Engineering and Technology Journal 42 (07) (2024) 895-911

Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

3D Printing for wind turbine blade manufacturing: a review of materials, design optimization, and challenges

Ahmed k. Zarzoor[a,b*], Alaa A. Jaber[b], Ahmed A. Shandookh[b]

[a]Mechanical Engineering Dept., University of Al-Qadisiyah, Al- Dewaniyah, 58001, Iraq.
[b]Mechanical Engineering Dept., University of Technology-Iraq, Alsina'a Street, 10066 Baghdad, Iraq.
*Corresponding author Email: me.21.18@grad.uotechnology.edu.iq

HIGHLIGHTS

- 3D printing optimizes wind turbine blades for greater cost-effectiveness and durability.
- The review emphasizes design optimization to enhance aerodynamics and structural efficiency.
- Challenges such as material limitations and the need for structural integrity are identified.
- AI and hybrid manufacturing are proposed to address these limitations and reduce costs.

ARTICLE INFO

Handling editor: Miqdam Chaichan

Keywords:

3D printer

Structural optimization

Infill structure

Additive manufacturing (AM)

LSAM

ABSTRACT

Wind energy has become an easy-to-harness source by converting captured wind currents into electrical energy. Powerful and customizable wind turbines are used to convert wind energy efficiently. However, wind turbine development in terms of structure is still an active area of research aiming at efficiently building capable and long-lasting turbines. Additive manufacturing technology, particularly 3D printing, has revolutionized multiple industries, including its potential to create wind turbine blades with high cost-effectiveness and optimizable shapes and rigid structures. In this review, various 3D printing-based techniques, including Fused Deposition Modelling (FDM), Continuous Fiber Reinforcement (CFR), Stereolithography (SLA), and 3D Printing-enhanced Large-Scale Additive Manufacturing (LSAM), are examined in detail for complex and large-scale wind turbine blade production. Materials used in 3D printing wind turbine blades, such as thermoplastic composites, epoxy resins, and fiber-reinforced polymers, are assessed with a focus on their mechanical strength, durability, and environmental considerations. Furthermore, the importance of design optimization and customization for wind turbine blades, including aerodynamic and structural design optimization, is emphasized. Customization for site-specific conditions, infill structural optimization, and infill printing speed and cost are also discussed. The review highlights the importance of structural optimization in developing efficient and cost-effective 3D-printed wind turbine blades, customization for site-specific conditions, and infill structure. The review also mentions these technologies' challenges, such as material limitations, surface finish quality, size limitations, and structural integrity. Therefore, addressing these challenges to utilize these technologies' potential fully is crucial.

1. Introduction

Renewable energy is derived from naturally occurring and replenishable sources that are not exhausted when used. These energy sources are sustainable over the long term and have a significantly lower environmental impact compared to fossil fuels and other non-renewable energy sources. Renewable energy technologies harness the power of nature to generate electricity, heat, or other forms of energy. These technologies are environmentally friendly because they produce little to no greenhouse gas emissions or air pollution during energy generation. Additionally, they are not subject to the same resource depletion issues as fossil fuels, making them a sustainable and reliable power source for the future. The transition to renewable energy is crucial in mitigating climate change and reducing dependence on finite fossil fuel reserves. For example, solar panels and photovoltaic cells convert sunlight into electricity or heat for residential, commercial, and industrial applications without increasing global warming. Similarly, energy from the movement of tides and ocean waves is captured to generate electricity apart from the energy generated by the movement of water, typically by damming a river and/or directing the flow through turbines to produce electricity.wind energy is another primary source of unlimited energy generation potential [1-3]. Wind turbines are a technology used to capture and convert the wind kinetic energy into electricity. They consist of large rotor blades attached to a

https://doi.org/10.30684/etj.2024.144841.1646
Received 25 November 2023; Received in revised form 17 February 2024; Accepted 17 February 2024; Available online 12 April 2024
2412-0758/University of Technology-Iraq, Baghdad, Iraq

hub connected to a generator. Wind turbines are mounted on tall towers to capture consistent winds at higher altitudes. The flowing wind currents over the curved rotor blades create a lift similar to an airplane's wings, causing blades to rotate at high speeds. In return, this rotation leads to rotating the generator's shaft to produce electricity through electromagnetic induction. The produced alternating current (AC) is converted to usable voltage and frequency and distributed to the electric network through power lines. Wind energy is a renewable and sustainable energy source relying on the planet's natural wind patterns. Wind energy does not produce greenhouse gas emissions or air pollutants while operating, making it an environmentally friendly alternative to carbon-emitting fossil fuels [4]. Wind power utilization continues to grow as a significant source of electricity generation in many regions worldwide [5]. Global cumulative wind power capacityy increased from 17 gigawatts (GW) in 2000 to over 837 GW by 2021, according to the Global Wind Energy Council (GWEC). Currently providing about 10% of the world's electricity, wind energy is essential to the shift to decarbonized power systems [6-7]. Wind turbines are an essential source of clean energy, harnessing wind energy into electricity. The blades of wind turbines capture and convert the wind energy into rotational energy to induce the turbine generator to produce electrical power. Thus, wind turbine blades must meet several criteria for efficiency, including lightweight, resistance to extreme fatigue loads, constrained tip deflections, avoidance of resonances, and cost-effectiveness [8-9]. Producing efficient blades with such criteria is challenging and may come at the expense of giving up some structural specifications. Therefore, selecting the optimal material and geometric properties with further optimization is key to enhancing the blades' efficiency and reducing the overall cost of wind turbines. Wind turbine blades are fabricated using additive manufacturing techniques, which offer rapid prototyping, efficient tooling and fabrication, and accurate testing while allowing top-notch design and flexible process configurations. AM also provides reduced material waste and tooling expenses, thus increasing cost-effectiveness. Polymer-based AM, in combination with composite materials, is the most used in manufacturing wind turbine blades [10]. 3D printing has emerged as a revolutionary AM technique. Unlike traditional manufacturing techniques that involve cutting, drilling, or machining, 3D printing builds high-fidelity objects layer by layer, guided by codes of digital designs. 3D printing provides many benefits, including better design possibilities, remarkable ease of producing intricate and detailed geometries, and reduced need for surface-finishing [11-12]. 3D printing involves placing and consolidating materials layer-by-layer, depositionsing a Computer-Aided Design (CAD) file sliced into thin cross-sectional layers [6-9], illustrated in Figure 1. Layers are sequentially printed and solidified using specialized machines or 3D printers that employ different techniques, such as powder bed fusion, material extrusion, or directed energy deposition [10-12].

The choice of approach depends on the used material, the desired resolution, and the application requirements. Interestingly, 3D printing allows the production of one-off parts with minimal setup cost [13]. Thus empowering designers and engineers to create leading-edge geometries, lightweight structures, and personalized products customized to individual needs. Since 3D printing is an additive process with highly localized material deposition, it results in substantial material savings and environmental advantages. 3D printing is used for localized manufacturing (on-site) to cut transportation costs and reduce carbon emissions of extended supply chains. Designing and optimizing wind turbine blades involves considering many elements to enhance the sustainability and overall efficiency of the blades. The application of modern mathematical modeling and simulation equipment in various engineering disciplines, along with additive manufacturing, has facilitated the enhancement of wind turbine blade design. This improvement has resulted in better aerodynamic performance, enhanced fatigue resistance, and the ability to customize the size and durability of the blades. The optimization objectives encompass reducing weight and cost, enhancing aerodynamic efficiency, increasing power output, minimizing noise generation, improving structural performance, and achieving feasible designs under specific restrictions. The design optimization system employs many optimization techniques, including multi-objective optimization, particle swarm optimization, genetic algorithms, and finite element analysis, to enhance the performance of wind turbine blades. The optimization techniques consider several design variables, such as chord, twist angle, blade material thickness, cross-sectional area, radius of gyration, length of each section, and fiber angle of blade layer, to achieve the optimization objectives [14]. The design and optimization of wind turbine blades also incorporate the utilization of various materials, such as thermoplastic composites, epoxy resins, and fiber-reinforced polymers, to enhance the structural efficiency of the blades. Utilizing 3D printing techniques such as Fused Deposition Modeling (FDM), Continuous Reinforced Fibers (CRF), and Stereolithography (SLA) is the most efficient method for producing wind turbine blades. This approach offers high design flexibility, improved performance, and reduced costs. It has the potential to contribute to the sustainable development of wind energy sources, minimize waste, and reduce carbon emissions, as well as offer design flexibility and customization options for optimizing wind turbine blade performance . The novelty of this work lies in the comprehensive review of various manufacturing technologies and optimization methods for wind turbine blades, focusing on 3D printing techniques, continuous fiber reinforcement, and structural design optimization. The work contributes to the existing literature by providing a clear and concise overview of the state of the art in wind turbine blade manufacturing and optimization, focusing on innovative technologies and methods that can lead to improved performance and sustainability. The review aims to highlight the potential of these technologies in improving performance and sustainability The review aims to highlight the potential of these technologies in improving the performance and sustainability of wind turbine blades by comparing and evaluating different optimization methods and techniques used to enhance wind turbine blades.

