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EMERGING ADDITIVE MANUFACTURING TECHNOLOGIES FOR COMPOSITE MATERIALS: A CRITICAL REVIEW

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Abstract

Additive Manufacturing (AM) employs diverse technologies to produce physical objects by sequentially layering materials such as powder, wire, or resin, all derived from digital 3D models. The development of composite materials, formed by combining two or more distinct elements to enhance technical properties, represents one of its growing applications. This overview highlights several primary additive manufacturing processes utilized in composite manufacturing, including Laminated Object Manufacturing (LOM), Fused Deposition Modelling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Direct Energy Deposition (DED). The essay, featuring a well-organized and comprehensive summary, aims to serve as a crucial resource for individuals at all levels of expertise. The uniqueness lies in addressing a gap in the literature by offering a concise yet thorough summary of essential concepts. The article outlines the key features, benefits, and drawbacks of each additive manufacturing technique. The document includes a concise SWOT analysis, detailing strengths, weaknesses, opportunities, and threats, along with practical usage examples. Ultimately, additive manufacturing holds significant potential to enhance the production of composite materials, potentially transitioning the process from simple prototyping to comprehensive full-scale manufacturing. Nonetheless, there is no singular methodology that proves effective in all scenarios; the optimal strategy depends on the specific requirements of the application at hand.

Keywords: Additive Manufacturing (AM), Composite Materials, 3D Printing Technologies, Stereolithography (SLA), Fused Deposition Modelling (FDM), SWOT Analysis.

1. Introduction

Additive Manufacturing (AM) is the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies," according to ISO/ASTM 52900:2021 [1]. AM includes a number of processes [2], each with unique advantages and disadvantages [3], including binder jetting, Direct Energy Deposition (DED), material extrusion, material jetting, Powder Bed Fusion (PBF), sheet lamination, and vat photo polymerization. The words additive fabrication, layer manufacturing, additive processes, solid freeform fabrication, and freeform fabrication have also been used historically to refer to AM [1]. Charles Hull received the first patent for stereolithographic (SLA) in 1986, marking the beginning of AM's more than three-decade history [4]. Since then, AM has emerged as the go-to technique for creating quick prototypes and unique parts, particularly for small-batch production [3]. After starting with polymers, the variety of printable materials has grown dramatically in recent years [4, 5], encompassing ceramics, metals, and composites. Materials designed to combine two or more different components, known as composites, are especially well suited for AM. However, only a small number of additive manufacturing technologies have been successfully used to the production of composites. Laminated Object Manufacturing (LOM), Selective Laser Sintering (SLS), Fused Deposition Modelling (FDM), SLA, and DED are a few of these [6]. This study investigates how these technologies are used in the creation of composite materials.

The use of Additive manufacturing (AM) in composite production offers numerous advantages, particularly the ability to produce highly complex and customized geometries that are difficult or unfeasible to achieve with traditional subtractive or formative methods [7–11]. The significant reductions in cost and lead-time associated with AM enable rapid design iterations and enhance development processes, thereby facilitating efficient prototyping [12, 13]. Furthermore, integrating structural and functional properties within a single construct enables the fabrication of functionally graded materials (FGMs), thereby reducing the total number of components and overall production costs [13, 14]. Although achieving performance parity with conventional composites remains a challenge, additive manufacturing enables the creation of advanced composite architectures, including co-continuous phase reinforced composites with precisely designed internal structures [10, 15]. According to ISO/ASTM 52900:2021, additive manufacturing is categorized into seven distinct process groups to establish a standardized framework for these technologies. Binder Jetting (BJT) selectively joins powder materials using a liquid binding agent [16]. Directed Energy Deposition (DED) employs concentrated thermal energy to simultaneously melt and deposit materials [17–20]. Material Extrusion (MEX) dispenses material selectively through a nozzle [21]. Material Jetting (MJT) deposits fine droplets of materials such as photopolymers or waxes [22]. Powder Bed Fusion (PBF) utilizes thermal energy to selectively melt or sinter regions of a powder bed. Sheet Lamination (SHL) joins material sheets layer by layer to form parts [23]. Vat Photo polymerization (VPP) uses light sources to cure liquid photopolymers in a vat, resulting in solid structures [24].

A composite material is described as a combination of two or more insoluble materials that maintain their identities while working together to produce improved qualities in the ASTM D3878-16 standard, which was revised in 2023 as ASTM D3878-20b [25]. For engineering purposes, these materials can be regarded as macroscopically homogeneous even though they are microscopically diverse. As illustrated in Figure 1, composites can be divided into four primary categories: bio-composites, scale-based composites, reinforcement-based composites, and matrix-based composites.

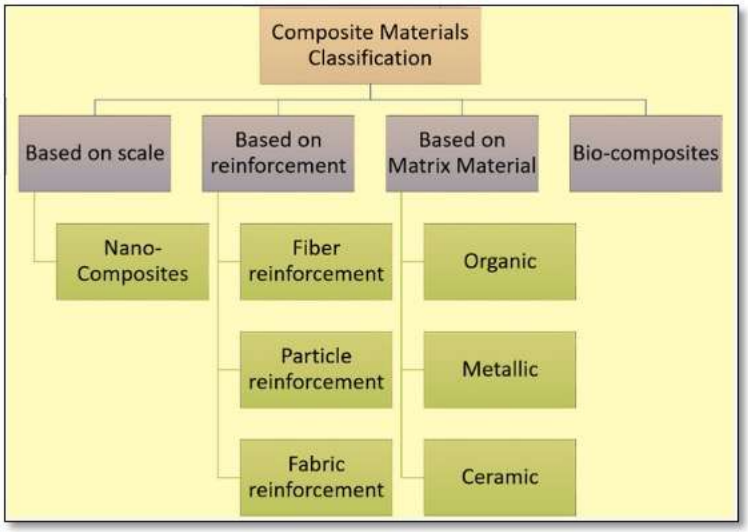

Figure 1. Classification of composite materials based on various criteria (adapted from [26–29]).

Composites are frequently divided into groups according to the type of reinforcing or matrix component. Metal-matrix composites (MMCs), ceramic-matrix composites (CMCs), and organic-matrix composites (OMCs) are the three primary groups. The two forms of "organic-matrix composites" that are commonly referred to by this term are carbon-matrix composites (also known as carbon-carbon composites) and polymer-matrix composites (PMCs), as shown in Figure 2. The matrix is often the continuous phase in these systems. On the other hand, as seen in Figure 3 [19], composites can be classified according to the kind of reinforcement: particle reinforcements, continuous or discontinuous fiber reinforcements, and fabric reinforcements, which include knitted and braided fabrics.

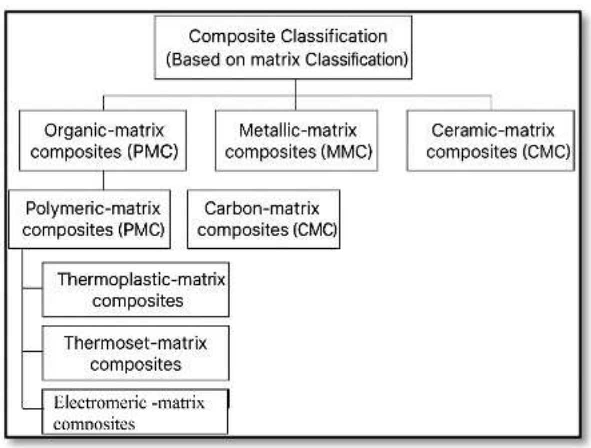

Figure 2. Composite classification by matrix material [26, 30].

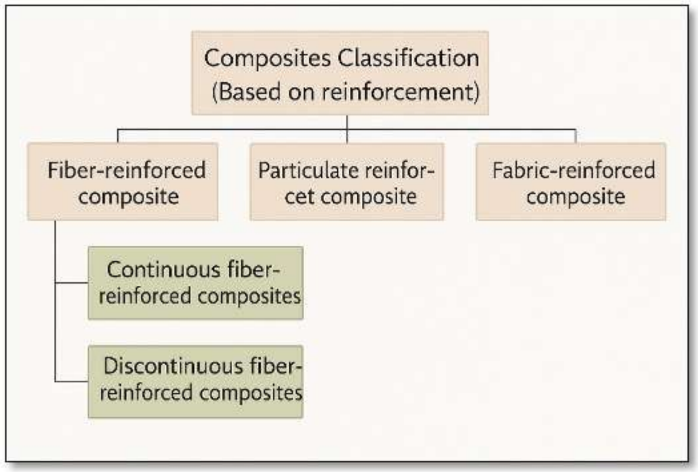

Figure 3. Reinforcement-based classification of composites (adapted from [26, 30]).

2. Methodology

In order to conduct this review study, subjects pertaining to "Additive Manufacturing Techniques" were examined using the SCOPUS scientific database. With an emphasis on titles, abstracts, and keywords published between 2000 and 2020, an advanced search was carried out. Figure 4 illustrates that the search produced roughly 7,500 articles. The scientific community's increasing interest in this field is evident in the notable rise in publications in recent years. A succinct, thorough, and organized overview is timely and beneficial in light of this tendency, especially for researchers and students who want to become acquainted with the foundations and most recent developments in the subject. The most pertinent papers were carefully chosen from among all the articles that were retrieved to serve as the foundation for this review.

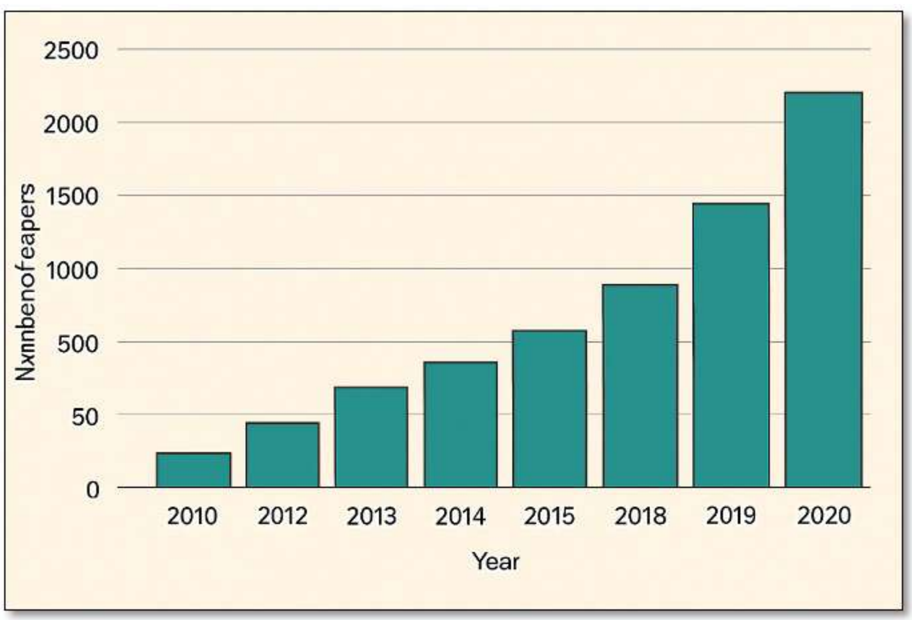

Figure 4. Research publications on additive manufacturing techniques (2010–2020).

