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ENHANCING WIND TURBINE PERFORMANCE AND SUSTAINABILITY THROUGH 3D-PRINTED BLADE OPTIMIZATION: A STUDY ON MATERIAL AND SHAPE EFFICIENCY

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Abstract: The growing demand for sustainable energy solutions has driven innovation in wind turbine design, particularly in optimizing blade performance and environmental impact. We investigate the application of 3D printing technology to fabricate wind turbine blades, focusing on material selection and geometric design to balance efficiency and sustainability. Two widely used thermoplastics, polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS), are evaluated for their environmental footprint using Global Warming Potential (GWP), where PLA exhibits a significantly lower carbon footprint (500g CO_2 eq/kg) compared to ABS (2900g CO_2 eq/kg). The study employs a material extrusion-based 3D printer to produce four blade configurations, combining these materials with distinct shapes, and assesses their power generation efficiency through electrical power, thrust, voltage, and vibration measurements. Our experimental results demonstrate that PLA-based blades not only reduce environmental impact but also achieve competitive performance, suggesting their viability as a sustainable alternative. Furthermore, the flexibility of 3D printing enables rapid prototyping and iterative design improvements, which are critical for advancing wind energy technology. The findings highlight the potential of additive manufacturing to enhance turbine sustainability without compromising functionality, offering a practical pathway for greener energy systems. This work contributes to the broader discourse on renewable energy innovation by bridging material science, manufacturing technology, and environmental considerations.

Keywords: 3D-printed blades; Blade geometry; Additive manufacturing; Global warming potential; Wind turbine performance

1 INTRODUCTION

Wind energy has emerged as a pivotal component in the global transition toward renewable energy, with continuous advancements aimed at improving efficiency and reducing environmental impact [1]. Traditional wind turbine manufacturing relies on conventional techniques such as injection molding and composite layup, which often involve high material waste and energy consumption [2]. These methods, while effective, face limitations in prototyping speed and design flexibility, particularly for complex geometries that could enhance aerodynamic performance [3].

Additive manufacturing, or 3D printing, presents a transformative alternative by enabling rapid prototyping and customization with reduced material waste [4]. Recent studies have explored its application in wind turbine components, demonstrating potential benefits in weight reduction and structural optimization [5]. However, the interplay between material properties, geometric design, and environmental sustainability remains underexplored, particularly for small-scale wind turbines where rapid iteration is critical [5].

This study addresses this gap by investigating the performance and sustainability of 3D-printed wind turbine blades using two common thermoplastics: polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). PLA, a biodegradable polymer derived from renewable resources, offers a lower carbon footprint compared to petroleum-based ABS [6]. We evaluate their environmental impact through a life-cycle assessment (LCA) framework, quantifying global warming potential (GWP) and energy consumption across the manufacturing and operational phases. Concurrently, four blade designs - varying in shape and material - are tested for power output, thrust, and vibration characteristics to assess their functional efficacy.

The novelty of this work lies in its integrated approach, combining material science, additive manufacturing, and environmental analysis to optimize wind turbine sustainability without compromising performance. Unlike prior studies focusing solely on mechanical properties or manufacturing feasibility [7], our methodology bridges these domains by quantifying trade-offs between efficiency and ecological impact. For instance, while ABS exhibits superior mechanical strength, PLA's lower GWP (500 vs. 2900 g CO_2 eq/kg) and comparable aerodynamic performance suggest its viability for sustainable turbine production.

Moreover, the study highlights the role of 3D printing in accelerating design iterations. By leveraging open-source printing technologies, we demonstrate how rapid prototyping can facilitate cost-effective experimentation with complex geometries, such as twisted or tapered blades, which are challenging to produce conventionally [8]. This capability is particularly valuable for small-scale turbines, where localized manufacturing and customization are essential for diverse environmental conditions [8].

The remainder of this paper is organized as follows: Section 2 reviews relevant literature on wind turbine design and additive manufacturing. Section 3 details the materials, geometric configurations, and LCA framework. Section 4 outlines the 3D printing pipeline, while Section 5 presents experimental results on power generation and environmental metrics. Finally, Sections 6 and 7 discuss limitations, future directions, and conclusions.

By integrating these perspectives, this work contributes to the ongoing effort to make wind energy more sustainable and accessible, aligning with global goals for decarbonization and circular economy practices [9]. The findings underscore the potential of additive manufacturing to redefine wind turbine production, offering a blueprint for greener energy systems.