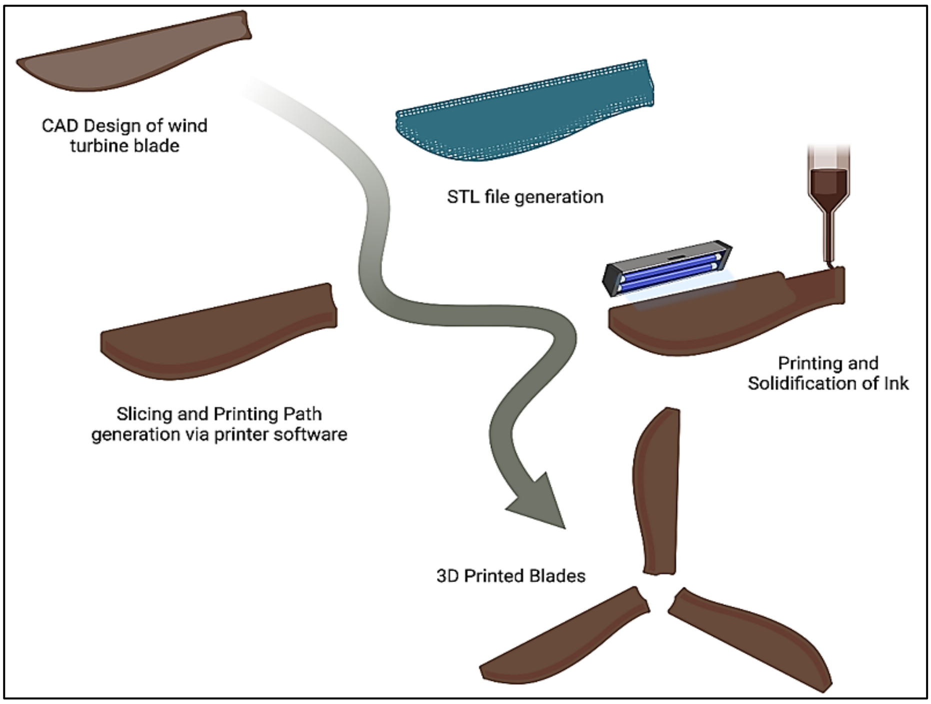

Figure 1: Illustration of wind turbine blade 3D printing steps

2. Additive manufacturing techniques for wind turbine blade

Additive Manufacturing (AM) techniques, particularly 3D printing, offer the most efficient approach to producing wind turbine blades with high design flexibility, improved efficiency, and reduced costs. This section explores different 3D printing-based techniques used to manufacture wind turbine blades.

2.1 Fused deposition modeling (FDM)

FDM is a 3D printing-based technique that extrudes melted materials selectively, following an encoded printing path to build multi-layer structures [15-16]. Long thermoplastic polymer filaments are used as a printing ink to develop 3D objects. The filament is preheated at the printing head and extruded through a nozzle with a specific diameter. The printing head moves in three degrees of freedom (DOF) along the x-y-z axis of the plane of printing Figure 2.

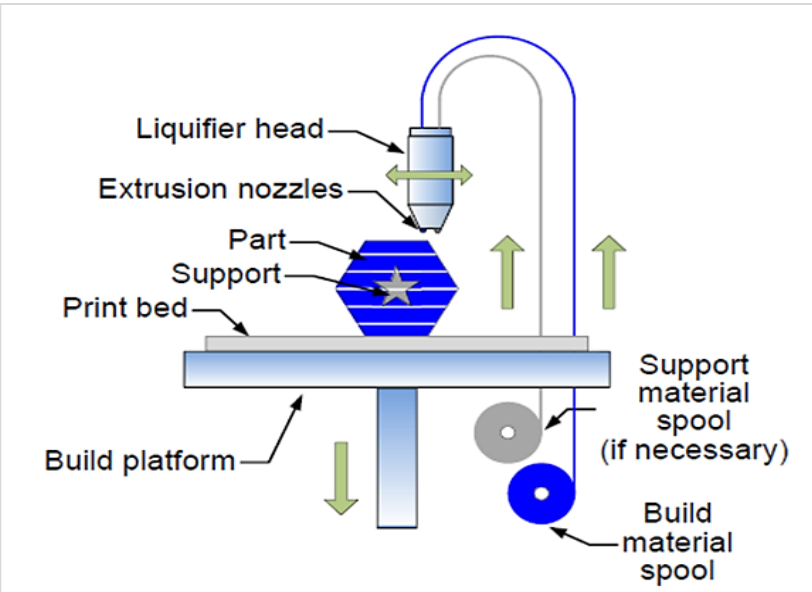

Figure 2: Schematic of the FDM process [17]

The materials are deposited within a defined printer stage, specified by known machine and material parameters within G-code instructions [16,18]. FDM was suggested for printing wind turbine blades using highly extrudable polymers, such as acrylonitrile butadiene styrene (ABS) or polycarbonate (PC) [19,20]. FDM has become popular in manufacturing wind turbine blades due to its low cost, reduced wastage, and efficient and easy mode operationality. FDM was used to produce cross-axis wind turbine blades and their supporting parts using ABS [21]. FDM was also used to produce a blade of ABS with efficient airfoil [22]. Most recently, FDM was also used to 3D print blades of PLA for low-wind-speed applications of wind turbines, which showed high efficiency when tested in a wind tunnel. The FDM system required 6-12 hours to produce the one-meter-long PLA blade, showing FDM's high cost-effectiveness [23]. However, using FDM for wind turbine blade manufacturing faces different challenges. FDM is limited to printing thermoplastic polymers, which may not have strength and durability similar to traditional materials (i.e., fiberglass and carbon fiber composites) used to produce wind turbine blades [24-25]. Besides, FDM-produced products have limited surface quality, which may induce high surface roughness that does not support the required aerodynamic performance of wind turbine blades . The limitation of the printing platform and nozzle diameter may significantly limit the size of the produced wind turbine blades, which can reach 50 meters in length. Moreover, FDM-produced blades may have low structural integrity (weak points or voids), affecting their overall structure and performance [26]. Therefore, despite the advantageous use of FDM technology to produce low-cost and less wastage wind turbine blades, limitations of materials, surface finish quality, size, and structural integrity must be addressed to utilize the technology further.

2.2 Continuous fiber reinforcement

CFR is a Fused Filament Fabrication (FFF) printing technique that involves the embedment of reinforcement fibers in matrix materials to form composite-based products with enhanced strength and performance. The technique allows the precise and flexible orientation of individual layers of the diversely reinforced composite laminate, targeting superior mechanical properties [27]. Thus, CFR is used in many fields to manufacture high-strength, lightweight, and durable end-products and has been explored along with automated fiber placement (AFP) to fabricate wind turbine blades with high strength and stiffness and elongated fatigue resistance. For example, the embedment of continuous carbon or glass fibers into the 3D-printed composite-based blades considerably improved their performance and durability [11-34]. Besides improving the mechanical properties, CRF-produced products have better shape fidelity and thermal properties, which makes CRF useful for diverse applications. Interestingly, the core concept of CRF can be adopted to improve the capacity of the existing printers, including FDM-based printers. Recently, CFR was integrated into different desktop 3D printers, where highly flexible desktop printers showed increased potential for creating lightweight complex parts [28]. However, disposed of CRF-produced products are challenging to recycle. Thus, exploring methods to better reuse CRF-based materials, including disposed wind turbine blades, is deemed necessary.

2.3 Stereolithography (SLA)

SLA is a resin-based 3D printing additive manufacturing technology that utilizes photopolymerization, where resin polymerization (chemical crosslinking) is initiated by wavelength of light, typically ultraviolet (UV) light. Herein, photopolymerization allows a localized and instant resin transformation from liquid to solid Figure 3. Post-photopolymerization of a layer, the built printing platform moves downwards progressively to photopolymerize the second layer with slightly different light beam patterns, eventually constructing well-detailed high-resolution 3D objects [23,29]. For example, SLA was recently used to print three wind turbine blades with a diameter of 1.5 m (158 g each) in one go within 12 hours, indicating the applicability of SLA to print scalable and cost-effective blades rapidly. Therefore, the SLA technique has great potential to build complex blade architectures with efficient geometries and smooth surfaces for efficient wind energy conversion into electrical energy. However, the current mechanical and structural properties of SLA-printed blades may be limited to the nature of the resin materials used, which is a promising research area to explore.

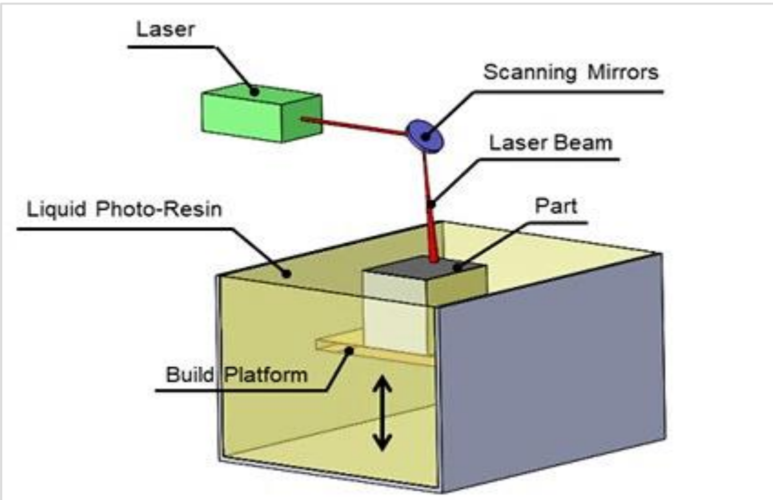

Figure 3: Schematic of stereolithography (SLA) [26]

2.4 3D Printing-enhanced large-scale additive manufacturing (LSAM)

LSAM is a lining of different AM techniques brought together to produce complex and large structures and components (known to be challenging to produce using traditional approaches) to advance the capacity of aerospace, automotive, and construction industries. 3D printing is implemented within LASM processes, such as large-scale automated blade manufacturing lines, in combination with in situ thermowelding, robotic-assisted machining, and spray coating. In wind turbine blade LSAM, 3D printing takes part in extruding thermoplastic materials onto a blade-like build platform Figure 4 (A- the process of printed side section of blade, B- assembled blade mold, C-high/low pressure mold after assembling) and Figure 5, which is also 3D printed using big area additive manufacturing (BAAM)-based printer [30]. Besides building massive blade molds, 3D printing can create blade core structures and coreless blade tails in 3D Printing-enhanced LSAM lines [28]. Combined, 3D printing-enhanced LSAM offers rapid production, lower material costs, and improved properties besides being customizable and upgradable [31]. This study covers advanced 3-D printing methods employed for the production of wind turbine blades, including Fused Deposition Modeling (FDM), Continuous Fiber Reinforcement (CFR), Stereolithography (SLA), and Large-Scale Additive Manufacturing (LSAM) processes specifically tailored for 3-D printing. Fused Deposition Modeling (FDM) is a technique that uses 3D printing to extrude melted materials selectively. On the other hand, Carbon Fiber Reinforcement (CFR) involves embedding reinforcement fibers in matrix materials to create composite products that have enhanced strength and performance. SLA is a 3D printing technology that uses resin and photopolymerization. LSAM is a combination of many additive manufacturing processes used to create intricate and huge systems and components.