Since 2010, there has been a noticeable increase in research on additive manufacturing (AM) techniques. This is primarily due to the integration of information technologies (IT) to improve AM processes in industries like consumer goods, automotive, aerospace, and medicine. As seen by the exponential rise in scientific publications, this growth in research output is a reflection of increased interest and significant investment in the subject. AM has advanced significantly thanks to the use of IT, which has increased productivity, accuracy, and process capabilities in general. These developments in technology have expanded the range of applications in numerous industries and produced creative solutions [31–33].

3. Additive Manufacturing Techniques

3.1. Laminated Object Manufacturing (LOM)

In 1991, Helisys, a company based in Torrance, California, USA, introduced sheet lamination, also known as Laminated Object Manufacturing (LOM) (Figure 5). With this method, sheets of material are layered one after the other and bonded together with an appropriate glue to create three-dimensional parts [10, 34–37]. Usually, the raw material is delivered as a continuous sheet wound on a spool.

A hot roller is used to adhere the sheet once it has been drawn over the build platform. The extra material is subsequently sliced away by a laser or mechanical cutter to define the two-dimensional cross-section of the specified geometry. On a different take-up spool, the non-part parts are gathered. The platform is lowered once each layer is finished, and a fresh sheet is applied and adhered to the one before it. Until the last 3D component is built, this cycle is repeated. Paper, plastics, metals, synthetic textiles, and composite sheets are among the materials that LOM can be used with [10, 34–37]. The thickness of the sheet and the cutting system's accuracy have a significant impact on the manufactured part's accuracy. Depending on the material type and curing needs, standard LOM systems can apply new layers at rates ranging from 13 to 40 mm/s and heat exposure periods ranging from 5 to 20 seconds. Depending on the characteristics of the material, layer thickness might vary, but it usually begins at 0.04 mm.

Although LOM falls under the category of additive manufacturing, the distinction between the two techniques is blurred because it combines subtractive aspects because of the material removal that occurs during the patterning of each layer. To obtain the ultimate dimensional accuracy, post-processing operations like drilling or machining are frequently necessary. Depending on the bonding agent used, more curing can also be required [4, 36, 38, 39]. For creating large-scale structural prototypes, LOM is especially well suited. Even though it lacks the mechanical robustness offered by methods like Selective Laser Melting (SLM), it is nevertheless an affordable option for early design and prototype [40].

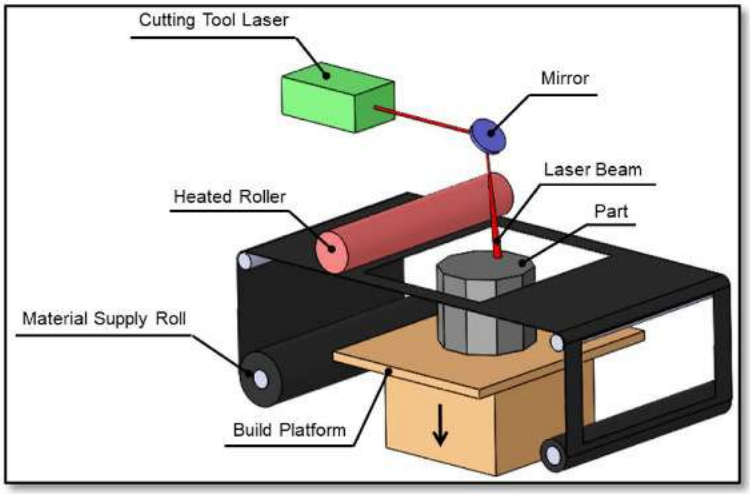

Figure 5. LOM system schematic showing basic setup and operation [41].

A polymer matrix composite C-shaped panel was shown to be manufacturable by Klosterman et al. [42] through the use of a curved LOM method (Figure 6a). The final product and a similar body armor panel are depicted in Figure 6b, while the specially made laminator utilized for this procedure is shown in Figure 6a. The LOM paper mandrel shrank by around 11% in the z-direction throughout the curing process, but neither its width nor length changed much. As illustrated in Figure 6b, the manufactured "C9" shell nevertheless showed little dimensional distortion from spring-back effects and fit almost precisely onto a freshly made mandrel. A commercial preparation of continuous unidirectional glass fibers embedded in an epoxy matrix was utilized in this investigation. The range of the fiber volume fraction (vt%) was 52% to 55%. Green composite laminates were laid up and shaped from the prepared feedstock with the help of a curved LOM machine. The fabrication was finished using oven curing and vacuum bagging procedures.

With variations around 1% in the majority of orientations, dimensional accuracy was well maintained. But there was more variation in the height direction, with variances up to about 7.9%. For typical applications, the resultant composite's shear strength of about 25 MPa is deemed adequate. The incapacity of the heated roller to fully consolidate and cure the pieces was one of the main drawbacks of the LOM process. Weak interfacial connection between layers was established by microstructural studies. In order to improve interfacial adhesion and lower the void content to less than 5%, a post-consolidation cycle is advised [4, 34, 42, 43].

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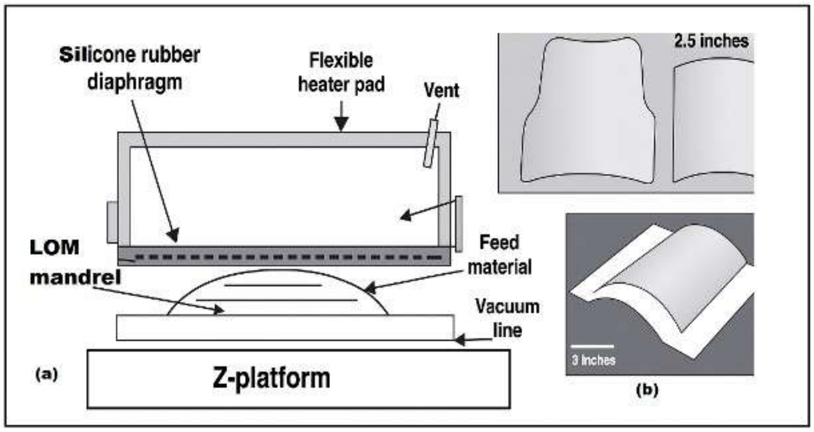

Figure 6. (a) Cross-section of Curved LOM laminator and platform; (b) glass fibre epoxy composites produced by Curved LOM (adapted from [42]).

Sonmez and Hahn [44] examined the distribution of stress and heat transfer in the LOM process to assess the impact of processing parameters on mechanical and thermal behavior. According to their research, employing larger rollers reduces localized stress concentrations by more evenly dispersing stress, which leads to better bonding conditions.

Relatedly, Kansas State University researchers created a new method for creating continuous fiber-reinforced thermoplastic composites through the use of laser-assisted additive manufacturing (AM) (Figure 7). This technique was presented as a way to cut down on material waste that is frequently connected to traditional LOM procedures. The suggested method makes use of continuous prepare tape in place of pre-cut prepare sheets. A CO_2 laser beam and a heated roller are used to deposit and solidify these tape strips, and each layer is then defined by laser cutting. Due to a number of significant benefits, including continuous fiber reinforcement, a high fiber-weight ratio, decreased void content, and increased interfacial bonding; this laser-assisted AM process provides superior mechanical performance. Figure 8 compares the tensile characteristics of conventional composite manufacturing methods and different AM techniques [34, 42–45]. ELF stands for End Light Fibre [48], GF for Glass Fibre [47], SF for Sustainable Fibre [46], and CF for Carbon Fibre [49] in this image.

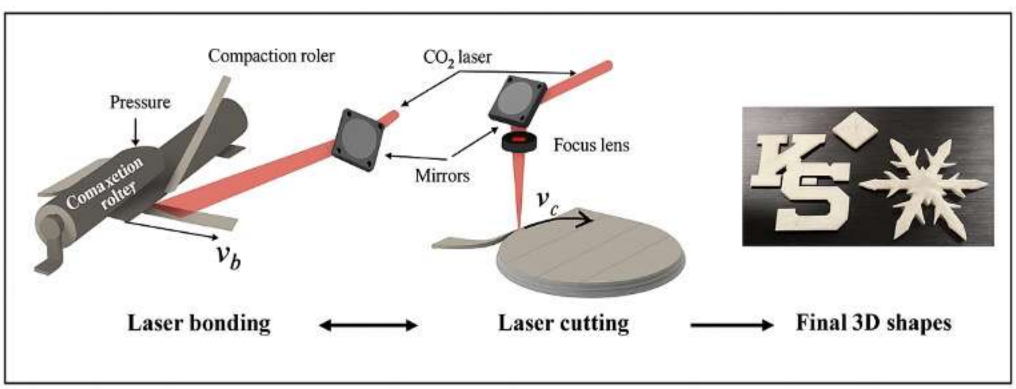

Figure 7. Schematic of the proposed additive manufacturing method.

Additionally, LOM makes it possible to fabricate continuous fiber-reinforced ceramic composites and large-scale monolithic ceramic components, two applications that are generally challenging to accomplish with other additive manufacturing processes [36]. Notwithstanding its benefits, LOM has a number of drawbacks that prevent wider implementation. These include a limited ability to create complicated shapes, anisotropic mechanical qualities in the planar dimensions, the possibility of delamination, and substantial material waste. Consequently, as Table 1 summarizes, its utilization is still limited to particular applications [10, 49].

