

A Comparative Review of Mechanical Properties and Environmental Sustainability for Thermoplastics Processed by Fused Deposition Modeling and Selective Laser Sintering

Adithyan Sasikumar*, Dr. Navdeep Sharma Dugala**

*Research scholar, Department of Automobile Engineering, Chandigarh University, Mohali, India, adithyans3797@gmail.com

**Associate professor, Department of Automobile engineering, Chandigarh University, Mohali, India,
navdeepdugala@gmail.com

Abstract:

This paper presents a comparative review of Fused Deposition Modeling (FDM) and Selective Laser Sintering (SLS) for thermoplastic additive manufacturing, focusing on mechanical properties and environmental sustainability. FDM is valued for its affordability, ease of use, and wide material compatibility, but its mechanical performance is hindered by significant anisotropy. SLS, while more costly and energy-intensive, produces stronger and more isotropic parts suitable for functional applications. The review synthesizes recent research on tensile, flexural, and fatigue properties, as well as energy consumption, material efficiency, and waste generation. The findings underscore the need for application-specific process selection and further investigation into sustainable materials and long-term performance metrics. FDM and SLS both provide unique benefits that make them more complementary to each other, rather than rivals in the larger construct of additive manufacturing. Future progress in material science and process optimization are critical in addressing performance and reducing environmental impact for many others to come.

Keywords: Additive Manufacturing, Fused Deposition Modeling, Selective Laser Sintering, Thermoplastics, Mechanical Properties, Sustainability, 3D Printing, Lifecycle Assessment

I. Introduction

Additive Manufacturing (AM), often stated to as 3D printing, is a layer-by-layer fabrication process that enables the creation of complex parts directly from its virtual counterparts. Among the popular AM technologies, polymer based methods are leading and it has been reported that over 60% of the 3D printing research centers on polymers. FDM and SLS are two of the most widely used thermoplastic AM techniques. Fused Deposition Modeling (FDM) is done by extruding a continuous filament of thermoplastic through a heated nozzle and build the parts layer by layer. It is known for its convenience and the broad range of materials (from standard plastics like PLA and ABS to composites and experimental polymers) available. However, FDM parts typically display an anisotropic (different behavior in different directions) mechanical behavior due to the layer-wise deposition and inadequate inter-layer bonding [1], [2]. Selective Laser Sintering (SLS) on the other hand is a powder bed fusion process which was first developed in the 1980s, uses a powerful laser to melt the powdered thermoplastics and fused into solid layers. SLS can

produce near-isotropic parts with mechanical properties often potential to those of injection-molded thermoplastic parts [2]. It also offers greater design freedom as it doesn't require a support structure (since the surrounding powder itself provides support needed for the work during printing). Though, These advantages results in a higher cost of the equipment and material expense and more complex process control (e.g., maintaining a heated build chamber) [2].

Regardless of the extensive use of both FDM and SLS for thermoplastic manufacturing, the selection an optimal process for a given application necessitates careful consideration of their basic differences. This review involves a comparison of FDM and SLS in terms of working principles, feasible mechanical properties (tensile, flexural, impact, fatigue), and environmental sustainability (energy usage, material waste, and emissions). The goal of this review is to provide a crisp, up-to-date understanding of both the strengths, limitations, and suitable use cases, of these technologies, and thus the guiding material and process selection for sustainable additive manufacturing. The scope is limited to common thermoplastics (such as PLA, ABS for FDM

and PA12 for SLS) and draws on recent literature to highlight key findings and trends.

II. Process Fundamentals and Material Considerations

A. Fused Deposition Modeling (FDM)

The FDM process involves building the parts by melting and extruding thermoplastic filament through a nozzle, depositing the material layer by layer which consolidates upon cooling. The filament (typically 1.75 or 2.85 mm diameter) is driven by feed gears into the heated nozzle, where it is near melted and deposited onto a build platform following a programmed toolpath. Each new layer fuses on top of the previous layer as it cools. Figure 1 showcases a basic FDM setup, including the filament spool, drive motor, heated chamber/nozzle, and build platform. The simplicity of this mechanism motivates its popularity, but it also introduces distinct characteristics in the resulting parts. Key process parameters like layer thickness, nozzle temperature, speed of extrusion, raster orientation, and infill density has a strong influence on the part quality and mechanical performance [2], [4]. For instance, for an improved inter-layer bonding and strength thinner layers and higher nozzle temperatures are desired, while raster (road) orientation affects how loads are carried relative to filament deposition direction. A wide variety of thermoplastics are available as FDM filaments, including amorphous plastics like ABS and PLA, which print easily, as well as semi-crystalline polymers like nylon, PETG, or PEEK that require careful temperature control. Specialty filaments with fillers (carbon fiber, metal, wood, etc.) further extend the material palette. The microstructure of FDM parts is characterized by directional loads of material and inter-road gaps or pores; because each filament strand bonds to the one below it rather than forming a continuous solid. The highest strength is obtained in the plane of the layers, though it reduces significantly in the build (vertical) direction because of the weaker inter-layer bond [1]. Internal cavities between rasters can also reduce density and it may act as stress concentrators. These characteristics could make the FDM parts with lower tensile strength and impact toughness compared to fully dense molded parts of the same material [5]. However, FDM remains particularly convenient for rapid prototyping and custom or low-load applications. The ongoing improvements in process parameters and toolpath strategies focuses on avoiding anisotropy and

improve bonding [6]. Figure 1 shows a representation of the FDM process and highlights some of the critical parameters and orientations.