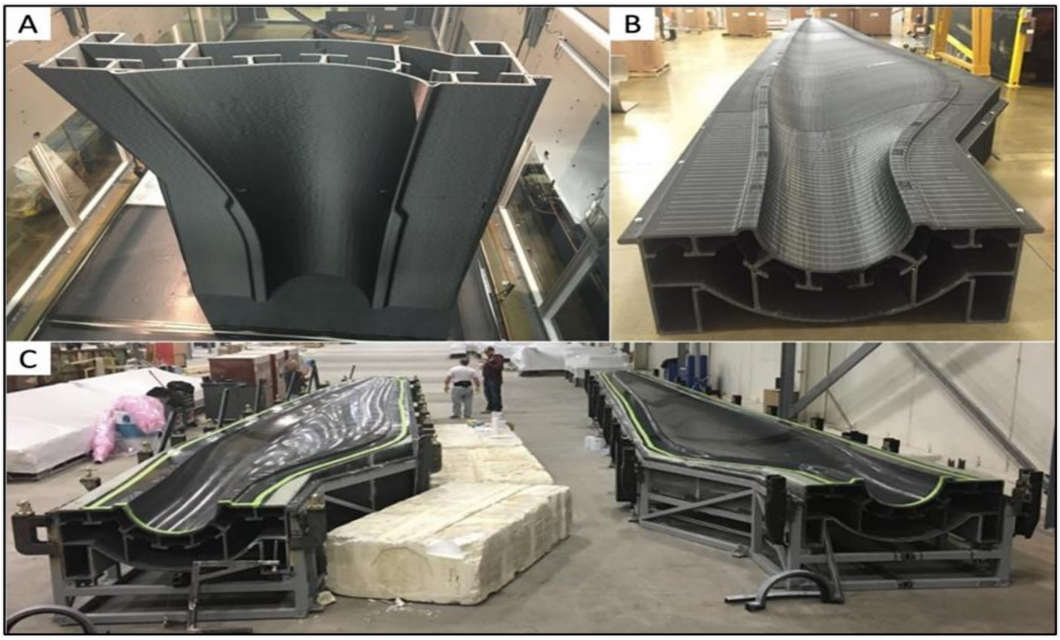

Figure 4: (A) Printed side section using BAAM printer (B) Assembled units of high-pressure blade mold (C) High- and low-pressure blade molds after assembling and machining for wind turbine blade manufacturing [30]

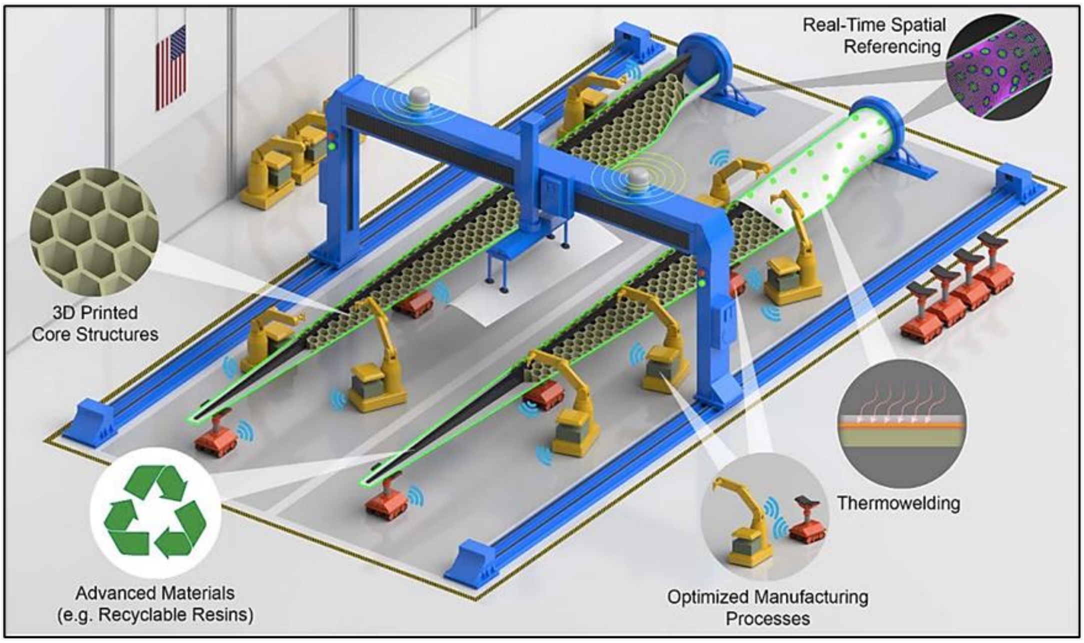

Figure 5: Illustration of an LSAM-based factory for automated wind turbine blade manufacturing [31]

3. Materials for additive manufacturing of wind turbine blade

Materials selection and design for blade printing are vital to ensure the optimal mechanical strength, durability, and fatigue resistance required for high efficiency and reliability. Materials selection also aligns with cost-effectiveness, performance requirements, and environmental considerations [10-12]. This section reviews materials commonly used in wind turbine blade manufacturing and their specification to meet the needs of wind energy applications.

3.1 Thermoplastic composites

Composite materials combine two or more materials with different properties and configurations, aiming to develop materials with unique physical properties and overall performance. Reinforced composite materials are commonly used to manufacture wind turbine blades due to their high strength-to-weight ratio. Composite filaments with high fiber content used for 3D printing can be challenging to print. Issues like nozzle clogging may arise due to the high reinforcement content, making it essential to optimize printing parameters, which can reduce printing speed and accuracy and alter the overall printability. Moreover, products made with thermoplastic composites are challenging to recycle; thus, they require proper materials selection to increase reuse and recyclability. In an exciting study, Murray [33] described manufacturing a 9-meter thermoplastic composite wind turbine blade using a vacuum-assisted resin transfer molding process Figure 6. The blade was made using Johns Manville fiberglass and an Arkema thermoplastic resin called “Elium”. The author highlights the development of thermoplastic resin formulations, including an additive designed to control the peak exothermic temperatures. Infusion and cure times of less than 3 hours are also demonstrated, highlighting the efficiency and energy savings of manufacturing thermoplastic composite blades.

Figure 6: Nine-meter thermoplastic composite blade [33]

3.2 Epoxy resin

Traditionally, wind turbine blades are manufactured using a labor-intensive process of molding and curing fiber-reinforced composites, such as fiberglass or carbon fiber, in a large-scale production setup. However, additive manufacturing techniques utilizing epoxy resins offer the potential for more efficient and cost-effective blade production [34]. Epoxy resins are thermosetting polymers with excellent mechanical properties, high strength, and chemical resistance [35]. These resins can be combined with reinforcing fibers, such as carbon or glass, to form composite materials with enhanced structural performance . Additive manufacturing with epoxy resins allows placing these reinforced materials precisely, resulting in optimized load distribution and improved overall blade performance.Wind turbine blades are exposed to significant stresses from their movement, wind, and environmental factors such as temperature cycling, humidity, and bird strikes while in operation. Failures of these composite blades have been attributed to fiber/matrix delamination and cracking. Jacob et al. [36] has made significant technical advances to understand the critical resin formulation attributes required for use in wind turbine blades and provide solutions to address these failures, as illustrated in Figure 7. They have achieved this by understanding the critical resin formulation attributes required for use in wind turbine blades and leveraging key novel technologies developed within their Epoxy Systems.