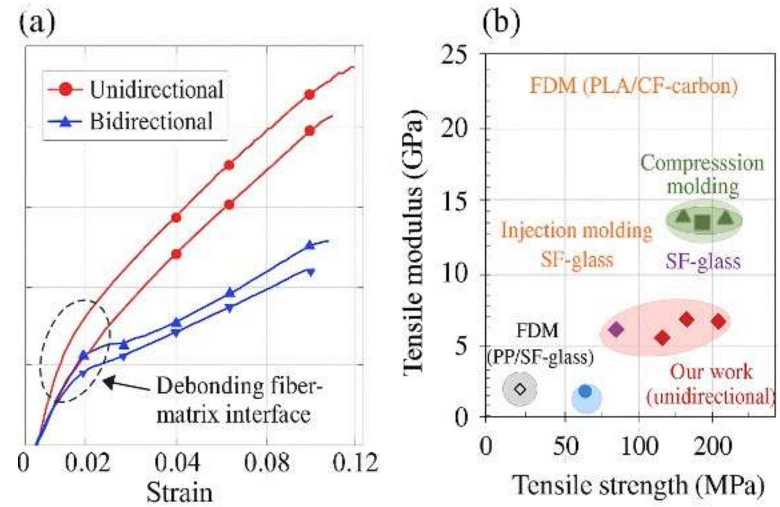

Figure 8. Tensile properties of samples printed via the proposed method: (a) stress–strain behavior and (b) E–σ_u comparison with FDM data [46–49].

Table 1. Limitations & Capabilities/Strengths of the LOM process

Capabilities/Strengths	Limitations
Enables the construction of large prototypes (800 × 500 × 550 mm3)	Models' stability and resistance can be limited by the bonding strength between the glued layers, which varies with the materials' physical properties.
Simple and economical setup	The sheets' thickness determines the height of the layers.
Fast processing time	It does not provide the opportunity to include intricate details or delicate contours.
No support structures are required.	The excess material that is generated during the manufacturing process goes to waste, which in turn increases the overall production costs.
	The model requires post-processing, which involves removing excess material, sanding, and applying paint or varnish to preserve it.

The creation and integration of composite laminates is crucial to the fabrication of composites using the LOM process. One of LOM's main benefits is its capacity to create heterogeneous composites by utilizing laminates made of various materials to change the material composition layer by layer. LOM is a special additive manufacturing method because of its adaptability. For instance, TiC/Ni composites and functionally graded materials (FGMs) have been effectively fabricated employing LOM as a post-processing step in combustion synthesis [50]. Its scalability and industrial acceptance are, however, constrained by the need to integrate several different laminate sets, which adds complexity and presents automation issues [6, 51].

3.2. Fused Deposition Modelling (FDM)

The Wohlers Report from Stratasys, Inc. states that the most popular additive manufacturing technology at the moment is fused deposition modeling, or FDM. It is commonly known as Fused Filament Fabrication (FFF) when utilized in desktop-scale equipment. More than 15,000 FDM commercial systems had been shipped by the end of 2010, accounting for around 41.5% of the global market share for additive manufacturing. A thermoplastic filament is fed into an extrusion head in FDM, where it is heated and extruded via a nozzle. To create the desired object, the material is put onto a build platform layer by layer. In order to determine the geometry of each layer, the nozzle usually moves in the X and Y directions while the build platform moves along the Z-axis. The liquefier, print head, gantry system, build surface, and filament feed mechanism are the essential parts of an FDM system [34, 52, 53]. Figure 9 displays a schematic of the FDM procedure. The final three-dimensional structure is created by the successive deposition of thermoplastic filaments in the FDM process, which solidify when cooled. Each layer's cross-sectional geometry is determined by filling the inside after defining the perimeter with extruded filament. To maximize material use, minimize part weight, and speed up print times without sacrificing functional performance, this infill can be either solid or sparse and is frequently set up as a geometric pattern (such as grid or honeycomb) [52, 54]. In the medical field, FDM has become widely used, especially in the production of affordable, patient-specific orthopaedic models and prosthetics. Its use in healthcare has been further broadened by the creation of thermoplastics that are sterilisable and biocompatible [46]. When printing intricate geometries or overhangs, support structures are frequently required. Some FDM systems have two extrusion heads—one for support material and one for structural material to combat this. After printing, the support material can be eliminated by hand or by chemical dissolution, usually with the use of sodium hydroxide (NaOH) or other caustic solutions [45, 47].

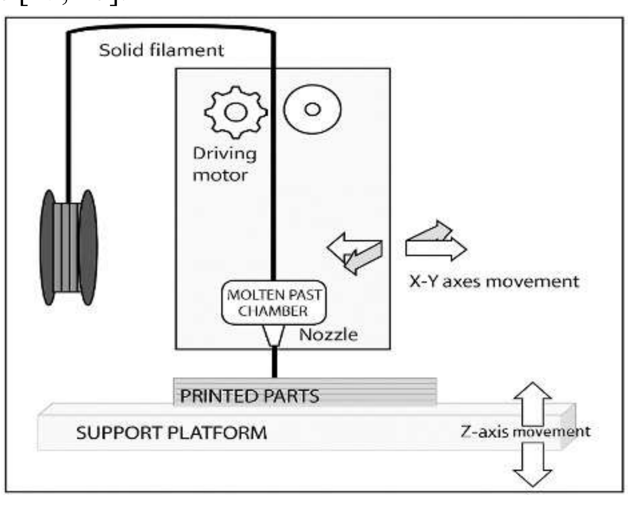

Figure 9. FDM process schematic based on the description by Acierno and Patti [55].

Fused Deposition Modelling (FDM) is known for being easy to use and straightforward. FDM does not need certain operating conditions, like a sealed build chamber or a controlled atmospheric environment, like other additive manufacturing methods do. Additionally, it is simple to handle, store, and obtain the raw thermoplastic ingredients needed for FDM [52, 54]. Despite its apparent simplicity, some process parameters, such as bead width, air gap, model build temperature, and raster orientation, have a big impact on the quality and functionality of FDM-printed items. Because of its significant influence on the tensile and compressive characteristics of printed components, raster orientation has been the subject of the most research among these [56]. Infrared thermography is frequently used during printing to track temperature distribution across the part and platform in order to guarantee constant quality [57]. Enhancing surface roughness and managing the cross-sectional form of deposited filaments are the main goals of current FDM research. A number of design and process guidelines have been put forth to improve the dimensional accuracy and mechanical strength of objects that are FDM-fabricated. These include aligning tensile load routes with the print direction, choosing smaller bead widths (which, despite taking longer to print, result in a superior surface polish), reducing stress concentrations at corners, and using negative air gaps to increase stiffness and strength [56]. The use of fiber reinforcing in FDM techniques has significantly increased recently. More recent research has moved toward investigating long fiber reinforcement to further improve mechanical qualities, whereas earlier discoveries primarily concentrated on adding short fiber additions to thermoplastic filaments. Figure 10 [34] provides a schematic representation of long-fiber 3D-printed composites made with FDM.

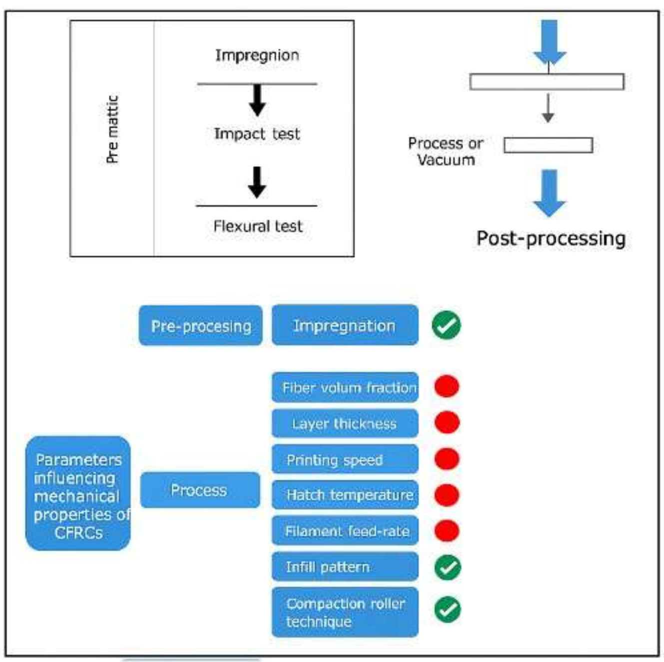

Figure 10. Schematic of fibre-reinforced composite fabrication via FDM 3D printing [58].

It has been demonstrated that adding fibers to thermoplastic filaments greatly improves the mechanical and thermal characteristics of FDM components. Fiber reinforcing improves overall print quality and dimensional stability by increasing stiffness and decreasing tape swelling during deposition [59]. For instance, while comparing glass fiber-reinforced polypropylene (PP) to unreinforced PP, Carneiro et al. [46] found that the former had a tensile strength of 40% and a Young's modulus (E) of about 30%. Thermotropic liquid crystalline polymers (TLCPs) like polypropylene (PP) and acrylonitrile butadiene styrene (ABS) have been used as matrices in fiber-reinforced FDM parts to solve problems related to low aspect ratios in short fiber-filled composites [60]. The surface morphology and subsequent mechanical performance of TLCPs are significantly influenced by the processing temperature. ABS and PP composites demonstrated 100% and 150% increases in E when filled with 40 weight percent TLCP fiber, respectively. Excellent thermal stability was also facilitated by higher breakdown temperatures brought about by an enhanced carbon fiber (CF) ratio [34]. The effects of fiber length and CF concentration on the mechanical characteristics of ABS-based FDM products were investigated in a study by Ning et al. [61]. According to the findings, adding 5–7.5 weight percent CF improved Young's modulus and tensile strength (σ_u), respectively. Longer CFs improved these metrics even more, but they also made the material less robust and ductile. The resulting composite outperformed aluminum in terms of strength when 30 weight percent CF was aligned during the FDM process, increasing mechanical strength by 115% and modulus by 700%. By lowering die swell, CF improved thermal conductivity and dimensional accuracy by reducing inter-bead spaces and triangular channels. Internal voids were also created by the addition of CF to the deposited beads, which served as stress concentrators and accelerated failure under loading [53, 62].