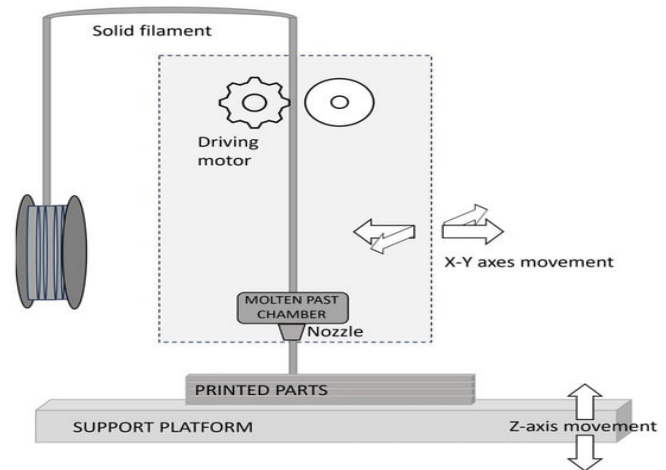


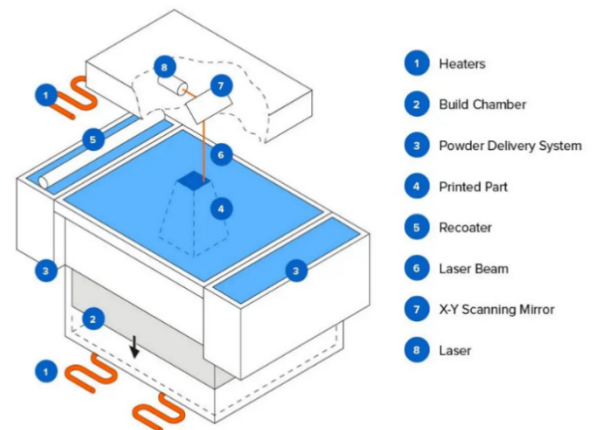
Fig 1. Schematic diagram of the FDM 3D printing process, showing a filament feedstock being driven into a heated chamber and nozzle to deposit material onto a build platform. The X–Y motion of the nozzle and incremental Z-axis movement of the platform create the layered part. [7].

B. Selective Laser Sintering (SLS)

The SLS process selectively fuses powdered thermoplastic material dispersed in thin layers inside a heated build chamber using a high-power laser. A roller or recoater applies a layer of polymer powder, usually 50–150 μm thick, to the build platform at the beginning of a project. The powder bed is preheated just below the melting point of the polymer. After scanning the part's cross-section on the powder layer, the laser raises the temperature of the particles as it passes through, causing them to melt and then sinter into a solid mass. The process is repeated layer by layer until the part is finished. After the sintering of each layer, the build platform goes down by a short distance (by one layer thickness) and a new layer of powder is put on top. The downward movement of the platform totally depends on the degree of the slicing done during the part design. A significant benefit of SLS is that the unfused powder surrounding the sintered object supports it during printing, eliminating the need for dedicated support structures, which is a big advantage for the complex geometries. Laser power, scan speed, hatch spacing (the distance between adjacent scan lines), layer thickness, and part bed temperature are important

factors in the process [2]. These variables are frequently integrated into a single energy density metric, which needs to be managed because too high energy could result in excessive sintering or thermal degradation, while too low energy results in poor particle fusion. SLS printers typically maintain the powder bed at an elevated temperature (around 150 °C for nylon) to reduce thermal gradients and avoid warpage. The material considerations for SLS differ from FDM SLS powders are usually limited to a few polymers (most commonly polyamide-12 nylon, PA11, TPU, or polyesters) that have suitable thermal properties (a relatively narrow melt temperature range to allow sintering) and form free-flowing fine powders [8]. Powder particles are often made by cryogenic grinding or precipitation and tend to be irregularly shaped. To ensure consistent layering and uniform sintering, the powder must have a controlled particle size distribution (commonly 20-80 μm) and good flowability [9]. The powder reuse is a unique aspect of SLS technique: after a build, unsintered powder can be recovered and mixed with fresh powder for subsequent builds, though there is a limit to reuse because repeated heating can reduce the polymer's quality (reducing molecular weight and altering melt viscosity) [10]. The microstructure of SLS parts consists of fused polymer particles; density is high but not 100%, with a typical porosity of a few percent resulting from small voids between partially sintered particles. SLS can produce a more homogeneous fused geometry without distinct layers, SLS parts are generally more isotropic than FDM

parts, mechanical properties are much more similar between the X/Y plane and the Z (build) direction [2]. For example, an SLS nylon part can exhibit tensile strength on the order of 45–50 MPa (comparable in X, Y, and Z), whereas an FDM ABS part might show ~30 MPa in X/Y



but only ~20 MPa in Z [4], [6]. Figure 2 provides a description of the SLS process and major components.

Fig 2. Schematic of the SLS powder bed fusion process (Infographic courtesy of Formlabs) A recoater spreads a thin layer of polymer powder (blue) across the build platform inside a heated chamber. A CO₂ laser beam, directed by scanning mirrors, selectively sinters the powder in the shape of each layer. The platform then lowers and the process repeats. Unfused powder supports the part and is later removed. Key components: (1) heaters maintain chamber temperature; (2) build chamber; (3) powder delivery system; (4) printed part; (5) recoater mechanism; (6) laser beam; (7) scanning mirror; (8) laser source.

III. Comparative Mechanical Properties

The mechanical performance of FDM vs. SLS parts is an important consideration when choosing between these processes for functional applications. Below we compare specific properties.

A. Static Mechanical properties

The static mechanical behavior of FDM and SLS parts including tensile, flexural and impact performance is governed by their process mechanisms and resulting microstructures.

FDM parts exhibits lower strength compared to SLS due to layer-wise deposition and limited inter-layer diffusion.

Tensile strength in FDM strongly depends on raster orientation, build direction and layer bonding quality. When loaded along the filament paths, FDM parts can approach the base material strength, but it can drop by 30-50% when loaded perpendicular to the layers. Few papers has reported that the tensile strength for common FDM materials like Polylactic Acid (PLA) and Polyethylene terephthalate Glycol (PETG) ranges from 30-50 MPa, with modulus values around 2-3.5GPa under optimized printing conditions [1],[6],[11]. Improved extrusion temperature, reduced layer height and higher infill density enhances interlayer bonding and overall strength. Flexural performance follows a similar trend: specimens printed with layers aligned to the bending direction exhibit higher flexural strength (50-60 MPa for PLA), whereas transverse builds tend to fail by delamination or interlayer cracking[5], [12]. Impact resistance is also

orientation-dependent; cracks propagate easily along layer boundaries, making FDM parts more notch-sensitive. Reinforced filaments or post-processing such as annealing can moderately improve toughness [1], [5], [31].

SLS parts, in contrast, show a more uniform and near-isotropic mechanical behavior due to their homogeneous microstructure. The laser-sintered powder layers achieve better inter-particle fusion, minimizing weak planes. SLS PolyAmide12 (PA12) typically attains tensile strength in the range of 45-50 MPa with elongation at break of 10-20%, approaching those of injection molded nylon [2], [8], [14]. Flexural strength (60-70 MPa) and modulus are

consistent across orientations because of uniform bonding throughout the part [2]. The improved toughness of SLS parts enables them to absorb higher impact energy and resist brittle fracture, whereas residual porosity remains the main factor slightly reducing stiffness and fatigue life [8], [15].