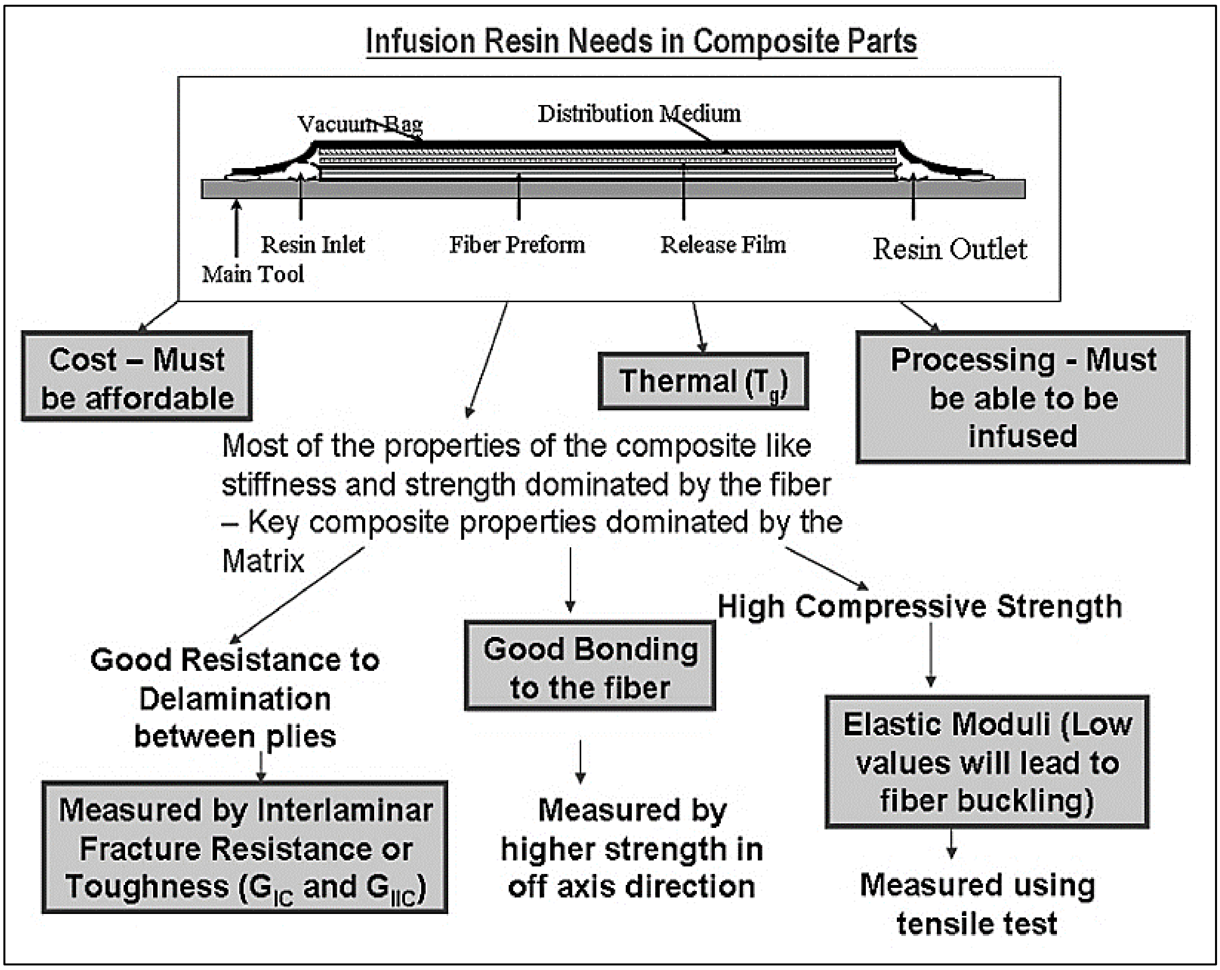

Figure 7: Summary of infusion resin needs in wind turbine blade composites [36]

3.3 Fiber-reinforced polymers (FRPs)

The use of carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP) has proven to remarkably improve wind turbine blade manufacturing, leading to a high strength-to-weight ratio and excellent fatigue resistance [28, 31,33-39]. Continuous fiber reinforcement or chopped fibers are used to enhance the ink material properties to enable the production of complex geometries.

4. The Importantce of advanced material

The following points highlight the importance of advanced materials, surface finishing, and cost-effectiveness in the design of wind turbine blades.

4.1 Advanced materials

The utilization of modern materials, such as thermoplastic composites, epoxy resins, and fiber-reinforced polymers, can augment the mechanical characteristics, longevity, and resistance to fatigue of wind turbine blades, resulting in enhanced efficiency and dependability. These materials can be integrated with additive manufacturing techniques like 3D printing to fabricate intricate and lightweight blade structures [40-41].

4.2 Surface finishing

Adopting advanced materials and surface finishing techniques can effectively minimize the requirement for supplementary finishing procedures, resulting in cost reductions and enhanced performance. 3D printing processes, such as FDM and CFR, can produce surfaces with excellent surface quality and decreased roughness. This is essential for optimizing the aerodynamic performance of wind turbine blades [42].

4.3 Cost-effectiveness

Applying modern materials and surface finishing processes can save costs during manufacturing by minimizing the requirement for extra materials, processing stages, and assembly procedures. In addition, using additive manufacturing methods may reduce material wastage and lower production expenses, enhancing the affordability and accessibility of wind turbine blades [43]. Further research and development are required to ascertain the characteristics of wind turbine blades only by utilizing advanced materials, surface finishing techniques, and cost-effectiveness. This may involve exploring novel materials, surface finishing processes, and optimization methodologies that may improve wind turbine blades' overall performance and cost-effectiveness. Additionally, establishing defined suggestions and certification procedures special to additive production-produced wind turbine blades might assist in ensuring beneficial dependability and safety, simplifying widespread use, and boosting the growth of the wind strength industry.

5. Design optimization and customization in wind turbine blades

Proper design optimization must be carried out to develop efficient and high-performance wind turbine blades. The advances in mathematical modeling and simulation tools used across different engineering fields and additive manufacturing allowed better wind turbine blade design optimization with enhanced aerodynamic performance, improved fatigue resistance, and customized size and durability. This section provides insights into the design optimization and customization used for 3D printing wind turbine blades. Studies covered have employed different optimization methods, such as multi-objective optimization, particle swarm optimization, genetic algorithms, and finite element analysis, to improve wind turbine blade performance. The optimization goals include reducing weight and cost, enhancing aerodynamic efficiency, increasing energy production, minimizing noise production, improving structural performance, and achieving feasible designs within specific constraints [14-20,44-60], as summarized in Table 1.

Table 1: The optimization method and technique used to enhance the wind turbine

The results	Design variable	Objective function	Optimization method	Ref.
The blade noise was reduced by 3.1 dB, and the power coefficient was increased by 6.9%	Airfoil, chord, length, twist angle	Structural strength, stiffness, noise reduction	Particle swarm optimization	[14]
The SG6043 airfoil has the highest power coefficient, while the BW-3 airfoil has the shortest startup time.	Selected ten low Reynolds number airfoil	Increase power coefficient and decrease startup time	Differential evolution algorithm	[15]
Enhance the dynamic characteristics of the optimized spar structure	Cross-sectional dimension and material properties along the spanwise direction of the blade spar.	Minimization of the total structural mass of the blade and reduction of the overall vibration level	Sequential quadratic programming (SQP)	[16]
The minimization of mass required more (CFRP), while the minimization of the cost required an excellent arrangement of (GFRP) combined with (CFRP)	The number and location of layers in the spar cap The width of the spar cap The position of the shear webs	Minimize the weight and cost of the blade	Combing FEM and multi-objective evolutionary algorithm	[17]
The result is a lighter blade, lessening the wind turbine's applied load. This will have a significant impact and cause the weight of the turbine system design optimization process to be reduced	No ply in the spar cap No ply in the skin No ply in the root No of ply in the shear web Shear web location Shear web foam thickness	Reduce weight	genetic algorithm	[18]
The optimization results indicate significant improvements in the aerodynamic and structural performances of the blades when a commercial 1.5MW wind turbine blade is used as a case study.	Chord, twist angle, blade material thickness	Increasing the annual energy production (AEP) and reducing blade mass	Multi-objective algorithm (NSGA) II	[19]
A blade structure with enhanced aerodynamic efficiency at all wind speeds below the rated wind speed was generated after the blade geometry was adjusted using the linearization parameter ranges discovered through the analysis.	The blade linearization parameters (chord length, chord profile slope, and twist profile)	Multiple tip speed ratio (TSRS) to satisfy the optimal aerodynamic efficiency at various wind speed	Simulated annealing algorithm (SA)	[20]
The results shown enhance the resistance of static and dynamic load with risen the number of layers and reduction in the blade tip	Number of layers of glass fabric and mat	Reduction blade mass	Finite element analysis	[44]
The findings demonstrate that, when compared to a reference or baseline design, the methodology used in this study is effective and yields better designs.	The cross-sectional area, radius of gyration, and length of each segment	Maximum frequency	Non-linear mathematical programming	[45]
Modal analysis was used to verify the blade's dynamic performance, serving as a guide for structure design and other evaluations.	Blade element chord, twist angle	Dynamic performance analysis	MATLAB tool	[46]
The outcomes demonstrate that the modified blade performs more aerodynamically and structurally than the previous one.	Aerodynamic and structural parameters	Increasing annual energy production (AEP)	(PSO) algorithm	[47]