The efficient integration of continuous fiber reinforcements is still a significant difficulty in additive manufacturing, despite the obvious benefits of short fiber reinforcing. Although standardized techniques for integrating continuous fibers into the 3D printing process are still being developed, they offer better mechanical qualities than their discontinuous counterparts do. A novel in-nozzle impregnation technique was presented by Matsuzaki et al. [49], in which continuous fiber and thermoplastic filament are supplied into the print head independently. After being internally heated and combined, the two parts are extruded onto the build platform. Figure 11 provides a schematic illustration of this procedure and the test specimens that are produced as a result. This technique uses twisted strands of natural jute fibers and carbon fibers (CF) as reinforcement materials. Figure 12 highlights the potential of this technology in high-performance additive manufacturing applications by demonstrating the higher mechanical performance of continuous fiber-reinforced composites over their short fiber and unreinforced 3D-printed equivalents.

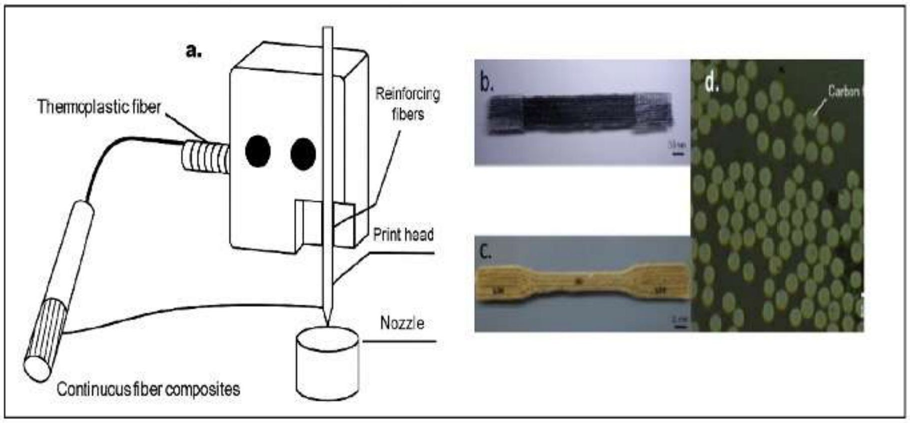

Figure 11. (a) In-nozzle impregnation FDM printer head; (b) CFRTP and (c) dumbbell-shaped JFRTP specimens; (d) cross-section of CFRTP (adapted from Matsuzaki et al. [49]).

According to Parandoush and Lin [34], Tian et al. [63] used a method for printing composite parts that used carbon fiber (CF) reinforced polylactic acid (PLA). Their findings did, however, point to the existence of spaces between PLA filaments, which might be avoided by improving printing resolution. According to Li et al. [64], continuous CF-reinforced PLA made by FDM might have an ultimate tensile strength (σ_u) of up to 91 MPa. In contrast, PLA composites reinforced with short CF exhibited a lower σ_u of 68 MPa. Yu et al. [65] pointed out that the mechanical performance of the composites is greatly reduced when there is inadequate interfacial bonding between CF and PLA. However, modifying the surface of CF bundles with PLA particles and methylene dichloride improved interfacial adhesion, which in turn improved tensile and flexural strength. Additionally, Tian et al. [66] carried out a thorough examination of the performance and interface properties of continuous CF-reinforced PLA composites, paying particular attention to how process variables affected pressure and temperature during printing.

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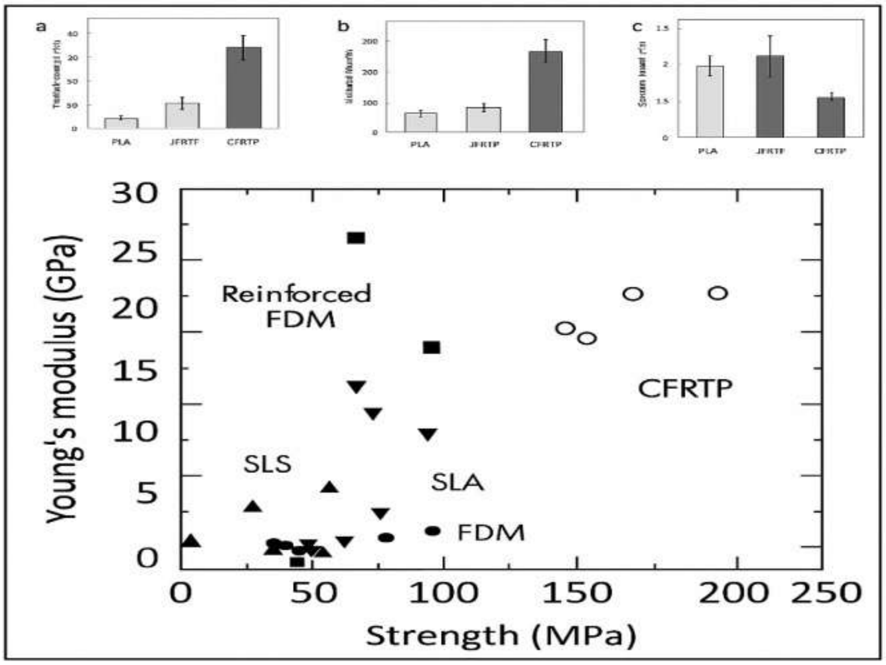

Figure 12. Mechanical properties of 3D-printed specimens: (a) E, (b) σ_u, and (c) strain-to-failure. Lower section compares carbon fibre composites from this study with FDM [62, 67, 68], SLS [69], SLA [50], and commercial FDM systems [70, 71].

Melenka et al. [72] studied the tensile characteristics of continuous Kevlar fibre-reinforced nylon structures manufactured using commercial desktop 3D printers. Their results showed that stiffness and ultimate tensile strength are greatly increased by increasing the fiber volume fraction. Similarly, carbon fiber (CF) reinforcements added between layers of 3D-printed polymers have been found to improve strength and fatigue life. Thermal post-treatment can be used to improve mechanical performance even more [73]. However, Zak et al. [74] observed that an excessive number of CF layers can lead to increased void formation, which adversely affects the ultimate tensile strength (σ_u). The impregnation of polymer into the fibre bundles is commonly accomplished at processing temperatures ranging from 200 °C to 230 °C. Maintaining a layer thickness between 0.4 mm and 0.6 mm, together with a hatch spacing of roughly 0.6 mm, helps to increased bonding strength between printed lines and layers. When these characteristics are optimized, flexural strength can reach up to 335 MPa, with a corresponding flexural modulus of 30 GPa [34]. Table 2 outlines the fundamental advantages and limits of the FDM technique, based on insights from numerous key studies [34, 50, 63].

TABLE 2. Capabilities And Limitations Of The Fused Deposition Modeling (FDM) Process (Adapted from [34, 50, 63])

Capabilities / Strengths	Limitations
Simple and easy-to-use process; does not require specialized operational conditions or industrial facilities.	Parts often require support structures during fabrication.

Cost-effective acquisition and operation of desktop equipment compared to other additive manufacturing technologies.	Surface finish is striated and layer-dependent, requiring additional smoothing.
Raw materials are easy to acquire, handle, and store.	Post-processing is required to remove supports and improve surface finish.
Parts exhibit good mechanical durability and can undergo post-processing similar to conventionally produced items.	Parts exhibit anisotropy, especially in the Z-direction, limiting structural applications.
Efficient and economical for manufacturing appearance models and semi-functional prototypes with minimal material waste.	Slower process compared to other technologies like Selective Laser Sintering (SLS) or Multi Jet Fusion (MJF).
	Low-cost desktop printers have limited dimensional accuracy and resolution.

3.3. Stereo lithography (SLA)

The 3D printing process known as stereolithographic (SLA) utilizes an ultraviolet (UV) laser to cure layers of thermosetting resin, resulting in the creation of parts. High-energy lasers are occasionally employed for thermal curing to enhance material performance [74]. This method employs a semi-viscous, photo-reactive liquid resin that can be modified with reinforcement elements or additives according to the requirements of the final product [10]. A resin vat functions as the foundation for both top-down and bottom-up configurations commonly employed in the SLA process [4, 75]. In specific advanced applications, as illustrated in Figure 13, discontinuous fibers are combined with the adhesive and aligned through the use of external fields. The build platform is immersed in the resin during the top-down method. The sweeper blade ensures a uniform dispersion of the resin layer, followed by selective curing of specific areas using a laser. The platform descends to create space for the next resin layer once the previous layer has solidified. This method proves effective for producing larger components with commendable precision and promotes the incorporation of additives. The build platform is positioned above the vat in the bottom-up approach. The laser, positioned beneath the vat, cures each delicate layer of resin. The process is repeated layer by layer as the platform elevates, enabling resin to flow beneath the cured section [74, 76].

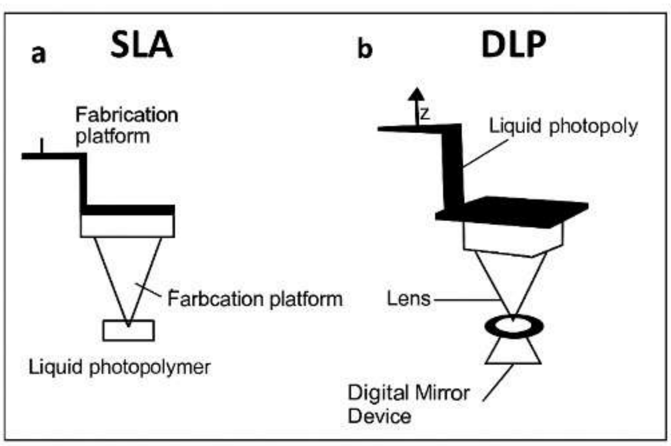

Figure 13. Schematic Illustration of (a) Top-Down Stereolithography (SLA) and (b) Bottom-Up Digital Light Processing (DLP) [77].

Digital Light Projection (DLP) technology (Figure 13b) is a major improvement over conventional point-by-point laser curing and can be used to improve the bottom-up SLA process. This technique uses UV light as the energy source to project a cross-section image onto the bottom of the resin vat, curing the entire resin layer at once. The projection technique, which is only constrained by the projected image's pixel resolution, enables the entire cross-section to solidify in a single step, greatly accelerating printing speed and preserving excellent precision (Figure 14).