In summary, FDM provides adequate static strength for prototypes and moderate-load applications. But its mechanical performance is highly process-sensitive and direction dependent. While, SLS consistently produces parts with superior and more predictable strength, stiffness and impact resistance [2], [4], [11], [12].

Table I: Representative Tensile Properties of FDM and SLS Thermoplastics

Technology	Material	Orientation / Raster Angle	Testing Standard	Tensile Strength (UTS) [MPa]	Young's Modulus [GPa]	Elongation at Break [%]	Source
FDM	ABS	LBO (Longitudinal Build, 0°/90° Raster, 100% Infill, 0.25mm Layer)	ASTM D638	~24	~1.1	~3.1	[2]
FDM	ABS	TBO (Transverse Build, 0°/90° Raster, 100% Infill, 0.15mm Layer)	ASTM D638	~18	~0.9	~2.0	[2]
FDM	PLA	(Optimized Parameters)	ASTM D638	~55-60	~3.5	~2-6	[5]
FDM	PETG	(Optimized Parameters)	ASTM D638	~50-55	~2.0-2.3	~5-20	[5]
SLS	PA12	XY (Flat)	ASTM D638	~44.7	~1.6-1.7	~8-11	[15]
SLS	PA12	XZ/YZ (Edge)	ASTM D638	~43-45	~1.6-1.7	~7-11	[15]
SLS	PA12	ZX/ZY (Upright)	ASTM D638	~29-32	~1.4-1.5	~3-4	[15]
SLS	TPU	0° (BNC Specimen)	-	~8.5 (Yield)	-	~350	[16]
SLS	TPU	90° (BNC Specimen)	-	~10.5 (Yield)	-	~450	[16]

B. Long-Term Performance (Fatigue and Creep)

Long-term mechanical behavior under cyclic or sustained loads is an area of ongoing research for AM parts. FDM

components under cyclic fatigue loading tend to fail sooner than equivalent injection-molded parts due to the stress concentrations at layer interfaces and voids. For example, fatigue tests on FDM ABS have shown dramatically reduced lifetime when the loading induces inter-layer tension; cracks nucleate at voids or imperfect bonds and grow with each cycle. Printing parameters that improve static strength (higher temperatures, smaller layer heights) also improve fatigue life by reducing defects. SLS parts have shown better fatigue performance than FDM in limited studies, but data is somewhat sparse. SLS PA12 specimens can endure a greater number of cycles at a given stress amplitude compared to FDM specimens of the same material, owing to their more uniform microstructure [17]. However, SLS parts still contain some porosity, which can initiate fatigue cracks. Creep (time-dependent deformation under constant load) is another consideration, especially for thermoplastics at elevated temperature. FDM parts under constant stress may creep faster along layer lines as the polymer chains slip at the relatively weak interface; one needs to be cautious using FDM for structural parts under continuous load at high temperature (e.g., a bracket in a warm environment). SLS parts, especially fully dense nylon, act closer to bulk material in creep tests, with gradual deformation depending on temperature and stress but no unique weak planes [2]. An important study gap is the lack of comprehensive, standardized fatigue/creep data for AM parts, as identified in several reviews, more testing is needed to quantify long-term durability for both FDM and SLS across different materials [18]. For now, the consensus is that SLS parts offer superior fatigue resistance to FDM parts under similar conditions, primarily because FDM's layer adhesion is a limiting

factor in repetitive loading scenarios. Table 2 summarizes key findings regarding fatigue and creep behavior.

In summary, the variation in reported tensile strength and modulus values among different studies arises mainly from differences in experimental methodologies, specimen geometry, and parameter control. For FDM, the results can change a lot depending on the settings like print orientation, infill density, extrusion temperature, raster angle etc., even for the same material. Whereas in SLS, the strength depends more on laser power, energy density and powder characteristics such as size and flowability. Because of these differences, it is not easy to directly compare data across studies.

While most reports agree that SLS produces stronger and more uniform parts, a few studies show that optimized FDM prints can reach comparable in-plane strength, especially for certain materials like PETG and PLA. This shows that the gap between the two processes depends on how well the parameters are controlled rather than only on the technology itself. Another point is that there is still limited data on long-term properties like fatigue and creep, especially for SLS. Producing and testing SLS samples is more costly and requires specialized equipment, so fewer studies focus on this area. This creates a lack of standardized data to compare both processes fairly. Future research should therefore aim to use more uniform testing methods and include long-term behavior to build a clearer picture of how FDM and SLS parts perform over time.

Table 2: Summary of Fatigue and Creep Behavior Findings for FDM and SLS Thermoplastics

Technology	Material	Property	Key Findings / Data Points	Source(s)
FDM	ABS	Fatigue	Significantly lower fatigue strength vs. Injection Molding (~41% lower). Sensitive to raster orientation, infill, layer height.	[19]
FDM	ABS	Fatigue	Avg. cycles to failure: 3796 @ 30N load, 128 @ 60N load (Rotating Bending). Paris Law derived crack growth rate: ~0.0341 mm/cycle.	[20]
FDM	ABS	Creep	Printing orientation affects creep resistance; 90° orientation found most resistant (lowest creep model 'k' value = 0.2).	[20]
FDM	PLA	Fatigue	Fatigue behavior studied, influenced by parameters.	[19]
FDM	PLA, Others	Creep	Creep behavior investigated for PLA, CPE, TPLA, PC, Nylon.	[21]

SLS	PA12	Fatigue	Limited data available compared to tensile. Fatigue resistance linked to sintering quality.	[17]
SLS	TPU	Fatigue	S-N curves generated (Fig 5 in source). Fatigue limit ~1.5-1.8 MPa. Strength sensitive to orientation ($0^\circ > 90^\circ$) and stress ratio ($R=0.1 > R=-1$). Fatigue ratio ~0.5.	[16]
SLS	PA11 / PP	Fatigue	Cyclic fatigue performance compared; PP better at low stress, PA11 better at high stress.	[21]
SLS	General	Creep	Relevant for load-bearing applications, but specific data limited in reviewed sources.	[17]