Table 1: Continued

The results	Design variable	Objective function	Optimization method	Ref.
The outcomes demonstrate that the first blade model was an infeasible design due to a high amount of maximum stress, surpassing the top limit of the stress constraint. However, gradually, the process converged to a feasible solution at the cost of increased total blade mass.	Thickness of material	Reduce the mass	ANSYS software	[48]
The findings enabled us to identify the ideal geometric and material characteristics for a wind turbine blade	(Thickness of shell, thickness of shear webs, and thickness of ribs	Reduce the mass and minimize the vertical deflection of wind turbine blade	The weighted sum method and modified genetic algorithm	[49]
Maximizing annual energy production frequently results in significantly inefficient designs (in terms of energy cost), even after the internal structure has been adjusted	Chord, twist angle, Spar cap thickness	To optimize a wind turbine rotor: maximizing AEP, minimizing the ratio of turbine mass to AEP and minimizing cost of energy	MATLAB tool	[50]
The findings show that employing the suggested greedy algorithm rather than the genetic algorithm results in cheaper processing costs and more optimized outcomes	multiple hub height wind turbines	optimize the wind turbine layout	greedy algorithm	[51]
It produces an aerodynamic design that is more friendly to the blade's structure by distributing loads and stresses evenly over the blade span and preventing stress concentration areas.	Distributions of the chord, twist, and thickness throughout the blade span	maximize the energy production of wind turbines and minimize the mass of the blade	(NSGA-II (QMEA (MOEA/D), (MODE)	[52]
The findings demonstrate that the optimization model can lower the energy cost of the original rotors, particularly for the 2 MW and 5 MW rotors under investigation	blade shape parameters	minimize the cost of energy	aerodynamic/aero-elastic code	[53]
The findings demonstrate that raising the rated power always increases the cost of energy	geometric characteristics of the blade	minimize the cost of energy	multi-level system design (MLS) algorithm	[54]
The calculated results demonstrate the model's effectiveness and potential as an ideal design tool for engineering design.	The thickness and the location of the layer on spar caps	Minimum blade mass to reduce the cost of wind turbine production	Improved particle swarm optimization (PSO) with (FAST) code	[55]
The influence of the power coefficient for various blade angles, tip speed ratios, ratios of drag and lift coefficients, and blade solidity are described, and the optimal set value is achieved.	For different blade angles, tip speed ratio, the ratio of the coefficient of drag and coefficient of lift, and blade solidity	Maximum power coefficient	Blade element momentum (BEM)	[56]
The findings demonstrate that the optimized blades' mass is lowered when compared to the initial blade, with the position of the blade spar cap being one of the parameters that shows the most significant mass savings	the thickness of laminates, the thickness of the unidirectional laminate, the thickness of the bi-axial laminate, and the thickness of the tri-axial laminate	The minimum mass for the wind turbine blade	PSO algorithm and FE program	[57]
To maximize the amount of wind energy captured and improve the quality of the electricity, it is demonstrated that the pitch angle and generator torque may be regulated	the pitch angle and generator torque	optimization of power factor and power output of wind turbines	Evolutionary computation algorithm	[58]
The research clearly illustrated the difficulties in meeting the demands for strength, durability, and stiffness while maintaining high wind-energy capture efficiency and low production costs.	Spar caps and trailing edge thickness	Minimization cost of energy	MATLAB tools	[59]
Decrease in blade mass	The sequences of materials, ply, and spar thickness	Reduce blade mass	ANSYS software	[60]

The table appears to be a compilation of research findings about enhancing wind turbine blade performance. The research encompasses different blade design aspects, including aerodynamic performance, structural integrity, materials choice, and manufacturing factors. Various optimization methods, including particle swarm optimization, genetic algorithms, differential evolution, and simulated annealing, were employed to improve performance measures such as power coefficient, startup time, structural mass, and aerodynamic efficiency. The studies highlight the significance of considering many objectives, such as optimizing annual electricity production, reducing blade weight, and limiting power cost, during the design optimization. The study emphasizes the intricate and interdisciplinary aspects of optimizing wind turbine blades. The interaction between design elements, objective features, and optimization methodologies is essential for achieving the desired overall performance outcomes. The study showcases the application of advanced computational methods, such as finite element analysis, genetic algorithms, and evolutionary computation, to address the challenging issues associated with designing and optimizing wind turbine blades. The literature study provides valuable insights into the current advancements in wind turbine blade optimization and the various methodologies researchers employ to improve the efficiency and cost-efficiency of wind power systems. The results emphasize the significance of employing integrated and multi-objective optimization methodologies in developing environmentally friendly and economically feasible wind turbine blades.

The impact of the provided review is significant as it contributes to the knowledge base in the following ways:

1) **In-Depth Analysis of Additive Manufacturing Techniques:** The review provides a comprehensive analysis of the application of additive manufacturing techniques, such as Fused Deposition Modeling (FDM), Continuous Fiber Reinforcement (CFR), and Stereolithography (SLA), in the production of wind turbine blades. It offers detailed insights into these techniques' advantages, limitations, and potential, thereby enhancing the understanding of their suitability for wind energy.
2) **Focus on Material and Surface Finishing Challenges:** The review addresses the challenges related to advanced materials, surface finishing, and cost-effectiveness in the context of additive manufacturing for wind turbine blades. By highlighting the limitations and opportunities associated with these factors, the review offers valuable guidance for researchers and industry professionals seeking to optimize wind turbine blade production's structural and economic aspects.
3) **Novelty in Addressing Site-Specific Durability and Customization:** Unlike other related reviews, this paper emphasizes the importance of site-specific durability testing and customization in wind turbine blade design. By integrating discussions on thermal residual stress, leading edge erosion, and infill structure optimization, the review offers a holistic perspective on the factors influencing the performance and longevity of wind turbine blades in diverse environmental conditions.
4) **Practical Implications for Manufacturing and Design:** The review's emphasis on the practical implications of additive manufacturing techniques, such as rapid production, lower material costs, and improved properties, makes it a valuable resource for industry practitioners and decision-makers. The detailed analysis of 3D printing-enhanced Large-Scale Additive Manufacturing (LSAM) further underscores the potential for scalable and cost-effective blade production, thereby contributing to advancing wind energy technologies.

5.1 Aerodynamic design optimization

Shape, twist, and airfoil profile for efficient wind energy conversion. Simulations and optimization algorithms of computational fluid dynamics (CFD) are also used to assess and enhance wind turbine blade designs [59-61]. For example, a recent study examined the behavior of multi-cross-section horizontal axis wind turbine HAWT blade designs with and without fences. Blades with three different airfoils (along the blade radius) were developed and compared to a single-cross-sectional blade Figure 8(a-NACA4412 cross-section b-multi-cross section blades c-multi-cross section with fenes). Numerical analyses using BEM theory, CFD, and experimental tests indicated that multi-cross-sectional blades demonstrated superior performance, achieving an 8% increase in power coefficient for a miniature wind turbine and even more significant improvements for more giant turbines. Additionally, fences designed using boundary layer theory and strategically positioned on the multi-cross-sectional blades showed impressive results, yielding a 16% increase in total power coefficient and enhanced flutter stability. Thus, using such techniques is essential to design blades with maximized energy capture, minimized turbulence, and reduced aerodynamic losses, thus promoting the overall efficiency of wind turbines.

Figure 8: (a) NACA4412 cross-section blades (b) multi-cross-section blades (c) multi-cross-section blade with fences [61]

5.2 Structural design optimization

The design of a wind turbine blade plays a crucial role in achieving successful structural performance, including weight and cost reduction, resistance to extreme and fatigue loads, constrained deflections, and avoidance of resonances. Optimizing blade design becomes increasingly essential as wind turbines increase in size, rated power, and load capacity. The primary function of a wind turbine is to capture wind energy and generate electrical power efficiently. The optimization of each component's efficiency during the design process is essential to achieve this goal. However, as wind turbine rotor size grows, structural performance and durability constraints become more challenging. Therefore, researchers have proposed various goals, approaches, algorithms, tools, and models to address the optimization challenge in wind turbine design . Structural optimization is crucial in developing efficient and cost-effective 3D-printed wind turbine blades. By establishing suitable objective functions, carefully selecting design variables, and imposing necessary constraints, engineers can craft wind turbine blades that simultaneously enhance energy capture, reduce weight, and adhere to a spectrum of operational and safety prerequisites. Structural design optimization also aims to improve wind turbine blades' structural integrity and reliability while minimizing weight [62,63]. A structural analysis utilizing the Finite Element Method is conducted to validate the design's strength in extreme loading scenarios. To demonstrate the effectiveness and reliability of the invention, a practical case study is carried out using a commercial 2.1-megawatt HAWT blade. Thus, applying structural optimization algorithms helps designers identify the optimal distribution of materials, thicknesses, and reinforcement patterns to balance strength, stiffness, and weight.

5.3 Customization for site-specific conditions

Site specificity is also an essential design criterion for wind turbine blades to meet the best outcome harnessing energy. Wind speed, direction, turbulence, frequency, and environmental conditions can significantly influence turbine performance. A wind turbine site suitability test is performed before the design process to ensure the turbine body and blades have high site-specific durability against erosion, thermal residual stress, and other conditions for a longer product life cycle [36, 61, 64]. Customization may also involve modifying blade length, shape, and profile and incorporating adaptive features to optimize performance under varying wind variations.

5.4 Infill structure

Infill 3D printing is also used to build the interior structure of wind turbine blades with optimized structures of pattern or lattice. Infill helps customize the mechanical, structural, and functional properties of the 3D-printed object while minimizing material consumption and printing time.

5.4.1 Infill structural optimization

The infill pattern and density choice can influence wind turbine blades' strength, stiffness, and resistance. Different lattice patterns, such as honeycomb, gyroid, octet, triangle, and rectilinear, are currently used to achieve favorable mechanical characteristics. For example, square grid, honeycomb, and iso-grid lattice patterns and their rotated counterparts Figure 9(a,b-sequare grid c,d-Honeycomb grid e,f-Iso grid) were used to print ABS-reinforced carbon fibers to evaluate the lattice behavior under uniaxial compression (30% strain). It was found that the square grid pattern presented excellent oscillating stress–strain (11.5 MPa), the iso-grid pattern presented high peak stress (10 MPa), and the honeycomb pattern showed low initial stiffness [65]. It is crucial to notice that the orientation (0∘/90∘ directions, −45∘/+45∘ directions, and vertical/horizontal) of these grids can also significantly impact the object's mechanical properties. In a study by Galvez, Olivar et al. [66], a homogenized infill was developed as a promising substitute for the traditional spar cross-section turbine blades.