Upon the elevation of the cured layer by the platform, new resin is introduced beneath, allowing for the subsequent cross-section to undergo curing in an identical manner. The arrangement of layers constitutes a green part, characterized by dimensional accuracy; however, it remains non-functional until it is subjected to a final thermal-curing process to enhance its mechanical strength. DLP provides faster production rates in comparison to conventional SLA; however, it is generally more appropriate for smaller parts or less complex geometries [78–80]. DLP technology encompasses two main variations: static and continuous. The static DLP method cures each layer in distinct increments, projecting a 2D cross-sectional image as the platform is gradually elevated. The continuous DLP process, referred to as Continuous Liquid Interface Production (CLIP), employs a consistently moving projected image that synchronizes with the ascending platform, facilitating an uninterrupted flow of resin beneath the component [81]. A range of DLP printers utilizing these techniques is presently accessible in the commercial market.

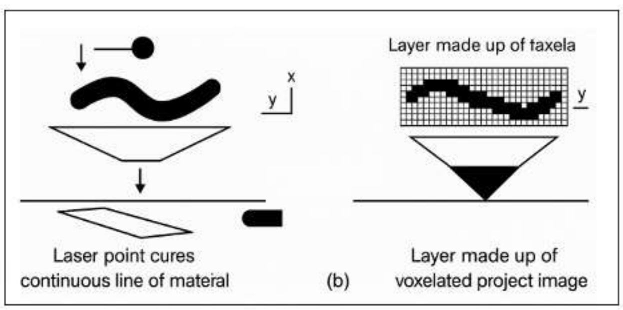

Figure 14. Printing principles of (a) Stereolithography (SLA) and (b) Digital Light Processing (DLP) [78–80].

The majority of Digital Light Processing (DLP) printers offer build volumes ranging from 0.67 to 4.56 liters, with resolutions varying between 47 µm and 100 µm [82]. DLP has demonstrated significant utility across multiple sectors, such as fashion, jewelry, and sports goods. Additionally, it has established itself as an effective technique in the medical and dental domains, particularly when dealing with biocompatible materials. The main benefits of DLP include its remarkable precision and swift processing abilities, making it well suited for competitive small-scale manufacturing [83].

The DLP process utilizes a stationary UV laser, directed by mirrors, to gradually solidify photopolymer resin in a precise, layer-by-layer manner. As the laser moves along the x- and y-axes, it initiates semi-permanent polymerization in the resin, effectively linking each point to the neighboring areas and forming a solid, unified structure. Nonetheless, the initial product, known as a green body, often requires post-curing to attain its full mechanical and thermal strength [76]. Both top-down and bottom-up SLA configurations require support structures, especially for features such as overhangs and bridges that exceed 30°. The preservation of dimensional stability and surface quality is significantly dependent on these supports. It is crucial to recognize that top-down systems typically demand fewer supports, while bottom-up systems often require more, especially in situations with reduced cross-sectional areas [84].The dimensions of SLA machines differ according to the resin vat and the desired output. For example, desktop SLA printers typically offer build volumes of approximately 145 × 145 × 145 mm^3, while industrial versions can accommodate dimensions up to 2000 × 2000 × 2000 mm^3. The typical dimensional accuracy falls within the range of 0.15% ± 0.01 mm to 0.5 ± 0.10 mm, while the layer thickness can be adjusted between 25 and 100 µm [86–88]. SLA is recognized as one of the quickest single-point additive manufacturing methods, even though its overall build speed is comparatively slower than certain alternatives, typically ranging from 10 mm/h to 17 mm/h [89]. Stereolithography (SLA) serves as a method for producing composite materials through the combination of photopolymers with reinforcing fibers or particles, thereby improving the strength and overall characteristics of the printed components. Nevertheless, the integration of these solid fillers presents a number of challenges. The inclusion of reinforcement particles elevates the viscosity of the resin, thereby complicating the process of layer formation. Furthermore, the settling of particles may cause an uneven distribution of fillers throughout the resin, which can lead to variations in mechanical performance. During the mixing or printing process, the entrapment of air bubbles can lead to porosity, serving as a potential site for the initiation of cracks. Additionally, the scattering of laser light by solid fillers disrupts the absorption of UV light, which can delay the curing process and may jeopardize both print quality and structural integrity [90–92].

To tackle these challenges, the Opt form process utilizes resin pastes rather than liquids, which enhances particle suspension [93]. The integration of thermal curing with photo polymerization has demonstrated effectiveness in the production of reinforced polymer composites [93, 94]. SLA is widely recognized for its effectiveness in fabricating ceramic matrix composites (CMCs), attributed to its impressive resolution, surface finish, and satisfactory build speed [95–99]. Nonetheless, engaging with materials such as boron carbide (B_4C), graphene, and carbon nanotubes presents certain challenges. Their elevated light absorption and refractive index restrict UV penetration, posing challenges in attaining adequate cure depth. Creating thick-walled components that exhibit minimal porosity and cracking presents challenges, particularly due to substantial shrinkage occurring during the debinding process, especially in samples containing high levels of organic material. The debinding phase, crucial for eliminating binder agents, requires significant time and is greatly affected by the thickness of the part [100, 101]. In contrast, glass fibers demonstrate superior compatibility with SLA due to their enhanced transparency to UV light, rendering them particularly suitable for fiber-reinforced composites (FRCs) [102]. Studies focused on SLA have investigated the use of short fibers, continuous fibers, and fiber mats [103–105]. Although continuous fibers typically provide enhanced mechanical performance, short fibers with elevated aspect ratios have also shown impressive outcomes [102]. Nonetheless, augmenting the fiber volume fraction to improve properties could adversely affect layer formation and complicate subsequent processing steps. The application of surface coatings to fibers has the potential to decrease resin viscosity and enhance flow [105].

Fibers enhance interlayer adhesion by infiltrating the uncured areas of previous layers [103]. Nonetheless, the uneven distribution and arbitrary alignment of short fibers could undermine the integrity of the material and elevate the risk of fractures during the fabrication process. Investigations highlight that the arrangement and orientation of reinforcements play a crucial role in determining the mechanical properties of fiber-reinforced composites. Furthermore, throughout the processing phase, the alignment of fibers in concentrated suspensions changes, influencing the ultimate performance of the composite [106, 107]. Table 3 presents a comprehensive analysis of the advantages and disadvantages associated with the SLA process.

Table 3. Capabilities and Limitations of the SLA Process

Capabilities/Strengths	Limitations
Manufacture highly detailed 3D models with ultra-thin layer thicknesses (1–25 µm) and superior surface quality.	The printing time for this process is longer than that of other printing technologies.
3D models produced are isotropic, allowing for better molecular bonding between layers.	Requires support structures which may collapse during printing or break during final curing if not properly managed.
A variety of resin formulations are available to replicate engineering materials for specific applications.	Resins are brittle and photosensitive; exposure to sunlight can distort or degrade printed models.
Enables larger build volumes without sacrificing precision.	Printed models are generally unsuitable for outdoor use, lamp housings, or mechanical testing.
	Resins are often proprietary and cannot be interchanged between different brands of SLA equipment.
	SLA printing is generally more expensive than FDM, both in terms of equipment and consumables.

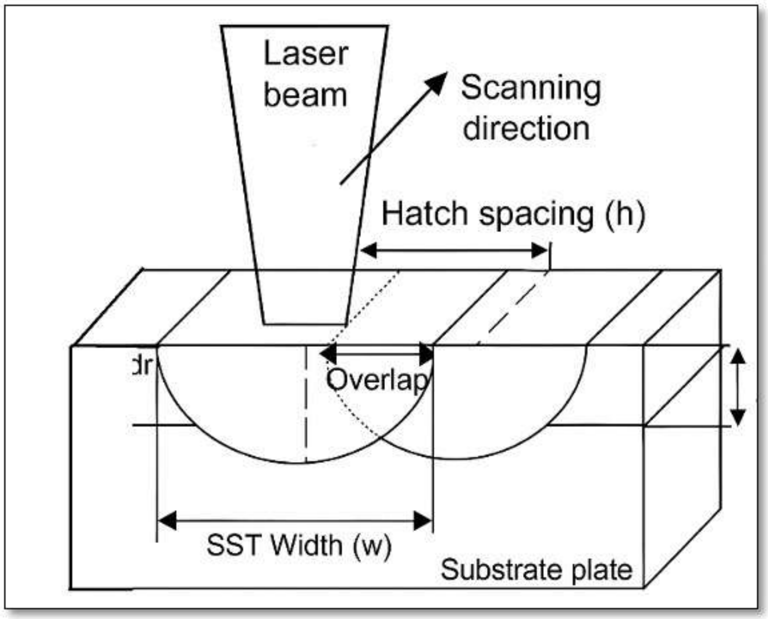

Figure 15. Schematic illustration of the Selective Laser Sintering (SLS) process [110].

Selective Laser Sintering (SLS) has found widespread application in numerous industries, thanks to its ability to work with a diverse range of materials. The materials discussed encompass a range of categories, including waxes, cermets, and ceramics such as Al_2O_3, FeO, NiO, ZrO_2, SiO_2, and CuO. Additionally, polymers like PVC, PE, PP, PMMA, PS, PET, PA, and PC are included, along with metals such as Al, Cr, Ti, Fe, and Cu. The metallic systems mentioned consist of combinations like Fe-Cu, Fe-Sn, and Cu-Sn. Furthermore, various alloys are highlighted, including cobalt- and nickel-based alloys, bronze-nickel combinations, INCONEL® 625, Ti-6Al-4V, stainless steels (notably gas-atomized 316L), AISI 1018 carbon steel, high-speed steels, pre-coated foundry sands, and alumina paired with polymer binders. Furthermore, the technology has been utilized in biomaterial composites that incorporate metal–polymer and metal–ceramic systems [111]. The main reasons for employing SLS in composite processing are: (1) improving particle bonding during sintering, (2) combining various materials to enhance mechanical or functional properties [112], and (3) its exceptional ability to create lightweight, geometrically intricate structures utilizing polymer and metal powders. SLS is especially appealing for aerospace applications, utilized in the production of components like ducting, brackets, and housings, appreciated for their exceptional dimensional accuracy and isotropic material properties [113].