C. Microstructure–Property Relationships

The microstructure of the parts made through FDM and SLS can vary significantly. This could create a difference in their mechanical properties as well. In FDM, the deposited roads of filament fuse together within each layer and partially with the layer below, but the interfaces are never as fully integrated as the bulk material. Microscopic examination of FDM fracture surfaces reveals unbonded or weakly bonded filament edges and voids between rasters [7]. These act as crack initiation sites, reducing strength and especially elongation (FDM parts often exhibit brittle behavior in tension across layers, failing at relatively low strains). Efforts to improve FDM part strength such as increasing extrusion temperature, using enclosed build chambers to keep parts warm, or employing chemical vapor smoothing are essentially aimed at promoting greater inter-diffusion of polymer across layers to approach a homogeneous structure. In SLS, the microstructure is more uniform: each layer of powder is sintered into the previous one, and while individual powder particles can still be discerned in SEM images of SLS parts, the necks between particles form a continuous matrix. The remaining porosity in SLS parts (often a few percent) is usually distributed throughout the part rather than concentrated in planes, and pore size tends to be small (tens of microns) [8]. This yields a material that behaves more like a foamed solid than a laminate. Thus, SLS parts can sustain higher loads without catastrophic delamination. Both methods are constrained by their defects: In FDM, the critical defect is the layer interface; in SLS, it is residual pores or partially sintered regions. Improving mechanical properties for each technology revolves around mitigating these defects e.g., optimizing raster strategies and adding fiber reinforcements in FDM to strengthen layer bonds, or

refining powder properties and laser parameters in SLS to reduce porosity.

IV. Environmental Sustainability Assessment

Beyond their performance, the environmental footprint of FDM and SLS is very much important as additive manufacturing is evaluated for sustainable fabrication. Key factors like energy consumption during printing, material waste and recyclability, and emissions or health hazards associated with the processes possess significant value. Here we compare these aspects for FDM and SLS.

A. Energy Consumption

Energy use is one of the main environmental concerns in additive manufacturing. In FDM, most of the energy is utilized in heating up the nozzle (typically 200–250 °C), and in many cases, the print bed (50–110 °C for materials like PLA or ABS to prevent warpage). The motors and cooling fans use much less in comparison. Because it only heats a small area, FDM is usually more energy efficient, especially for small and medium parts. Energy consumption typically ranges between 50-150MJ/Kg depending on part settings and part size [4], [22]. Simpler desktop FDM machines often draw only a few hundred watts during printing. SLS machines, on the other hand, consumes more energy (typically a CO2 laser of 30-100 W), and a heated build chamber that stays close to the melting point of the material (around 170 °C for PA12). Even when the laser is not running, the chamber must stay hot, which increases the power demand. One analysis found that an SLS machine could consume 2 to 4 times more energy per unit of material than an FDM machine for similar parts. However, when the SLS

chamber is packed with many parts, the energy per part becomes more reasonable. In summary, FDM is better for single part production, while SLS becomes efficient for batch printing [4].

Table 3 provides a comparative overview of energy consumption data.

Table 3: Comparative Energy Consumption Aspects of FDM and SLS

Feature	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)	Source(s)
Primary Energy Consumers	Nozzle Heater, Bed Heater (optional), Motors, Electronics	Chamber Heaters (Dominant), Laser, Motors/Rollers, Electronics	[23]
Key Influencing Factors	Build Time (Layer Thickness, Infill, Speed), Bed/Nozzle Temp, Part Volume/Complexity	Build Time, Bed Temperature, Laser Parameters, Build Packing Efficiency	[23]
Relative Energy Efficiency	Generally more energy-efficient per job/part, especially low volume. Identified as most efficient in standby/in-work for single jobs.	Generally higher energy consumption due to bulk powder heating. Efficiency improves with build packing.	[4]
Specific Energy Consumption (SEC) Range (Order of Magnitude)	Lower end of AM processes	Higher end for polymers, lower than metal PBF	[24]

Note: Specific energy values (e.g., MJ/kg or kWh/part) are highly variable depending on machine, material, part geometry, and operational parameters.

Table 4: Summary of Comparative Lifecycle Assessment (LCA) Findings

Aspect	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)	Comparison / Key Factors	Source(s)
Dominant Impact Drivers	Process Energy Consumption, Material Production (esp. bio-based feedstock agriculture), Support Waste	Process Energy Consumption (Heating), Powder Material Production, Powder Recycling Efficiency	Energy consumption is key for both. Material choice and waste management strategies differ.	[22]
Comparison vs. Traditional Mfg.	Lower impact at very low volumes. Lower material waste, potentially higher energy vs. milling.	Lower impact at very low volumes (<~300-1000 parts) vs. IM due to avoided mold energy. Higher process energy.	Crossover volume is critical. AM favored for low vol / high complexity.	[25]
Direct FDM vs. SLS Comparison	Found more impactful in one study (EcoIndicator 99). Lower process energy but potential for higher waste/feedstock impacts.	Found less impactful in one study (EcoIndicator 99). Higher process energy but no	Highly context-dependent. No universal winner. MJF potentially	[4]

		support waste, relies on powder recycling.	lower impact than both.	
Key Sensitivities	Machine utilization, part geometry, material choice (PLA vs. ABS), energy grid mix.	Machine utilization, build packing efficiency, powder refresh ratio, powder LCI data source, energy grid mix.	Volume, utilization, material, energy source significantly affect results for all AM.	[25]
Material Specifics	PLA: High agricultural impacts (eutrophication, toxicity), potential End of Life benefits (biodegradability). ABS: Petroleum-based, higher printing emissions.	PA12: Petroleum-based, production impacts significant. Recycling efficiency crucial.	Material origin and end-of-life management influence overall sustainability.	[26]

B. Material Efficiency and Waste

Material utilization is a key sustainability metric, and FDM and SLS differ in their sources of waste. FDM printing is a near-net-shape process with essentially 100% of the filament going into either the part or required supports. The main material waste in FDM comes from support structures (for overhangs or complex geometries) and failed or test prints. This waste can be around 5–20% of the material used [27]. These supports are usually thrown away, though some studies explore recycling the back into filament form by reprocessing it. On the whole, FDM waste is relatively low and in solid form which is easy to collect. SLS is unique in that unused powder acts as self-support and is recovered. The leftover powder can

be reused by mixing it with fresh powder (usually a 30 - 50% refresh ratio), meaning that 50–70% of the powder in each build is reused from previous builds and the rest is new powder added to maintain performance [10]. But after a few cycles, the powder degrades due to repeated heating, then not all of it can be reused. The quality of the reused powder decreases over time, affecting the flow and part strength. Research is now focusing on improving powder reconditioning and closed loop recycling to increase the material reuse and reduce waste [9], [10]. Both processes avoid the large cut-away waste associated with subtractive manufacturing (like CNC milling), which is a positive for material efficiency. Table 5 compares the waste generation and recycling aspects of FDM and SLS.