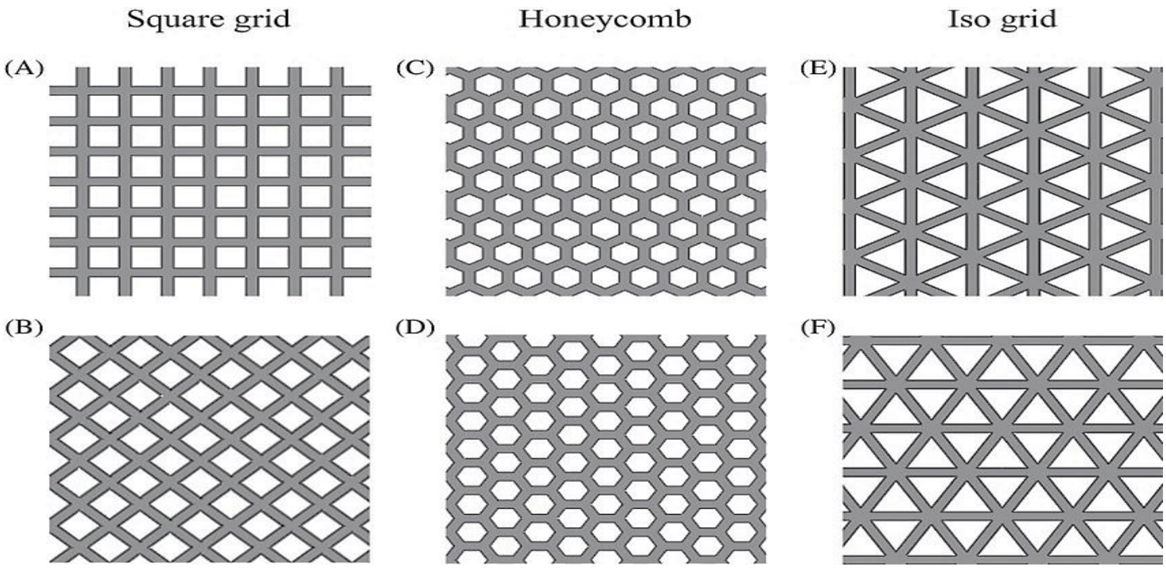

Figure 9: 2D lattice patterns are grouped by three grid patterns (A, C, and E) and their rotated counterparts (B, D, and F) [67]

While the optimal orientation of the infill relative to the blade's horizontal direction appears to be 0 degrees, the inconclusive trend prevents deformation, confirming this angle as the ultimate best infill orientation Figure 10. Similarly, Cabreira and Santana [67] explored how different infill patterns, using PLA affect the mechanical properties of the 3D objects. Impact resistance and tensile strength were tested with Rectilinear, Honeycomb, Triangle, and Grid patterns. Results show significant variations, with a rectilinear pattern deemed most economically advantageous [68]. On the other hand, the infill density plays a significant role in determining the mechanical properties of 3D printed structures. Infill density optimization is meant to specify the solidity of the structure, where objects with 50% infill density (partially solid) or lower can still provide the optimal needed mechanical properties while being cost-effective and easy to print [69-70]. In a recent study, Bolat and Ergene [70] explored the structural properties of PLA parts produced via FDM. The study mainly examined the impact of infill density on PLA behavior and found that an infill density of 40% had the lowest hardness and surface roughness, which increased with increasing the infill density (70% and 100%) [71]. This study and similar studies suggest the importance of customizing the infill density before printing wind turbine blades.

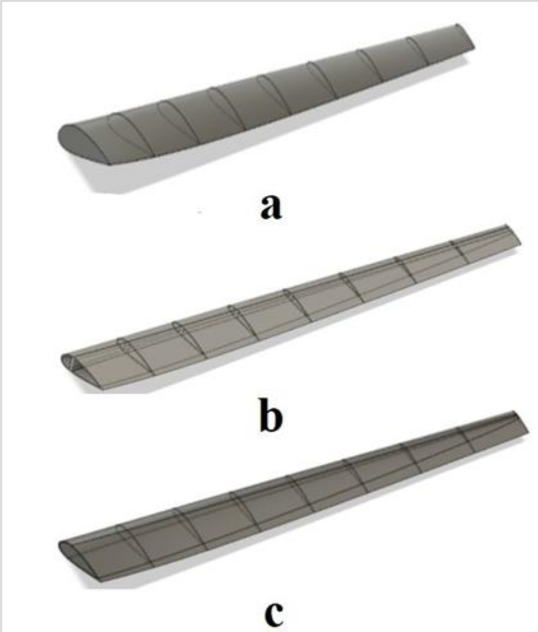

Figure 10: Three different models of blade: a-solid blade b-shell, spar, and c-shell-infill [66]

5.4.2 Infill printing speed cost

Printing with fewer infills can significantly reduce the print time and needed materials, leading to faster production and lower costs for large-scale manufacturing. For example, a study by Sharif et al. [71] concentrated on evaluating the mechanical properties of PLA using FDM with optimized printing parameters like speed, layer thickness, and infill density. The study demonstrates higher impact strength with 80% infill density, 0.1 mm layer thickness, and a 100 mm/s printing speed Figure 11. An ANOVA analysis highlights the significance of these parameters, with infill density having the most significant impact on impact strength, followed by layer thickness and printing speed.

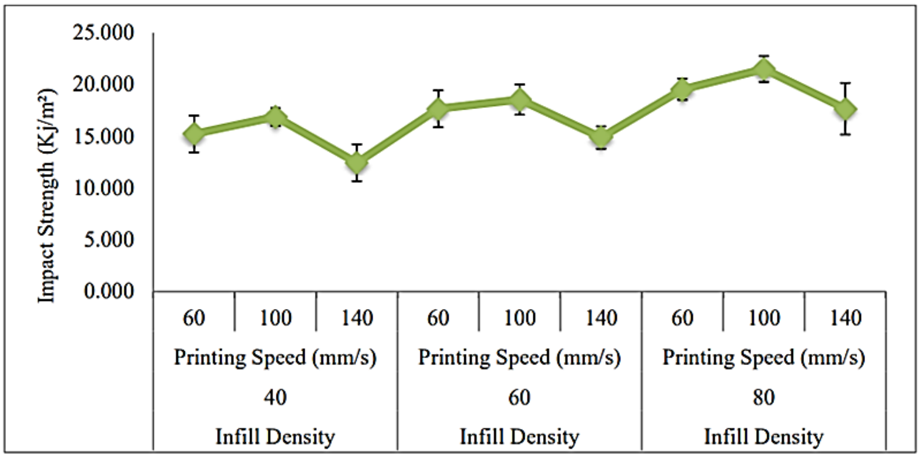

Figure 11: Effect of infill density and printing speed on impact strength [71]

6. Future suggestions

To summarize, the future of wind turbine blade manufacturing is promising, with advancements in materials, manufacturing techniques, and design optimization. Key areas for future research and development include:

1) **Integration of Circular Economy Principles:** The assessment demonstrates the use of circular economic system principles in the 3D printing of wind turbine blades to reduce waste and promote sustainable production methods. The circularity of 3D-printed wind turbine blades can be achieved by including recycled materials, implementing closed-loop production methods, and adopting end-of-life recycling strategies.
2) **Life Cycle Assessment (LCA) Studies:** Future research needs to be conducted on conducting comprehensive existence cycle evaluation studies to assess the environmental impact of additively manufactured wind turbine blades. This would assist in quantifying the advantages of 3D printing in terms of decreased energy intake, lower carbon emissions, and extended product lifestyles compared to conventional production methods.
3) **Standardization and Certification:** There is a desire to improve standardized hints and certification procedures particular to additive production-produced wind turbine blades. This would make certain high-quality, reliable, and protected, facilitating wider adoption and selling the increase of the wind electricity industry.
4) **Advanced Design Optimization Methods:** Further studies are warranted to discover superior design optimization strategies, which include artificial intelligence, machine studying, and multi-physics simulations, to enhance the overall performance and durability of additively synthetic wind turbine blades.
5) **Material Innovation and Testing:** Continued innovation in materials, which includes the improvement of bio-based totally and recyclable polymers, in addition to superior testing techniques, may be vital to improving the structural and environmental performance of 3D-revered wind turbine blades.

We can expect future advancements in materials, manufacturing techniques, and design optimization to continue shaping the wind turbine industry. Some key developments include:

1) **Modern Materials:** Materials with enhanced mechanical properties, improved fatigue resistance, and reduced environmental impact are being explored to optimize performance and sustainability.
2) **Hybrid Manufacturing:** Hybrid manufacturing approaches that combine AM with traditional manufacturing methods are emerging as promising solutions for producing large-scale wind turbine blades. Hybrid strategies can leverage the strengths of both techniques to overcome size limitations and achieve cost-effective production.
3) **Integrated Design and Optimization:** The integration of design optimization tools, simulation software, and artificial intelligence algorithms can enhance the efficiency and performance of AM-produced wind turbine blades. Automated design generation, topology optimization, and multi-objective optimization can lead to innovative designs that maximize performance while minimizing material usage and weight.
4) **Standardization and Certification:** Developing standardized guidelines and certification processes specific to AM-produced wind turbine blades is crucial for ensuring quality, reliability, and safety. Establishing industry-wide standards and certification protocols will enhance confidence in the technology and facilitate wider adoption.