An exemplary case of the initial method is the Fe-Cu composite system, in which copper serves as a transient binder, melting during sintering to unify iron particles. Nonetheless, it does not play a substantial role in the ultimate properties of the material [114].

Conversely, in systems such as polycaprolactone/hydroxyapatite (PCL/HA), hydroxyapatite is incorporated to specifically improve the strength and biocompatibility of the base polymer (PCL), a common application in biomedical engineering [115]. Although Liquid Phase Sintering (LPS) is sometimes, employed, selective laser sintering (SLS) predominantly utilizes selective laser energy to bond powder particles via partial melting. The powder bed experiences thermal cycling, facilitating the coalescence of particles according to their thermo-mechanical properties without achieving complete melting [116, 117]. Significant composite systems created through SLS encompass PCL/HA (Kumar and Kruth) [6], PEEK/HA (Tan et al.) [118], and PA/nano-clay composites (Kim and Creasy) [119]. In polymer matrix composites, particulate reinforcements are favored over fibers, as the latter can obstruct smooth powder layering and do not considerably improve the final mechanical properties or density. Nonetheless, research conducted by Yan et al. [120] revealed that the oxidation of carbon fibers (CF) prior to their incorporation resulted in enhanced dispersion and stronger interfacial adhesion, thereby positively affecting the composite's flexural strength and elastic modulus. SLS composites find practical applications in various sectors, including automotive components like Al-SiC composites, injection mould tooling such as Nylon12 filled with carbon black, turbine and engine parts like SiC/Ti, and biomedical devices, which encompass implants and prosthetics made from PEEK HP3 [111]. An illustration in automotive applications is the SLS-based production of an engine inlet manifold utilizing a mixture of carbon nanotubes (CNT) and polyamide (PA12) [121, 122]. The microstructures of these composites were favorable for electrical conductivity. Nonetheless, the existence of porosity within the laser-sintered matrix adversely affected thermal conductivity. The CNT/PA12 composite continues to show potential for practical application [121]. Utilizing composite powders such as glass-filled polyamide can streamline the fabrication process, eliminating the need to mix polymer and reinforcement powders separately [122]. This approach guarantees a consistent distribution and resolves any issues related to mixing inconsistencies. Nonetheless, obstacles remain when incorporating fibrous materials into composite powders, particularly concerning handling and dispersion challenges [6]. SLS has been employed in the development of Metal Matrix Composites (MMC) and Ceramic Matrix Composites (CMC). Instances encompass Fe–graphite [123, 124], WC–Co cemented carbides [125], WC–Co–Cu blends [126], and configurations involving Fe, Ni, and TiC [127]. Ceramic composites such as SiC have been advanced using this approach [128, 129]. Nonetheless, achieving fully dense ceramic and metallic components through SLS alone presents challenges when compared to PMCs. In order to tackle this issue, the incorporation of binders or additives is essential for achieving improved densification and consolidation [6]. An innovative method entails the in situ creation of reinforcement particles throughout the laser sintering process, utilizing laser-induced chemical reactions. The laser provides energy essential for the formation of chemical bonds and the maintenance of thermal reactions. This approach guarantees a more refined dispersion, better wetting, and superior binding because of the exothermic characteristics of these reactions [6]. An illustrative case is a copper-based MMC enhanced with TiB_2, created from a mixture of Cu, Ti, and B_4C powders [130]. A different approach integrates SLS with subsequent processing methods, including furnace infiltration and chemical reactions. The formation of Si/SiC composites serves as a standard application. The initial step involves the infiltration of SiC with phenolic resin through the SLS method. After furnace curing, the carbon from the resin interacts with the infiltrated silicon, resulting in the formation of more SiC. Through the modification of the resin treatment level, one can achieve precise control over the SiC content in the final composite [131]. Please consult Table 4 for an overview of the advantages and drawbacks of the SLS technique.

Table 4. Capabilities and Limitations of the SLS Process

Capabilities / Strengths	Limitations
Produces highly accurate and isotropic parts, ideal for functional prototypes.	Surface finish is naturally satin-matte and slightly grainy.
Faster than stereo lithography (SLA) and fused deposition modeling (FDM).	Dimensional variations and surface inconsistencies may arise due to material differences and process conditions.
Consistent build time for parts of similar height, making it efficient for small-batch production.	The build size is restricted by the powder container; typically around 300×300×300 mm^3, though some systems offer up to 700×380×580 mm^3.
No support structures are required, reducing material waste.	Parts must undergo a lengthy cooling phase before removal, and the machine needs thorough cleaning and setup.
Minimal post-processing is required as support removal is unnecessary; excess powder is easily brushed off.	Manual post-processing can cause slight variations in color and surface texture.
	High operational cost due to expensive machines, installation needs, and proprietary material prices.

3.5 Directed Energy Deposition (DED)

Directed Energy Deposition (DED) represents a significant breakthrough in Additive Manufacturing, especially within metal-based applications. This beam-based method entails the concurrent application of material and energy to a designated area, resulting in the melting and layering of the material in successive deposits [132]. DED processes are typically categorized into three primary types: Wire and Arc Additive Manufacturing (WAAM), Direct Electron Beam Deposition (DEBD), and Direct Laser Deposition (DLD), with DLD being the most commonly utilized. Figure 16 presents a schematic representation of the DLD process, providing a visual elucidation of its operational principle [17, 133].

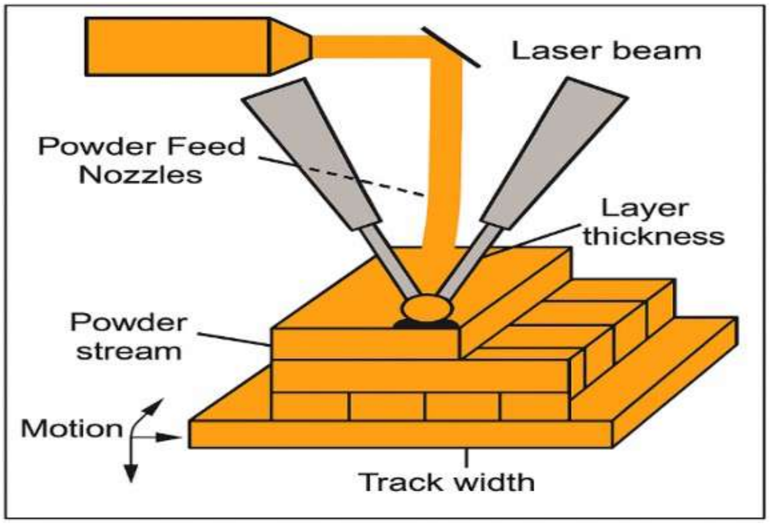

Figure 16. Schematic illustration of a typical laser-based Powder Directed Energy Deposition (DED) process (adapted from [131]).

In recent years, numerous technologies and terminologies associated with Direct Laser Deposition (DLD) have surfaced, such as Laser Engineered Net Shaping (LENS), Direct Metal Deposition (DMD), Laser Metal Deposition (LMD), and Laser Cladding (LC) [126]. In this investigation, these terms are collectively designated by the overarching term DLD [134]. DLD employs a laser as its energy source, presenting multiple benefits: it facilitates (1) swift prototyping of metal components, (2) the creation of complex and customized geometries, (3) cladding and restoration of valuable metallic parts, and (4) on-location manufacturing or repair in remote or infrastructure-challenged regions. In comparison to alternative additive manufacturing techniques, DLD offers (1) reduced production times, (2) decreased manufacturing costs, and (3) enhanced design and customization flexibility [135].

Contemporary DLD systems feature a variety of laser types, such as fiber lasers, diode lasers, and Neodymium-doped Yttrium-Aluminum-Garnet (Nd:YAG) lasers, which enhance processing efficiency and operational reliability [136, 137]. Alongside the laser type, various processing parameters play a crucial role in influencing the DLD process. The factors to consider are (1) the relative speed between the laser and substrate (traverse speed), (2) the laser scanning strategy, (3) laser power, (4) laser beam diameter, (5) hatch spacing, (6) inter-layer dwell time, and (7) powder feed rate. The parameters in question are significantly dependent on the specific materials used and differ across various DLD systems, which in turn directly affects the final quality and characteristics of the produced part [135, 138].

A notably significant function of DLD lies in its application for the fabrication of composite materials. The technique enables precise control over powder feed rates, allowing for variations in material composition throughout the build process, which facilitates the creation of Functionally Graded Materials (FGMs), as demonstrated in Figure 17 [139–141]. A diverse range of materials can be utilized for this application, such as stainless steels (e.g., SS316, SS316L, SS304L, SS420, and SS630), nickel-based alloys (e.g., INCONEL® 625, 690, and 718), and titanium-based alloys (e.g., Ti6Al4V and Ti48Al2Cr2Nb). Furthermore, specific metallic powders such as Stellite 6 and Metco 42C have been formulated for applications tailored to DLD [137].

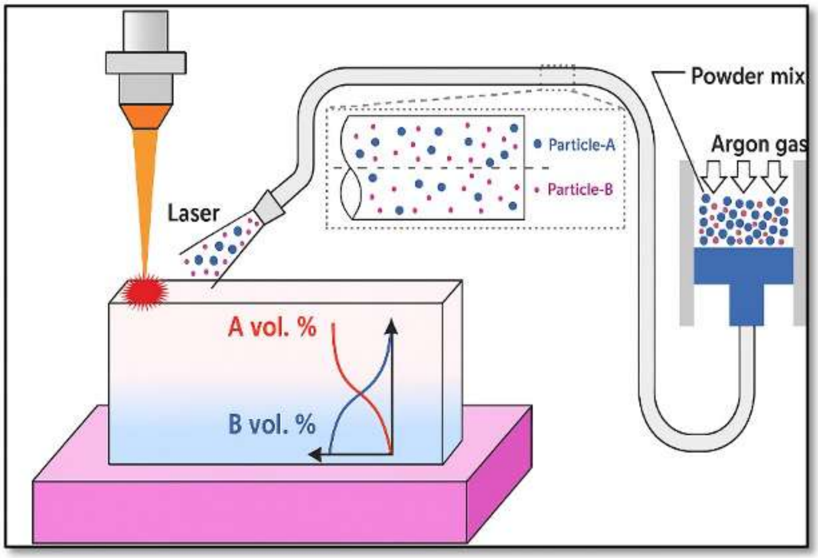

Figure 17. Schematic representation of the Directed Energy Deposition (DED) process for Functionally Graded Materials (FGMs), depicting the simultaneous deposition of two distinct materials onto a substrate using a laser-based energy source [141].