Table 5: Comparison of Material Waste and Recycling for FDM and SLS

Feature	Fused Deposition Modeling (FDM)	Selective Laser Sintering (SLS)	Source(s)
Typical Waste Quantity	~10-19% (or higher) of filament used (highly variable)	~80-95% of initial powder volume remains unsintered	[28]
Recyclability / Disposal	Depends on material: PLA (industrially compostable), ABS (recyclable). Challenging due to Type 7 classification, collection,	Unused powder is routinely recycled by mixing with virgin powder (refreshing).	[29]

	sorting. Property degradation with mechanical recycling.		
Recycling Efficiency / Limits	Limited by infrastructure and material degradation after multiple melt cycles.	Limited by thermal degradation (aging) of powder during printing. Typical refresh ratio: 30-50% virgin PA12. Typical cycles: 5-10 for PA12/PA11.	[29]
Recycling Process	Collection, sorting, cleaning, shredding, re-extrusion into filament.	Sieving, mixing with virgin powder. Potential for milling or chemical treatment.	[30]
Environmental Impact of Waste	Landfill burden (if not recycled/composted). Microplastic potential. Resource depletion (if using virgin material).	Resource depletion (if high refresh rates needed). Potential landfill burden for non-recyclable aged powder. Energy/cost of recycling process.	[30]

C. Emissions and Health Considerations

During the printing process, polymer vapors and particulates can be emitted, which pose environmental health and safety considerations. FDM printers can emit very fine plastic particles and gases when the filament melts. The level of emissions depends on the type of material. ABS releases more harmful compounds like styrene, while PLA emits fewer and less toxic gases. For safety, FDM machines should be used in well-ventilated rooms or fitted with air filters [15]. SLS operates in a closed chamber, so they emit less into the environment during printing. However, during post-processing, fine powder can become airborne when parts are cleaned or removed. Nylon powder for example, can irritate the lungs if inhaled. Therefore, users wear gloves and masks, and some systems now include built-in filtration. Overall, in sustainable design terms, extenuating these emissions is important: using PLA or enclosed ABS printers can reduce FDM's impact, and ensuring powder recovery systems of SLS are sealed will prevent powder loss to the environment.

D. Lifecycle and Sustainability Studies

Lifecycle assessment (LCA) studies comparing polymer AM technologies consistently identify energy consumption and material production as the primary environmental impact drivers. FDM generally uses less

energy per part and produces small amounts of solid waste. SLS consumes more energy but avoids support material and allows for a partial powder reuse. Which one is more sustainable depends on how it is used. FDM is better for single or short-run parts, while SLS is better when many parts are printed together. Table 4 gives a brief comparison on different aspect of the lifecycle of FDM and SLS.

Material type also affects sustainability. PLA has a smaller carbon footprint but comes with agricultural impacts. PA12 used in SLS is petroleum-based but has better durability. Future studies should include end-of-life management like recycling or composing to build a full picture of the environmental performance of these AM processes [22].

V. Discussion

After considering the above points, it becomes evident that FDM and SLS have distinct advantages and disadvantages. There is no on-point answer when it comes to selecting the most suitable option, as there are trade-offs in mechanical performance, material options, cost, and the environmental impact. Below is a summary of the main differences and typical uses for each technology, as well as potential improvements to be considered.

A. Key Differences and Trade-off

Geometrical Complexity: Both FDM and SLS can make complex shapes, but SLS has the edge for complex geometries. Since SLS uses the powder itself to support the part, it can create complex internal features, undercuts, and even interlocking parts without the need for detachable supports. FDM needs carefully designed supports for overhangs, which adds material and post-processing to remove them. Very fine features (on the order of <0.5 mm) are better resolved by SLS due to the precision of the laser spot, whereas FDM is limited by nozzle size (typically ~0.4 mm) and filament flow constraints.

Surface Finish and Accuracy: SLS parts typically shows a matte, slightly grainy surface (due to the powder) but no visible layers (depending of the thickness of slicing), and they normally achieve higher dimensional accuracy for complex shapes. FDM parts have visible layer lines and may require sanding or acetone vapor smoothing for a better finish. Warpage can significantly influence the dimensional accuracy in FDM (especially for ABS) and the need for support structures, while SLS's controlled environment yields good accuracy across the whole structure.

Cost and Accessibility: FDM is far more accessible and cost-effective at the entry and intermediate scales. Desktop FDM printers are inexpensive (hundreds to a few thousand dollars), and filament material costs are on the order of \$20-\$50 per kilogram for common plastics. SLS machines are expensive (tens to hundreds of thousands of dollars) and require specialized installation (inert gas for some systems, climate control) and skilled operation. SLS nylon powder is also costly, often \$100-\$200 per kilogram. Thus, for budget-limited scenarios or hobbyist use, FDM is the practical choice, whereas SLS is usually justified for industrial or high-value applications where its superior part quality is needed.

Throughput: SLS can build many parts at once (limited by packing density in the powder bed), which is ideal for batch production of small to medium parts its throughput can be much higher than a single-extruder FDM printer that produces one part at a time. Farms of multiple FDM printers can achieve parallel production too, but that introduces variability and more labor. If one needs 100 copies of a part, an SLS might make them in one build,

while an FDM might have to run 100 separate jobs (or a few parts per job). On the flip side, if only one or two parts are needed quickly, an FDM printer can start immediately and finish without the overhead of packing and powder handling that SLS entails.

These differences mean that FDM and SLS are complementary in many ways. FDM excels in low-cost prototyping, large yet lightly loaded parts (e.g., big display models or enclosures), and scenarios where material flexibility (both in choice and literal part flexibility) is important. SLS excels in making functional parts that require strength, precision, and complexity (e.g., medical device components, aerospace ducting, and automotive clips).

B. Applications of FDM and SLS

Fused Deposition Modeling (FDM): FDM is preferred for making Rapid prototyping of design ideas and models; also can be used for making custom jigs and fixtures; PLA material is commonly used for making biomedical models (e.g., anatomical models); Useful in situations where low cost and faster production is important than strength and accuracy.