7. Conclusion

The emergence of using 3D printing as a new additive manufacturing technique has revolutionized the industrial capacity across disciplines and enabled the manufacturing of architecturally sophisticated structures. Although 3D printing for wind turbine blade manufacturing offers a unique opportunity for design flexibility, cost reduction, and customization, several challenges must be addressed to harness its applicability fully. Thus, extra effort is needed in material selection and design, scalability, surface finishing, customizability, and cost. Process optimization, validation, and control are crucial for ensuring the repeatability and reliability of 3D-printed blades. While 3D printing can offer cost advantages regarding design freedom and reduced material waste, addressing the initial investment costs and material expenses is essential for economic viability. Automated design generation, topology optimization, and multi-objective optimization can lead to innovative designs that maximize performance while minimizing material usage and weight. Developing advanced materials tailored explicitly for 3D printing and exploring hybrid manufacturing approaches show promise in overcoming current limitations. Integrating design optimization tools, simulation software, and artificial intelligence algorithms can further enhance the efficiency and performance of 3D printing-produced wind turbine blades. Hybrid manufacturing integrating 3D printing in large-scale wind turbine blade production lines can leverage the strengths of current techniques to overcome size limitations and achieve cost-effective production. The review paper significantly enriches the existing knowledge base by providing a comprehensive and practical analysis of additive manufacturing techniques, material challenges, and site-specific considerations in wind turbine blade design and optimization. Its unique focus on addressing the practical implications and limitations of these factors sets it apart from other related rviews, it a valuable resource for researchers, industry professionals, and policymakers in the field of wind.

Author contributions

Conceptualization, A. zarzoor, A. Jaber and A. Shandookh; data curation, A. zarzoor, A. Jaber and A. Shandookh; formal analysis, A. zarzoor.; resources, A. zarzoor.; supervision, A. Jaber and A. Shandookh; writing—original draft preparation, A. zarzoor.; writing—review and editing, A. zarzoor. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] M. Grujicic, G. Arakere, B. Pandurangan, V. Sellappan, A. Vallejo, M. Ozen, Multidisciplinary design optimization for glass-fiber epoxy-matrix composite 5 MW horizontal-axis wind-turbine blades, J. Mater .Eng. Perform., 19 (2010) 1116–1127. http://dx.doi.org/10.1007/s11665-010-9596-2

[2] A. Brown, S. Müller, Z. Dobrotkova, Renewable energy: Markets and prospects by technology, IEA information paper, 2011.

[3] O. Ellabban, H. Abu-Rub, F. Blaabjerg, Renewable energy resources: Current status, future prospects and their enabling technology, Renew. Sustain. Energy Rev., 39 (2014)748–764. http://dx.doi.org/10.1016/j.rser.2014.07.113

[4] A. G. Olabi et al, Wind Energy Contribution to the Sustainable Development Goals: Case Study on London Array, Sustainability, 15 (2023) 4641- 2023. https://doi.org/10.3390/su15054641

[5] T. Burton, N. Jenkins, D. Sharpe, E. Bossanyi, Wind energy handbook. John Wiley & Sons, 2011. https://doi.org/10.1002/9781119992714

[6] S. A. Aladejare, Renewable Energy and Ecological Sustainability in Africa: Does Foreign Debt and Financial Globalisation Matter, 2023. https://doi.org/10.21203/rs.3.rs-2723366/v2

[7] A. Martinez , G. Iglesias, Global wind energy resources decline under climate change, Energy, 288 (2024)129765. https://doi.org/10.1016/j.energy.2023.129765

[8] P. Zouboulis, E. P. Koumoulos, A. Karatza, Wind Turbine Blade-Tip Optimization: A Systemic Computational Approach, Processes, 11(2023)1170, 2023. https://doi.org/10.3390/pr11041170

[9] A. Maheri, Multi-objective optimisation and integrated design of wind turbine blades using WTBM-ANSYS for high fidelity structural analysis, Renew. Energy, 145 (2020) 814–834. https://doi.org/10.1016/j.renene.2019.06.013

[10] L. Mishnaevsky, K. Branner, H. Petersen, J. Beauson, M. McGugan, B. Sørensen, Materials for wind turbine blades: An overview, Mater., 10 (2017)1285. https://doi.org/10.3390%2Fma10111285

[11] G. R. Kalagi, R. Patil, N. Nayak, Experimental study on mechanical properties of natural fiber reinforced polymer composite materials for wind turbine blades, Mater .Today. Proc., 5 (2018). 2588–2596. https://doi.org/10.1016/j.matpr.2017.11.043

[12] A. Jandyal, I. Chaturvedi, I. Wazir, A. Raina, M. Haq, 3D printing–A review of processes, materials and applications in industry 4.0, Sustainable Opera . Comp., 3 (2022) 33–42. https://doi.org/10.1016/j.susoc.2021.09.004

[13] S. Tofail, E. Koumoulos, A. Bandyopadhyay, S. Bose, L. O'Donoghue, C. Charitidis, Additive manufacturing: scientific and technological challenges, market uptake and opportunities, Mater. today, 21 (2018) 22–37. https://doi.org/10.1016/j.mattod.2017.07.001

[14] Y. Li, K. Wei, W. Yang, Q. Wang, Improving wind turbine blade based on multi-objective particle swarm optimization, Renew Energy, 161 (2020) 525–542. https://doi.org/10.1016/j.renene.2020.07.067

[15] T. Ngo, A. Kashani, G. Imbalzano, K. Nguyen, D. Hui, Additive manufacturing (3D printing): A review of materials, methods, applications and challenges, Compos B. Eng., 143 (2018)172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

[16] G. Goh, S. Sing, W. Yeong, A review on machine learning in 3D printing: applications, potential, and challenges, Artif .Intell. Rev., 54 (2021) 63–94. https://doi.org/10.1007/s10462-020-09876-9

[17] P. Parandoush and D. Lin, "A review on additive manufacturing of polymer-fiber composites," Compos Struct, vol. 182, pp. 36–53, 2017, doi: 10.1016/j.compstruct.2017.08.088.

[18] C. Zhu., Realization of circular economy of 3D printed plastics: A review, Polym., 13 (2021) 744. https://doi.org/10.3390/polym13050744

[19] S. Poole , R. Phillips, Rapid prototyping of small wind turbine blades using additive manufacturing, in 2015 pattern recognition association of South Africa and robotics and mechatronics int.conf., IEEE, (2015) 189–194. https://doi.org/10.1109/RoboMech.2015.7359521

[20] A. Kafle, E. Luis, R. Silwal, H. Pan, P. Shrestha, A. Bastola, 3D/4D Printing of polymers: Fused deposition modelling (FDM), selective laser sintering (SLS), and stereolithography (SLA), Polym. ., 13 (2021) 3101. https://doi.org/10.3390/polym1318 3101

[21] S. Sivamani, M. Nadarajan, R. Kameshwaran, C. Bhatt, M. Premkumar, V. Hariram, Analysis of cross axis wind turbine blades designed and manufactured by FDM based additive manufacturing, Mater .Today ., 33 (2020) 3504 –3509. https://doi.org/10.1016/j.matpr.2020.05.438

[22] A. L. Shashidhar, A. B. Basavaroodh, S. K. Shashir, A. D. Apsarraj, Design, Development and Testing of Model Wind Turbine Blades Using Additive, 4 (2017) 259–262.

[23] S. Arivalagan, R. Sappani, R. Čep, M. S. Kumar, Optimization and Experimental Investigation of 3D Printed Micro Wind Turbine Blade Made of PLA Material, Mater., 16 (2023) 2508. https://doi.org/10.3390/ma16062508

[24] L. Kumar , C. Krishnadas Nair, Current trends of additive manufacturing in the aerospace industry, Adv. Print. Addit. Manuf. Technol., (2017) 39–54. https://doi.org/10.1007/978-981-10-0812-2_4

[25] F. Ning, W. Cong, J. Qiu, J. Wei, S. Wang, Additive manufacturing of carbon fiber reinforced thermoplastic composites using fused deposition modeling, Compos B Eng., 80 (2015) 369–378. https://doi.org/10.1016/j.compositesb.2015.06.013

[26] V. A. Ramírez-Elías, N. Damian-Escoto, K. Choo, M. A. Gómez-Martínez, A. Balvantín-García, and J. A. Diosdado-De la Peña, Structural Analysis of Carbon Fiber 3D-Printed Ribs for Small Wind Turbine Blades, Polymers, 14 (2022) 4925. https://doi.org/10.3390/polym14224925

[27] P. Kapranos, C. Carney, A. Pola, M. Jolly, Advanced Casting Methodologies: Investment Casting, Centrifugal Casting, Squeeze Casting, Metal Spinning, and Batch Casting, Comp. Mater. Proc., 5 (2014) 39–67. http://dx.doi.org/10.1016/B978-0-08-096532-1.00539-2

[28] A. Rahimizadeh, J. Kalman, K. Fayazbakhsh, L. Lessard, Recycling of fiberglass wind turbine blades into reinforced filaments for use in Additive Manufacturing, Compos B Eng., 175 (2019) 107101. https://doi.org/10.1016/j.compositesb.2019.107101

[29] F. Guerrero-Villar, E. Torres-Jimenez, R. Dorado-Vicente, J.I Jiménez-González,Development of vertical wind turbines via FDM prototypes, Procedia Eng., 132 (2015) 78–85. https://doi.org/10.1016/j.proeng.2015.12.482

[30] B. Post, B. Richardson, P. Lloyd, L. Love, S. Nolet, J. Hannan, Additive Manufacturing of Wind Turbine Molds, ORNL/TM-20 (2017).http://www.osti.gov/servlets/purl/1376487/

[31] M Aboushama, S Beyerlein, M Bednarz, Evaluation of Continuous Fiber Reinforcement Desktop 3D Printers,2020. http://dx.doi.org/10.13140/RG.2.2.16640.87040

[32] W.S. Carron, D. Snowberg, P. Murdy, S Hughes, Using Large-Scale Additive Manufacturing for Wind Turbine Blade Core Structures Using Large-Scale Additive Manufacturing for Wind Turbine Blade Core Structures, Technical Report, 2023.

