential for further research and development (Jiao, Mueller, Raney, Zheng, & Alavi, 2023). Demonstrated in Figure 3 is a multi-material honeycomb metamaterial (Khatri & Egan, 2023) that is possible to construct through FDM printing and combinations of recyclable thermoplastics.
The multi-material honeycombs in Figure 3B are constructed from a stiff ABS polymer surrounding a flexible TPU polymer band, enabling the TPU to deform under load initially in the system. With higher loads, the ABS has a much higher energy absorption at failure and stiffness to protect the system from damage, such as during crashes. By combining metamaterials synergistically it is possible to create overall longer-lasting sustainable systems with functionality, although there is a need for design methods to fully optimize metamaterials for specified applications due to their inherent complexity.

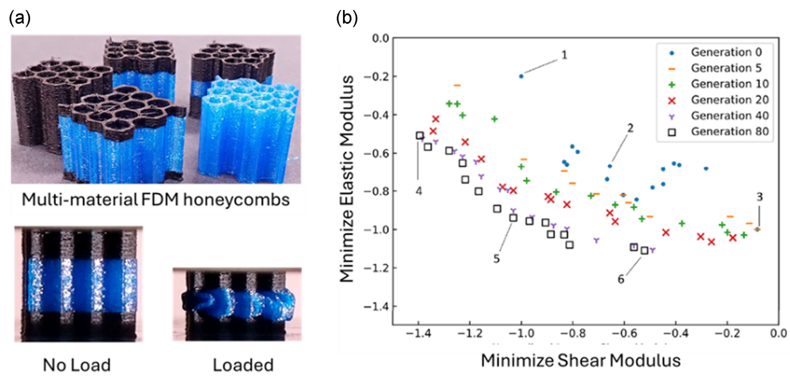

Figure 3. Design of efficient metamaterials demonstrating (A) Multi-material honeycombs with loading response and (B) Multi-objective mechanical design for complex lattices

4.2. Computational design

Computational design can enhance the functionality of metamaterials and the lifetime of designed products by optimizing their architected structure, thereby reducing resource uses and costs. Further, developing metamaterials with microstructural tunability allows for the creation of components with customized performance-enhancing functions (Pope, Roth et al. 2024). Using computational design and algorithms in combination with advanced modelling techniques, engineers can create geometry and material distributions that are impractical to achieve through traditional methods yet serve to enhance material properties and reduce material usage. In Figure 3B the results of a heuristic multi-objective search are demonstrated for metamaterials, where trade-offs in compression and shear response are navigated according to specific application needs through reorganization of unit cells in the metamaterial (Arefin et al., 2024). Heuristic design approaches are useful for metamaterial optimization due to metamaterial complexity and expensive objective functions that require evaluation with the aid of models such as finite element assessment.

Computational design approaches can optimize thermoplastic material placement through FDM printing technology. Advancements in FDM have enabled PLA's mechanical properties for effective topology optimization, mainly through techniques such as optimized infill patterns and layer-by-layer material distribution (Murrey, 2020). Computational design enables the configuration of infill densities and lattice structures with lightweight polymers that are tailorable for specified applications (Zhao et al., 2022). Computational design methods can also address material limitations in recycled thermoplastics. For instance, PLA's inherent brittleness can be mitigated in a system by strategic refinement of infill geometries and placement of load-bearing structures within the metamaterial. There is potential to enhance the performance of FDM metamaterials with novel optimization techniques (Gholipour, Shabgard, & Baraheni, 2024), and further emerging approaches in machine learning that can more directly redesign materials and structures for sustainability (Atasi, Kern, & Ramprasad, 2024; Blanco, Pauliks, Donati, Engberg, & Weber, 2024). By integrating advanced computational design and machine learning approaches with a materials and mechanics assessment of recyclable systems, there is great promise to use design methods to provide an overall improved sustainability to applications when considering the life-cycle as a whole.

5. Conclusions

This paper focused on materials lifecycle, mechanical properties, and design approaches to improve the sustainability of thermoplastics use in additive manufacturing applications. Each stage considered was found to have an important influence on final part sustainability and functioning. Each part discussed in the plastic life cycle is done with regards to making recycling more efficient that leads to a longer lifespan for each thermoplastic. Filler materials increase the lifespan of each thermoplastic as they ensure the functionality of recycled products meet design requirements. Metamaterials decrease the amount of material usage, leading to fewer polymer and filler materials required to extend the lifespan of the thermoplastics. When considering future design work, carefully chosen percentages of either natural or recycled polymers mixed with virgin polymers could be explored to optimize material strengths when compared to reusing the same polymer. Design approaches such as configuring materials to form metamaterial structures with enhanced mechanical efficiency or other desirable topologies can enable the use of less material for the same applications, thereby improving overall sustainability. As additive manufacturing continues to grow in use applications, it is essential for designers to begin considering and using sustainable design principles in selecting materials and configuring designs for varied mechanical applications. Recyclable thermoplastics offer a promising route forward with popular FDM technologies, where designers have many approaches to consider to optimize sustainability and performance. Future research can focus on further improving polymer sustainability, with great opportunities for achieving efficient material lifecycles that deliver high performance products constructed with additive practices.

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