Selective Laser Sintering (SLS): Applications for SLS includes creating functional prototypes and end-use parts in aerospace, automotive, and consumer products where injection molding tooling is not economical. SLS is commonly used for ducting, brackets, clips, connectors, and housings that need to withstand real-world conditions. It is much popular in medical applications these days for making orthotics, prosthetic components, or surgical guides from sterilized nylon material. Basically, whenever a design is too complex for molding and it requires good mechanical performance, then SLS is the best candidate.

C. Future Research Directions

Several knowledge gaps and development areas remain for improving FDM and SLS processes and expanding their sustainable use:

SLS Material Expansion: The material selection for SLS needs to go beyond the typical Nylon materials PA11/PA12. Research on polypropylene, PTEG or even

recycled plastics which can be sintered is an area to look forward to. Moreover, improving the recyclability of powder through better powder conditioning techniques or mixed particle sizes could reduce waste and cost [10].

Emission Mitigation: A thorough investigation on efficient filtering systems for FDM printer are necessary for controlling UFP and VOC emissions and make it safe for large-scale deployment, such as 3D printer farms in offices or schools. Additionally, research on the chemical emissions from SLS and mitigation measures will ensure that these processes are not harmful to the environment.

Process Automation and Efficiency: Automation could be used to reduce labor and energy requirements for FDM and SLS. The use of FDM-based automated part removal and printer farms with scheduling algorithms can result in a sustainable increase in the output. Smarter algorithms for part packing and real-time laser power adjustment (or use of multiple lasers) in SLS could be used to accelerate the build process, resulting in reduced energy per part. Several machine learning techniques are being applied to optimize process parameters while minimizing energy consumption [31].

Long-Term Performance Data: There is a scarcity of standardized data on the behavior of FDM and SLS components after long time usage. To achieve critical applications, it is essential to comprehend creep, fatigue, and environmental aging (UV exposure; moisture effects). This data-gathering exercise will enhance confidence in the use of AM parts for extended service and help identify whether one process has longer-lasting benefits over another.

Hybrid and New Processes: Lastly, novelties which blends the advantages of both methods could arise. Like, processes that can use filament deposition followed by selective laser heating to melt and deposit for improved bonding.

Essentially, the focus of research is to improve the reliability and environmental compatibility of FDM and SLS through rigorous testing and development. It can be expected that as these technologies mature, the

performance gap will narrow (with improved FDM properties) and the usability gap will narrow (by using SLS with greater affordability and flexibility). They will remain important in the toolbox of manufacturing.

VI. Conclusion

This review compared Fused Deposition Modelling (FDM) and Selective Laser Sintering (SLS) for thermoplastic additive manufacturing based on mechanical performance and environmental sustainability. SLS provides parts with higher strength, more uniformity and improved surface accuracy due to its laser powder-sintering process, while FDM remains attractive for its lower cost, simple and setup wide material options including recycled and composite filaments.

Environmentally, both have benefits and trade-offs. FDM uses less energy and produces limited waste, while SLS can reuse its leftover powder but requires much more power. The choice between these two technologies not only depends on the mechanical performance required but also on energy availability, material recyclability, and the intended production scale.

Overall, FDM can be considered a practical solution for rapid prototyping, educational use, and parts with moderate strength requirements, whereas SLS is more suited for functional components that need consistent strength and precision. Both technologies continue to evolve with advancements in materials, process control and automation.

Future research should focus on improving inter-layer bonding in FDM to reduce the anisotropy and developing more durable, easily recyclable powders for SLS. There is also a growing need for standardized testing and lifecycle studies to better compare the energy use, emissions, and material reuse between AM processes. As these technologies mature, FDM and SLS are likely to become complementary rather than competitive, working together to make additive manufacturing more efficient, sustainable, and accessible across industries.

References

- [1] N. Zohdi, P. Q. K. Nguyen, and R. Yang, "Evaluation on Material Anisotropy of Acrylonitrile Butadiene Styrene Printed via Fused Deposition Modelling," *Appl. Sci. Switz.*, vol. 14, no. 5, Mar. 2024, doi: 10.3390/app14051870.
- [2] F. Lupone, E. Padovano, F. Casamento, and C. Badini, "Process phenomena and material properties in selective laser sintering of polymers: A review," *Materials*, vol. 15, no. 1, Jan. 2022, doi: 10.3390/ma15010183.
- [3] E. Hozdić, "Characterization and Comparative Analysis of Mechanical Parameters of FDM- and SLA-Printed ABS Materials," *Appl. Sci.*, vol. 14, no. 2, p. 649, Jan. 2024, doi: 10.3390/app14020649.
- [4] V. Tagliaferri, F. Trovalusci, S. Guarino, and S. Venettacci, "Environmental and economic analysis of FDM, SLS and MJF additive manufacturing technologies," *Materials*, vol. 12, no. 24, Dec. 2019, doi: 10.3390/ma12244161.
- [5] M. Balasrinivasan, A. Varun Kumar, and K. Sathickbasha, "A comparative study on mechanical properties of PLA, PETG, and carbon fiber prepared by fused deposition modeling," *Proc. Inst. Mech. Eng. Part E J. Process Mech. Eng.*, p. 09544089241301961, 2024.
- [6] M. Algarni and S. Ghazali, "Comparative study of the sensitivity of pla, abs, peek, and petg's mechanical properties to fdm printing process parameters," *Crystals*, vol. 11, no. 8, Aug. 2021, doi: 10.3390/cryst11080995.
- [7] D. Acierno and A. Patti, "Fused Deposition Modelling (FDM) of Thermoplastic-Based Filaments: Process and Rheological Properties—An Overview," *Materials*, vol. 16, no. 24, Dec. 2023, doi: 10.3390/ma16247664.
- [8] G. Colucci, L. Fontana, J. Barberi, C. Vitale Brovarone, and M. Messori, "Chess-like Pieces Realized by Selective Laser Sintering of PA12 Powder: 3D Printing and Micro-Tomographic Assessment," *Polymers*, vol. 16, no. 24, Dec. 2024, doi: 10.3390/polym16243526.
- [9] F. M. Mwanja, M. Maringa, and J. G. Van Der Walt, "A review of the techniques used to characterize laser sintering of polymeric powders for use and re-use in additive manufacturing," *Manuf. Rev.*, vol. 8, 2021, doi: 10.1051/mfreview/2021012.
- [10] B. A. de Sousa Alves, D. Kontziampasis, and A. H. Soliman, "The Quest for the Holy Grail Of 3D Printing: A Critical Review of Recycling in Polymer Powder Bed Fusion Additive Manufacturing," *Polymers*, vol. 16, no. 16, Aug. 2024, doi: 10.3390/polym16162306.
- [11] A. Kafle, E. Luis, R. Silwal, H. M. Pan, P. L. Shrestha, and A. K. Bastola, "3d/4d printing of polymers: Fused deposition modelling (fdm), selective laser sintering (sls), and stereolithography (sla)," *Polymers*, vol. 13, no. 18, Sep. 2021, doi: 10.3390/polym13183101.
- [12] A. S. Belay, A. Sewale Belay, F. Getie Tsegaw, and S. G. Gebeyehu, "Optimization of Process Parameters Using Taguchi and ANOVA A B S T R A C T," *J Eng Ind Res*, vol. 5, no. 3, 2024, doi: 10.48309/jeires.2024.212593.
- [13] S. Wickramasinghe, T. Do, and P. Tran, "FDM-Based 3D printing of polymer and associated composite: A review on mechanical properties, defects and treatments," *Polymers*, vol. 12, no. 7, pp. 1–42, Jul. 2020, doi: 10.3390/polym12071529.
- [14] P. K. Penumakala, J. Santo, and A. Thomas, "A critical review on the fused deposition modeling of thermoplastic polymer composites," *Compos. Part B Eng.*, vol. 201, Nov. 2020, doi: 10.1016/j.compositesb.2020.108336.
- [15] J. J. Slager, B. C. Earp, and A. M. Ibrahim, "Influence of Build Orientation and Part Thickness on Tensile Properties of Polyamide 12 Parts Manufactured by Selective Laser Sintering," *Polymers*, vol. 16, no. 16, Aug. 2024, doi: 10.3390/polym16162241.