[33] R. Murray, D. Snowberg, D. Berry, R. Beach, S. Rooney, D. Swan, Manufacturing a 9-meter thermoplastic composite wind turbine blade, National Renewable Energy Lab, Golden, CO (United States), 2017. https://doi.org/10.12783/asc2017/15166

[34] Gibson, I. dditive Manufacturing Technologies 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing. springer publication, 2015.

[35] P. K. Mallick, Fiber-reinforced composites: materials, manufacturing, and design, CRC press, 2007. https://doi.org/10.1201/9781420005981

[36] G. C. Jacob et al., Technical advances in epoxy technology for wind turbine blade composite fabrication, Proc.tech. conf., 2009.

[37] NREL, Three-Dimensional Printing of Thermoplastic Blades Enables Thermal Welding, Improves Recyclability, 2021. https://www.nrel.gov/news/program/2021/manufacturing-next-generation-wind-turbines.html

[38] J. Joustra, B. Flipsen, R. Balkenende, Structural reuse of high end composite products: A design case study on wind turbine blades, Resour. Conserv. Recycl., 167 (2021)105393. https://doi.org/10.1016/j.resconrec.2020.105393

[39] A. Chiriță, P. Bere, R. RĂDOI, L. Dumitrescu, Aspects regarding the use of 3D printing technology and composite materials for testing and manufacturing vertical axis wind turbines, Mater. Plast., 56 (2019) 910-917. https://doi.org/10.37358/MP.19.4.5283

[40] C. Tong , C. Tong, Advanced Materials Enable Renewable Wind Energy Capture and Generation, Adv. Energy. Mater., (2019) 379– 444. http://dx.doi.org/10.1007/978-3-319-98002-7_6

[41] L. Mishnaevsky, Sustainable end-of-life management of wind turbine blades: Overview of current and coming solutions, Mater., 14 (2021) 1124. https://doi.org/10.3390/ma14051124

[42] P. Ferretti *et al.*, Molds with advanced materials for carbon fiber manufacturing with 3D printing technology, Polym., 13 (2021) 3700. https://doi.org/10.3390/polym13213700

[43] Z. Zhong, Processes for environmentally friendly and/or cost-effective manufacturing, Mater. Manuf. Proc., 36 (2021) 987–1009. https://doi.org/10.1080/10426914.2021.1885709

[44] S. Domnica, C. Ioan, T. Ionut, Structural optimization of composite from wind turbine blades with horizontal axis using finite element analysis, Proc. Technol., 22 (2016) 726–733. https://doi.org/10.1016/j.protcy.2016.01.031

[45] K. Maalawi , H. Negm, Optimal frequency design of wind turbine blades, J. Wind Eng. Ind. Aerody., 90 (2002) 961–986. https://doi.org/10.1016/S0167-6105(02)00214-3

[46] F. Song, Y. Ni, Z. Tan, Optimization design, modeling and dynamic analysis for composite wind turbine blade, Proc.Eng., 16 (2011) 369–375. https://doi.org/10.1016/j.proeng.2011.08.1097

[47] H. Yang, J. Chen, X. Pang, G. Chen, A new aero-structural optimization method for wind turbine blades used in low wind speed areas, Comp. Struct, 207 (2019) 446–459. https://doi.org/10.1016/j.compstruct.2018.09.050

[48] K. Chen ,C. Yung, Structural optimization of 3 MW wind turbine blades using a two-step procedure, Int. J. Simul. Multidisci. Des. Optim., 4 (2010) 159-165. https://doi.org/10.1051/ijsmdo/2010020

[49] M. Jureczko , M. Mrówka, Multiobjective Optimization of Composite Wind Turbine Blade, Mater., 15 (2022) 4649. https://doi.org/10.3390/ma15134649

[50] S. Andrew Ning, R. Damiani, and P. J. Moriarty, Objectives and Constraints for Wind Turbine Optimization, J. Sol. Energy Eng., 136 (2014) 12. https://doi.org/10.1115/1.4027693

[51] K. Chen, M. Song, X. Zhang, S. Wang, Wind turbine layout optimization with multiple hub height wind turbines using greedy algorithm, Renew. Energy, 96 (2016) 676–686. https://doi.org/10.1016/j.renene.2016.05.018

[52] J. Neto, E. Junior, S. Moreno, H. Ayala, V. Mariani, L. Coelho, Wind turbine blade geometry design based on multi-objective optimization using metaheuristics, Energy, 162 (2018) 645–658. https://doi.org/10.1016/j.energy.2018.07.186

[53] W. Xudong, W. Shen, W. Zhu, J. Sørensen, C. Jin, Shape optimization of wind turbine blades, Wind Energy: An Int. J.for Progress and Appl. in Wind Power Conv. Technol., 12 (2009) 781–803. https://doi.org/10.1002/we.335

[54] K. Maki, R. Sbragio, N. Vlahopoulos, System design of a wind turbine using a multi-level optimization approach, Renew .Energy, 43 (2012) 101–110. https://doi.org/10.1016/j.renene.2011.11.027

[55] C. Liao, X. Zhao, J. Xu, Blade layers optimization of wind turbines using FAST and improved PSO Algorithm, Renew Energy, 42 (2012) 227–233. https://doi.org/10.1016/j.renene.2011.08.011

[56] B. Bavanish , K. Thyagarajan, Optimization of power coefficient on a horizontal axis wind turbine using bem theory, Renew. Sustain. Energy. Rev., 26 (2013)169–182. https://doi.org/10.1016/j.rser.2013.05.009

[57] J. Chen, Q. Wang, W. Shen, X. Pang, S. Li, X. Guo, Structural optimization study of composite wind turbine blade, Mater.Design , 46 (2013) 247–255. https://doi.org/10.1016/j.matdes.2012.10.036

[58] A. Kusiak , H. Zheng, Optimization of wind turbine energy and power factor with an evolutionary computation algorithm, Energy, 35 (2010) 1324–1332. https://doi.org/10.1016/j.energy.2009.11.015

[59] J. Zhu, X. Cai, P. Pan, R. Gu, Optimization design of spar cap layup for wind turbine blade, Front. Struct. Civ. Eng., 6 (2012) 53–56. https://doi.org/10.1007/s11709-012-0147-9

[60] A. Muheisen, M. Yass, I. Irthiea, Enhancement of horizontal wind turbine blade performance using multiple airfoils sections and fences, J. University-Engi. Sci., 35 (2023) 69–81. https://doi.org/10.1016/j.jksues.2021.02.014

[61] A. Chehouri, R. Younes, A. Ilinca, J. Perron, Review of performance optimization techniques applied to wind turbines, Appl. Energy, 142 (2015) 361–388. https://doi.org/10.1016/j.apenergy.2014.12.043

[62] R. Barnes , E. Morozov, Structural optimisation of composite wind turbine blade structures with variations of internal geometry configuration, Compos .Struct., 152 (2016)158–167. https://doi.org/10.1016/j.compstruct.2016.05.013

[63] K. Yang, Geometry design optimization of a wind turbine blade considering effects on aerodynamic performance by linearization, Energies, 13 (2020) 2320. https://doi.org/10.3390/en13092320

[64] S. Kim et al., Compression and energy absorption characteristics of short fiber-reinforced <scp>2D</scp> composite lattices made by material extrusion, Eng.Repo., 5 (2023) 12701. https://doi.org/10.1002/eng2.12701

[65] Z. Li, Study of site suitability assessment of regional wind resources development based on multi-criteria decision, Clean .Techn. Environ. Policy., 20 (2018) 1147–1166. https://doi.org/10.1007/s10098-018-1538-y

[66] G. Galvez, K. Olivar, F. Tolentino, L. Danao, B. Abuan, Finite Element Analysis of Different Infill Patterns for 3D Printed Tidal Turbine Blade, Sustain., 15 (2022) 713. https://doi.org/10.3390/su15010713

[67] V. Cabreira , R. Santana, Effect of infill pattern in Fused Filament Fabrication (FFF) 3D Printing on materials performance, Matér ., 25 (2020). https://doi.org/10.1590/s1517-707620200003.1126

[68] P. Mishra, P. Senthil, S. Adarsh, M. Anoop, An investigation to study the combined effect of different infill pattern and infill density on the impact strength of 3D printed polylactic acid parts, Comp.Comm., 24 (2021) 100605. https://doi.org/10.1016/j.coco.2020.100605

[69] M. Tanveer, G. Mishra, S. Mishra, R. Sharma, Effect of infill pattern and infill density on mechanical behaviour of FDM 3D printed Parts-a current review, Mater .Today .Proc., 62 (2022) 100–108. https://doi.org/10.1016/j.matpr.2022.02.310

[70] Ç. bolat , B. ergene, an experimental effort on impact Properties of Polylactic Acid Samples Manufactured by Additive Manufacturing, Duzce University J. Sci. Technol., 11(2023) 998–1013. https://doi.org/10.29130/dubited.1075259

[71] A. Sharif, H. Khan, N. Bashir, W. Alam, Parametric optimization and evaluating mechanical properties of poly lactic acid proceed by FDM additive manufacturing, J. Mater. Manuf., 2 (2023) 11-20. https://doi.org/10.5281/zenodo.8020527