Direct Laser Deposition (DLD) is utilized in the fabrication of composites that combine metallic and ceramic powders to improve material performance. Li et al. [142] conducted an in-depth review of the latest advancements in additive manufacturing (AM) as it pertains to five distinct categories of Metal Matrix Composites (MMCs). Their work emphasizes emerging trends, including the understanding of formation mechanisms of strengthening phases, the optimization of materials and processing parameters to achieve performance targets, innovative design strategies specifically for laser AM MMCs, and advancements in simulation, monitoring, and process optimization techniques. Titanium (Ti) stands out as the predominant metal matrix utilized in these applications, while nickel-based alloys have also been investigated. Ceramic reinforcements often comprise compounds like titanium carbide (TiC), titanium boride (TiB), and titanium nitride (TiN) [143]. DLD finds significant application in the repair and remanufacturing of high-value components, including steam turbine blades, dies, molds, gears, diesel engine crankshafts, gas turbine burners, motor shafts, rail tracks, and a range of automotive parts. The applications leverage DLD's ability to create lightweight components that exhibit enhanced strength-to-weight ratios [144–150]. Conversely, practical applications of Functionally Graded Materials (FGMs) are predominantly in the experimental phase, frequently confined to the fabrication of samples and studies focused on material characterization [139]. For example, Humarán-Sarmiento et al. [151] utilized Directed Energy Deposition (DED) with a laser to create single-layer MMC coatings composed of Stellite 6, reinforced with 10%, 20%, and 30% WC-Co (12%). The study concentrated on enhancing process parameters including laser power, travel speed, and powder feed rate to manage dilution and porosity effectively. Furthermore, an analysis was conducted on the microstructure, hardness, surface roughness, and thermal response of the coatings.

In a separate investigation, Shalnova et al. [152] analyzed the structural and mechanical properties of Ti–6Al–4V/SiC MMCs produced through DED. The compositions were evaluated with different silicon carbide (SiC) content levels: 1 vol %, 3 vol %, 5 vol %, and 7 vol %. The addition of 1 vol% SiC markedly improved the tensile strength of the titanium alloy, increasing it to 1300 MPa, while elongation decreased to 2.1%. Romio et al. [153] showcased the effectiveness of DLD in part restoration through the reconstruction of the teeth of 16MnCr5 spur gears. A dual-material approach was employed to achieve this: INCONEL® 625 was utilized for the gear core, while AISI 413 (Metco 42C) served as a surface coating to enhance hardness. Figure 18 depicts the procedure. While the resulting structure does not meet the criteria for an MMC, the approach demonstrates the capability of DLD to incorporate material inserts into used components. The gear profile was precisely reconstructed through the application of Wire Electrical Discharge Machining (WEDM), utilizing a digitized model of an undamaged gear tooth as a reference. Further advancement in this field includes the work of Wang et al. [154], who employed Laser-Directed Energy Deposition (LDED) [155] to incorporate carbon nanotubes (CNTs) into a WE43 magnesium alloy. The integration led to a notable enhancement in wear resistance by utilizing the exceptional mechanical properties of CNTs along with their natural self-lubrication capabilities. The improvements were linked to better resistance to plastic deformation, the development of a protective carbon layer, and decreased friction during operation.

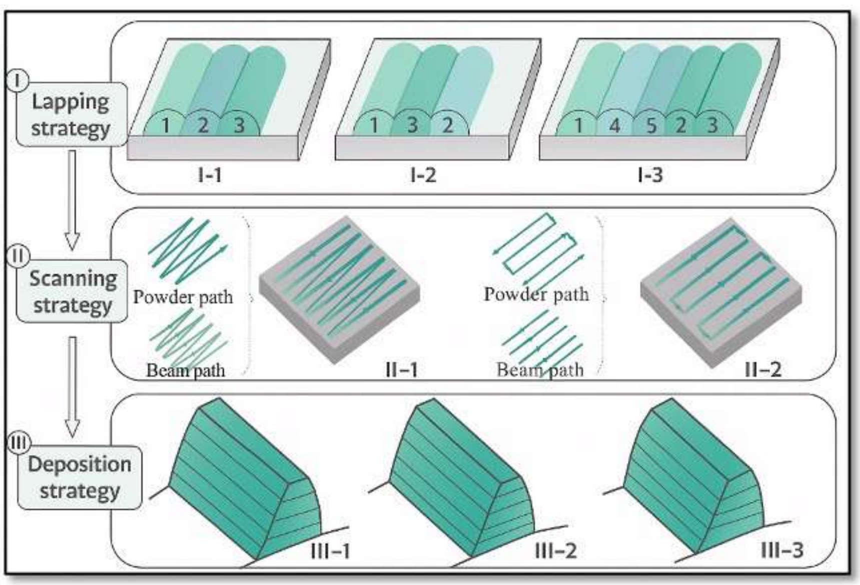

Figure 18. Optimized Deposition Strategies for Gear Tooth Fabrication: (I-1) Hot lap joint, (I-2) Cold lap joint, (I-3) Optimized cold strategy; (II-1) Co-directional scanning, (II-2) Reverse scanning; (III-1) Interlayer scanning perpendicular to the axial direction, (III-2) Interlayer scanning parallel to the axial direction, (III-3) Alternating interlayer scanning directions (perpendicular between adjacent layers) [156].

4. Discussion

This study provides an in-depth analysis of Additive Manufacturing (AM) technologies for composite materials, emphasizing their unique features, capabilities, and inherent limitations. The inclusion of a SWOT analysis (Table 6) offers valuable insights; nonetheless, the discussion could be enhanced by adopting a more structured, application-oriented framework. This framework will assist both experienced professionals and those new to the field in determining the most appropriate additive manufacturing technology for specific applications. The project should include clearly defined objectives, a systematic assessment of technologies, identification of critical internal and external factors, and the development of an accessible decision-making tool.

To effectively leverage Additive Manufacturing (AM) in the production of composite materials, it is essential to establish a clearly defined manufacturing context. A methodical approach to decision-making should begin by categorizing the intended element as structural, aesthetic, or functional. This classification helps to align the additive manufacturing process with the desired performance characteristics, such as ultimate tensile strength (σ_u), stiffness, surface quality, and production scale. Additionally, it is crucial to carefully assess operational limitations including time constraints, budget limitations, and resource accessibility. By clearly defining these parameters, professionals can select the most appropriate AM technology that corresponds with the unique requirements of a specific application, thus guaranteeing optimal efficiency and performance. Clearly defining these parameters is crucial for experts to align particular AM technologies with project needs. This approach lays a robust groundwork for selecting the most appropriate additive manufacturing technique.

This study offers a comprehensive examination of Additive Manufacturing (AM) technologies for composite materials, highlighting their distinctive characteristics, functionalities, and fundamental constraints. The incorporation of a SWOT analysis (Table 6) provides important insights; however, the discussion would benefit from the introduction of a more organized, application-focused framework. This framework would aid both practitioners and newcomers in identifying the most suitable AM technology for particular use cases. The project must encompass well-articulated objectives, a methodical evaluation of various technologies, recognition of essential internal and external elements, and the creation of an easily navigable decision-making instrument.

To effectively utilize Additive Manufacturing (AM) in the production of composite materials, it is crucial to establish a well-defined manufacturing context. A systematic approach to decision-making should initiate by classifying the intended element as either structural, aesthetic, or functional. This classification aids in aligning the additive manufacturing process with the intended performance characteristics, including ultimate tensile strength (σ_u), stiffness, surface quality, and production scale. Furthermore, it is essential to meticulously evaluate operational constraints such as time limitations, budgetary restrictions, and resource availability. By clearly defining these parameters, practitioners can choose the most suitable AM technology that aligns with the specific needs of a particular application, thereby ensuring optimal efficiency and performance. Clearly defining these parameters is essential for professionals to match particular AM technologies with project requirements. This method establishes a solid foundation for identifying the most suitable additive manufacturing process. The article expands on its examination of different additive manufacturing techniques, including Laminated Object Manufacturing (LOM), Fused Deposition Modeling (FDM), Stereolithography (SLA), Selective Laser Sintering (SLS), and Directed Energy Deposition (DED), to evaluate concerns regarding material compatibility, dimensional accuracy, surface finish, mechanical performance, efficiency, and sustainability. Essential findings encompass

4.1 Compatibility of Materials:

Stereo lithography (SLA) excels in the processing of photopolymer resins, delivering outstanding resolution and surface quality, which makes it perfect for applications that demand visual detail and precision. Fused Deposition Modeling (FDM) demonstrates compatibility with a diverse array of thermoplastic materials and composite filaments. The inherent flexibility of the material renders it exceptionally suitable for the creation of economically viable prototypes and functional models. Directed Energy Deposition (DED) can process metal and ceramic powders, making it a promising method for producing high-performance components that demand improved mechanical and thermal properties.

4.2 Production Capabilities:

Regarding geometric complexity, both SLA and Selective Laser Sintering (SLS) excel in creating intricate shapes and fine details. Nonetheless, components produced through SLA frequently necessitate extensive post-processing to attain their final functional state. FDM is notable for its straightforwardness and ease of use, providing an effective approach for quick prototyping and the creation of semi-functional parts with minimal preparation. DED possesses a distinctive ability to fabricate Functionally Graded Materials (FGMs), allowing for compositional variation within a single component. Nonetheless, this capability requires rigorous management of various processing parameters, including laser power, scan speed, and powder feed rate, to guarantee the integrity and consistency of the part.

4.3 Considerations for Sustainability:

Considering sustainability, Laminated Object Manufacturing (LOM) and Fused Deposition Modeling (FDM) tend to be more eco-friendly, generating less material waste in comparison to traditional subtractive manufacturing methods. However, certain additive manufacturing techniques, such as selective laser sintering, rely significantly on proprietary powder materials. This reliance not only escalates operational expenses but also brings forth issues regarding recyclability and the broader environmental implications. The SWOT analysis serves as an essential instrument by providing a comprehensive view assessing both internal strengths and weaknesses as well as external opportunities and threats in AM processes [159]. The data gathered for this analysis (Table 6) were sourced from a comprehensive examination of the current literature, featuring significant studies such as LOM by Park et al. [160], FDM by Jin et al. [54], SLA by Niendorf and Raeymaekers [75], SLS by Xiao et al. [106], and DED by Ahn [147], among others. The analysis of these sources was conducted meticulously to distill and summarize essential insights pertaining to the strengths and limitations of each additive manufacturing technology.