- [16] Z. Major, M. Lackner, A. Hössinger-Kalteis, and T. Lück, "Characterization of the Fatigue Behavior of SLS Thermoplastics," *Procedia Struct. Integr.*, vol. 34, pp. 191–198, 2021, doi: 10.1016/j.prostr.2021.12.028.
- [17] F. Jabri, A. Ouballouch, L. Lasri, and R. EL Alaiji, "A Review on Selective Laser Sintering 3D Printing Technology for Polymer Materials," in *Proceedings of CASICAM 2022*, K. Zarbane and Z. Beidouri, Eds., Cham: Springer Nature Switzerland, 2023, pp. 63–71.
- [18] A. A. M. Damanhuri, A. Hariri, S. A. Ghani, M. S. S. Mustafa, S. G. Herawan, and N. A. Paiman, "The Effects of Virgin and Recycled PA12 Powders in SLS Processes on Occupational Exposures," *Int. J. Environ. Sci. Dev.*, vol. 12, no. 11, pp. 339–345, Nov. 2021, doi: 10.18178/IJESD.2021.12.11.1359.
- [19] H. Bakhtiari, M. Aamir, and M. Tolouei-Rad, "Effect of 3D Printing Parameters on the Fatigue Properties of Parts Manufactured by Fused Filament Fabrication: A Review," *Appl. Sci.*, vol. 13, no. 2, p. 904, Jan. 2023, doi: 10.3390/app13020904.
- [20] H. Zhang *et al.*, "Tensile, Creep, and Fatigue Behaviors of 3D-Printed Acrylonitrile Butadiene Styrene," *J. Mater. Eng. Perform.*, vol. 27, no. 1, pp. 57–62, Jan. 2018, doi: 10.1007/s11665-017-2961-7.
- [21] M. Alagheband, M. Kosarimovahhed, Q. Zhang, and S. Jung, "Creep and failure of 3D-printed polymers: Impact of infill patterns and densities on shear strain and strength," *Eng. Fail. Anal.*, vol. 175, p. 109568, Mar. 2025, doi: 10.1016/j.engfailanal.2025.109568.
- [22] A. Sola, R. Rosa, and A. M. Ferrari, "Environmental Impact of Fused Filament Fabrication: What Is Known from Life Cycle Assessment?," *Polymers*, vol. 16, no. 14, Jul. 2024, doi: 10.3390/polym16141986.
- [23] A. S. Tiwari and S. Yang, "Energy Consumption Modeling of 3D-Printed Carbon-Fiber-Reinforced Polymer Parts," *Polymers*, vol. 15, no. 5, Mar. 2023, doi: 10.3390/polym15051290.
- [24] H. H. Shah, C. Tregambi, P. Bareschino, and F. Pepe, "Environmental and economic sustainability of additive manufacturing: A systematic literature review," *Sustain. Prod. Consum.*, vol. 51, pp. 628–643, Nov. 2024, doi: 10.1016/j.spc.2024.10.012.
- [25] M. Khalid and Q. Peng, "Sustainability and Environmental Impact of Additive Manufacturing: A Literature Review," *Comput.-Aided Des. Appl.*, vol. 18, no. 6, pp. 1210–1232, Feb. 2021, doi: 10.14733/cadaps.2021.1210-1232.
- [26] M. N. Nadagouda, M. Ginn, and V. Rastogi, "A review of 3D printing techniques for environmental applications," *Curr. Opin. Chem. Eng.*, vol. 28, pp. 173–178, Jun. 2020, doi: 10.1016/j.coche.2020.08.002.
- [27] M. Gopal, H. G. Lemu, and E. M. Gutema, "Sustainable Additive Manufacturing and Environmental Implications: Literature Review," *Sustain. Switz.*, vol. 15, no. 1, Jan. 2023, doi: 10.3390/su15010504.
- [28] G. S. Martynková *et al.*, "Polyamide 12 materials study of morpho-structural changes during laser sintering of 3d printing," *Polymers*, vol. 13, no. 5, Mar. 2021, doi: 10.3390/polym13050810.
- [29] M. Ali Saqib, M. S. Abbas, and H. Tanaka, "Sustainability and innovation in 3D printing: Outlook and trends," *Clean Technol. Recycl.*, vol. 4, no. 1, pp. 1–21, 2024, doi: 10.3934/ctr.2024001.
- [30] P. C. Gomes, O. G. Piñeiro, A. C. Alves, and O. S. Carneiro, "On the Reuse of SLS Polyamide 12 Powder," *Materials*, vol. 15, no. 16, p. 5486, Aug. 2022, doi: 10.3390/ma15165486.
- [31] H. M. Yehia, A. Hamada, T. A. Sebaey, and W. Abd-Elaziem, "Selective Laser Sintering of Polymers: Process Parameters, Machine Learning Approaches, and Future Directions," *J. Manuf. Mater. Process.*, vol. 8, no. 5, p. 197, Sep. 2024, doi: 10.3390/jmmp8050197.

- [32] J. Praneeth, S. Venkatesh, and L. S. Krishna, "A Review on Additive Manufacturing Processes," in *E3S Web of Conferences*, EDP Sciences, Oct. 2023, doi: 10.1051/e3sconf/202343001282.
- [33] M. U. Azam, I. Belyamani, A. Schiffer, S. Kumar, and K. Askar, "Progress in selective laser sintering of multifunctional polymer composites for strain- and self-sensing applications," *J. Mater. Res. Technol.*, vol. 30, pp. 9625–9646, May 2024, doi: 10.1016/j.jmrt.2024.06.024.
- [34] M. Zhou, W. Zhu, S. Yu, Y. Tian, and K. Zhou, "Selective laser sintering of carbon nanotube-coated thermoplastic polyurethane: Mechanical, electrical, and piezoresistive properties," *Compos. Part C Open Access*, vol. 7, Mar. 2022, doi: 10.1016/j.jcomc.2021.100212.
- [35] S. Wang, H. Feng, J. Hong, and G. Wang, "Enhanced foaming ability of thermoplastic polyurethane by crystallization during mold-opening foam injection molding with supercritical N₂ as blowing agents," *J. Mater. Res. Technol.*, vol. 22, pp. 2489–2501, Jan. 2023, doi: 10.1016/j.jmrt.2022.12.117.
- [36] E. Rogha *et al.*, "Flexural properties of additively manufactured continuous fibre reinforced thermoplastic polymers after exposure to elevated temperatures," *Compos. Commun.*, vol. 54, Feb. 2025, doi: 10.1016/j.coco.2025.102279.
- [37] Y. Zhang, K. Mao, S. Leigh, A. Shah, Z. Chao, and G. Ma, "A parametric study of 3D printed polymer gears," *Int. J. Adv. Manuf. Technol.*, vol. 107, no. 11–12, pp. 4481–4492, Apr. 2020, doi: 10.1007/s00170-020-05270-5.
- [38] S. Saleh Alghamdi, S. John, N. Roy Choudhury, and N. K. Dutta, "polymers Additive Manufacturing of Polymer Materials: Progress, Promise and Challenges," 2021, doi: 10.3390/polym13.
- [39] Ü. Çevik and M. Kam, "A Review Study on Mechanical Properties of Obtained Products by FDM Method and Metal/Polymer Composite Filament Production," *J. Nanomater.*, vol. 2020, 2020, doi: 10.1155/2020/6187149.
- [40] M. H. Hsueh *et al.*, "Effect of printing parameters on the thermal and mechanical properties of 3d-printed pla and petg, using fused deposition modeling," *Polymers*, vol. 13, no. 11, Jun. 2021, doi: 10.3390/polym13111758.
- [41] N. N. Ahmad, Y. H. Wong, and N. N. N. Ghazali, "A systematic review of fused deposition modeling process parameters," *Soft Sci.*, vol. 2, no. 3, Sep. 2022, doi: 10.20517/ss.2022.08.
- [42] J. R. Stojković *et al.*, "An Experimental Study on the Impact of Layer Height and Annealing Parameters on the Tensile Strength and Dimensional Accuracy of FDM 3D Printed Parts," *Materials*, vol. 16, no. 13, Jul. 2023, doi: 10.3390/ma16134574.
- [43] J. Bochnia, M. Blasiak, and T. Kozior, "A comparative study of the mechanical properties of fdm 3d prints made of pla and carbon fiber-reinforced pla for thin-walled applications," *Materials*, vol. 14, no. 22, Nov. 2021, doi: 10.3390/ma14227062.
- [44] M. S. Hassan *et al.*, "Selective Laser Sintering of High-Temperature Thermoset Polymer," *J. Compos. Sci.*, vol. 6, no. 2, Feb. 2022, doi: 10.3390/jcs6020041.
- [45] O. J. Oladunni, C. K. M. Lee, I. D. Ibrahim, and O. A. Olanrewaju, "Advances in sustainable additive manufacturing: a systematic review for construction industry to mitigate greenhouse gas emissions," *Front. Built Environ.*, vol. 11, 2025, doi: 10.3389/fbuil.2025.1535626.
- [46] J. J. Slager, B. C. Earp, and A. M. Ibrahim, "Influence of Build Orientation and Part Thickness on Tensile Properties of Polyamide 12 Parts Manufactured by Selective Laser Sintering," *Polymers*, vol. 16, no. 16, p. 2241, Aug. 2024, doi: 10.3390/polym16162241.

- [47] S. Vyavahare, S. Teraiya, D. Panghal, and S. Kumar, "Fused deposition modelling: a review," *Rapid Prototyp. J.*, vol. 26, no. 1, pp. 176–201, Jan. 2020, doi: 10.1108/RPJ-04-2019-0106.
- [48] M. A. Islam *et al.*, "Additive manufacturing in polymer research: Advances, synthesis, and applications," *Polym. Test.*, vol. 132, p. 108364, 2024.
- [49] L. O'Connor, "Comparative analysis of the mechanical properties of FDM and SLA 3D printed components," *J. Micromanufacturing*, vol. 0, no. 0, p. 25165984251364689, doi: 10.1177/25165984251364689.
- [50] S. D. Dipta, M. M. Rahman, M. J. Ansari, and M. N. Uddin, "A Comprehensive Review of Sustainable and Green Additive Manufacturing: Technologies, Practices, and Future Directions," *J. Manuf. Mater. Process.*, vol. 9, no. 8, p. 269, 2025.
- [51] S. Jung, L. B. Kara, Z. Nie, T. W. Simpson, and K. S. Whitefoot, "Is additive manufacturing an environmentally and economically preferred alternative for mass production?," *Environ. Sci. Technol.*, vol. 57, no. 16, pp. 6373–6386, 2023.