Table 6. SWOT Analysis of Additive Manufacturing for Composite Materials

Factors	Positive	Negative
Internal (Within the AM processes)	*Strengths* • Versatile use of materials like FRPs and MMCs tailored to load-specific needs. • Enables fabrication of complex and customized geometries. • Reduced material waste compared to traditional methods. • Accelerates prototyping and reduces lead times.	*Weaknesses* • Lower mechanical strength and poor layer bonding in FDM and SLA. • Rough surfaces and reduced precision in FDM and LOM. • Porosity and inconsistencies in DED and SLS, especially for MMCs. • High equipment and material costs in advanced processes like DED and SLS.
External (From the surrounding market and regulations)	*Opportunities* • Increasing demand for lightweight, strong parts in aerospace, automotive, etc. • Advances in fibre and matrix materials improve AM capabilities. • Real-time monitoring enhances part quality and efficiency. • Eco-friendly processes align with sustainability goals.	*Threats* • Traditional methods (e.g., molding, casting) offer lower costs and faster large-scale output. • Limited material choices and process constraints. • Skilled workforce needed for optimal use. • Regulatory and certification challenges in safety-critical industries.

5. Conclusion

This article offers a succinct overview of essential additive manufacturing techniques for composite materials, emphasizing well-known methods including LOM, FDM, SLA, SLS, and DED. The focus is on recent advancements in materials, such as melt-processable thermosetting resins and hybrid composites, which have broadened additive manufacturing applications in aerospace, automotive, and biomedical sectors. An organized examination assesses these techniques in terms of material compatibility, performance, and cost, indicating that the best approach is contingent upon the part’s function and production environment. The document presents a SWOT analysis, detailing internal strengths such as customization and reduced waste, as well as weaknesses like limited mechanical strength, in addition to external opportunities and threats. The existing challenges—such as void formation and fibre-matrix adhesion—underscore the necessity for additional investigation. The findings indicate that there is no one-size-fits-all additive manufacturing process and highlight the necessity of matching the selection of AM methods to the specific needs and limitations of each project. This work provides a strategic framework that facilitates informed decision-making and lays the groundwork for future advancements in additive manufacturing for composite production.

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2. Materials and Methods

2.1 First Level Heading

For a better understanding of the content in the article, we encourage authors to number the article headings in Arabic style format. Headings should follow title case, meaning that all words except

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for prepositions, articles, and conjunctions should be capitalized. All botanical names should be in italics. In-text Citations are cited as follows:

Single reference: denote it as 1 (superscript 1)

Two or more references: denote it as 1,2

Example

Single Reference

1. Introduction

Plant-based natural products, animal derived natural products and minerals have been the foundation of treatment of different human diseases[25]. Many people around the world, especially in the developing countries, are increasingly relying on plant-derived traditional medicines. The world health organization defined medicinal plants as any plant that possess bioactive compounds in one or more of its organs that can be used for healing purposes[13]. *Calotropis procera* (Figure 1.) a plant of family Asclepiadaecae is an Ayurvedic plant that possess significant medicinal characteristics. It exists in many parts around the world with a worm climate in dry, sandy and alkaline soils[4]. Arid and semi-arid areas, are the main areas where *Calotropis procera* grow substantially without the need of pesticides, chemical fertilizers and irrigation[47]. Different *Calotropis procera* parts were employed for therapeutic purposes in the traditional medicines and their medicinal characteristics were emphasized by many scientists[49]. *Calotropis procera* latex, for example, is characterized by its significant medicinal value and pharmacological activities due to its high content of different phytochemicals like cardiac glycosides, alkaloids and steroids[34].

Tribulus genus belongs to family zygophyllaceae that roughly contains 25 different plant species which grow as hairy herbs in tropical and warm areas[43]. *Tribulus terrestris* (Figure 2) is a well-recognized and vastly distributed plant of the genus Tribulus. *Tribulus terrestris* is known by various widespread names: puncture vine,

Example For Two or more references

2. Botanical Description

2.1 Taxonomy and Nomenclature

Barringtonia racemosa is one of the species in Plantae kingdom from genus Barringtonia which are classified under the family of Lecythidaceae. The Barringtonia genus got its name after Hon. Daines Barrington, 1727-1800, an English nobleman, lawyer, antiquary and naturalist who wrote a book on English trees[5,12]. Botanically, the 'racemosa' term at the later part of the scientific name are reflecting the racemes structure of the species that it possesses which depicts a string-like arrangement of stalked flowers[5]. The taxonomic hierarchy of *B. racemosa* could be arranged in the following order[13]:

Whenever cited references in range then it will be as follows:
Ex: Intestinal protozoan infections continue to remain a global public health challenge, particularly in developing countries3-6.
Abbreviations
All abbreviations should be defined on first mention in the text along with the abbreviation in parenthesis. E.g. Magnetic Resonance Imaging (MRI).
If too many abbreviations are there in full text then mention all those together in alphabetical order after keywords and use heading as "Abbreviations"
Units and Symbols
Symbols should be used while referring to alpha, beta, mu, etc (Ex: α, β, μ, etc). All units to follow the International System of Units (SI units).
Equations
Equations and formula should be readable, preferably written using equation editing softwares (E.g. MathType). Alternatively, authors have to provide the fonts used for creating the equations/formulae. Number the equations consecutively with equation numbers in parentheses flush with the right margin, as in (1)
Spreadability (S) = ML/T Eq.-1
Botanical/Zoological/ Names
Example : Calotropis procera

2.2 Second Level Heading

Sub headings are written in Title Case
Eg:

2.2.1 Sub Sub Heading

Sub sub headings are written in Title Case and are italicized.
Eg:
3. Results and Discussion
4. Conclusion
5. Acknowledgments
People who contributed to the work but do not fit the criteria for authors should be listed in the Acknowledgments, along with their contributions. Authors are requested to ensure that anyone named in the Acknowledgment agrees to being so named.

6. Funding/Conflicts of interests if any

7. Please mention what each author has contributed to the Manuscript.

Eg: Conceptualization, M.L.G. and M.K.; methodology, M.L.G. and M.K.; software, M.L.G. and M.K.; validation, M.L.G. and M.K.; formal analysis, M.L.G. and M.K.; investigation, M.L.G. and M.K.; resources, M.L.G. and M.K.; data curation, M.L.G. and M.K.; writing—original draft preparation, M.L.G. and M.K.; writing—review and editing, M.L.G. and M.K.; visualization, M.L.G. and M.K.; supervision, M.L.G. and M.K. All authors have read and agreed to the published version of the manuscript.

8. References

- Only published or accepted manuscripts should be included in the reference list. Meetings, abstracts, conference talks, or papers that have been submitted but not yet accepted should not be cited.
- In text citations: References cited in text should conform to the Vancouver style. Please refer the Vancouver Style of Referencing. Always follow ascending order of citation in full text.
- Reference List: This should only contain references to those works which you have cited in your text. It should appear at the end of your text. It should be arranged numerically by citation number.

Tables and Figures (Cite the figure and table numbers in full text of the article)

Table 1: The vernacular names of *B. racemosa* according to geographical regions

Language/ Country / Region	Vernacular Name	Reference
English	Barringtonia, brack-water mangrove, common putat, hippo apple, powderpuff tree, wild guava.	6, 14
Malaysia	Putat kampung, putat padi, putat darat, putat kedul.	15, 16
Brunei	Angas gimpalang, angas gimplang, putat aying.	6, 17
Indonesia	Butun, alakan, butun darat, kungkungan, putat.	6, 17
Myanmar	Kye-bin, kyi	6
Cambodia	Dawm trojiekbres, pchek tekbray	6
Philippines	Botong, ulam, kasouai, putat, tuba-tuba, kutkut-timbalon, nuling,paling	6, 17
Thailand	Chik	17
Laos	Som pawng	6
Papua New Guinea	Paniak, paopao	6
China	Yu rui	6
India	Samudrapandu	15
East Africa	Mtomondo	6
Southern Africa	Poeierkwasboom, iBhoqo, iBoqo (Zulu)	6
Tanzania	Mkuvumkuvu, mtomondo	6
Madagascar	Fotatre, magnondro, manondro, manontro	6

Tables: General guidelines

- Tables should be numbered consecutively in accordance with their appearance in the text and should be cited in full text.
- All tables should have a concise title and written as Table 1 with a period (.).

E.g. Table 1. Stimulation settings

Footnotes can be used to explain abbreviations. Tables extending beyond 1 page should be avoided.

Eg:

Figures: General Guidelines

- Figures Format & Resolution: Authors are requested to supply high-resolution versions of the figures in TIFF, JPEG or EPS format. We require figures to be created at a minimum resolution:
  Black & White Images - 900 dpi
  ColouredImages - 600 dpi
  Line art-grey colour - 600 dpi
-
- File size: The file sizes should not exceed 20 MB.
- File naming: Naming of figure files should be simple indicating the serial number and last name of author. E.g. if author's name is Bob Marley, Figure 1 should be named as "Fig 1_Marley".
- Figure submission: Figures should be submitted after uploading the article (in step 4 of the submission process in supplementary files). In case of multiple files, upload the figures in order. E.g. Figure 1 should be uploaded first followed by Figure 2, 3 and so on.
- Citation: All figures must be cited in the text and authors should indicate where they are to be inserted in the text. E.g. <insert figure 1 here>.
- Figure captions: These have to be provided sequentially at the end of the article. The captions should be short having 10-15 words in sentence case style. E.g. Figure 1. Percentage of detection rate vs. number of nodes.
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Eg:

Figure 1. An image of Calotropis procera grown in the UAE University Campus.

Manuscript content flow-
Title
Author name and affiliation
Abstract
Keywords

Abbreviations if any

1. Introduction
2. Materials and Methods
3. Results and Discussions
4. Conclusion
5. Acknowledgements
6. Funding/Conflicts of Interest –if any
7. Author contribution in this Research paper
8. References