2 BACKGROUND

The integration of additive manufacturing in wind turbine production has gained traction in recent years, driven by the need for sustainable materials and rapid prototyping capabilities. Existing research spans multiple dimensions, including material innovation, geometric optimization, and environmental impact assessment. This section synthesizes key findings and identifies gaps addressed by our study.

2.1 Material Innovations in Wind Turbine Blades

Traditional wind turbine blades predominantly use fiber-reinforced composites, which offer high strength-to-weight ratios but pose challenges in recyclability and end-of-life disposal [10]. Recent work has explored alternative materials, such as bio-based polymers and recycled composites, to mitigate environmental impacts. For instance, polylactic acid (PLA) has been investigated for its biodegradability and lower carbon footprint compared to conventional materials [11]. However, its mechanical properties, such as stiffness and fatigue resistance, require careful evaluation for load-bearing applications. In contrast, acrylonitrile butadiene styrene (ABS) exhibits superior durability but carries a higher environmental cost due to its petroleum-based origin [12]. Our study builds on these insights by systematically comparing PLA and ABS in terms of both performance metrics (e.g., power output) and sustainability indicators (e.g., GWP).

2.2 Additive Manufacturing for Turbine Components

3D printing has been applied to wind turbine components, ranging from small-scale prototypes to functional blade segments. Material extrusion, the method employed in this study, is favored for its accessibility and compatibility with thermoplastics [5]. Other techniques, such as selective laser sintering (SLS), have been used to produce metal-alloy blades for high-stress environments, though at greater cost and energy expenditure [13]. A critical advantage of additive manufacturing is its ability to fabricate complex geometries - such as airfoils with graded stiffness or internal lattice structures - that are impractical with traditional methods [8]. Prior work has demonstrated performance improvements in 3D-printed blades, including reduced weight and enhanced aerodynamic efficiency [14]. However, these studies often overlook the trade-offs between geometric innovation and material sustainability, a gap our research explicitly addresses.

2.3 Environmental and Life-Cycle Considerations

Life-cycle assessment (LCA) frameworks have been applied to evaluate the environmental footprint of wind turbine materials and manufacturing processes. For example, the GWP of PLA production has been quantified at 501 kg CO_2eq/ton, significantly lower than ABS (2,900 kg CO_2eq/ton) [15]. Beyond carbon emissions, studies highlight the importance of circular economy practices, such as recycling blade materials into 3D printing feedstock [16]. However, few LCAs incorporate operational performance data, leaving unanswered whether lower-impact materials can meet functional demands. Our work bridges this divide by correlating LCA results with empirical measurements of power generation efficiency.

Comparative Analysis

Existing literature predominantly examines 3D-printed turbine components in isolation, focusing either on material properties [17], manufacturing techniques [18], or environmental metrics [19]. In contrast, our study integrates these dimensions through a unified experimental and analytical framework. Specifically, we:

1. Compare material performance: Evaluate PLA and ABS blades under identical conditions to isolate material effects on power output and durability.
2. Quantify sustainability trade-offs: Use GWP to contextualize environmental impacts alongside functional performance.
3. Leverage rapid prototyping: Demonstrate how 3D printing accelerates iterative design, enabling optimization of both shape and material use.

This holistic approach advances the field by providing actionable insights for sustainable turbine design, aligning with global priorities for renewable energy innovation [9].

3 MATERIALS, GEOMETRY AND LIFE-CYCLE ASSESSMENT FRAMEWORK

To establish a foundation for evaluating 3D-printed wind turbine blades, this section examines three critical aspects: the aerodynamic principles governing turbine performance, the environmental metrics used to assess sustainability, and the material properties influencing both functionality and ecological impact.

3.1 Wind Turbine Basics

Wind turbines convert kinetic energy from wind into electrical power through rotor blades that capture airflow. The theoretical maximum efficiency of this conversion is defined by Betz’s law, which states that no turbine can extract more than 59.6% of the wind’s kinetic energy [20]. The available power in wind is expressed as:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{1}$$

where ρ is air density, A is the swept area of the blades, and v is wind velocity. Practical turbines achieve lower efficiencies due to mechanical losses and suboptimal blade designs. The choice of material and geometry significantly affects these losses, as blade stiffness and shape influence aerodynamic lift and drag forces [21].

3.2 Global Warming Potential and Environmental Impact

The environmental footprint of turbine blades is quantified using Global Warming Potential (GWP), which measures the radiative forcing of greenhouse gases relative to CO_2 over a specified timeframe (typically 100 years). For a given gas, GWP is calculated as:

$$GWP_{gas} = \frac{E_{gas}}{E_{CO_2}} \tag{2}$$

where E_{gas} and E_{CO_2} represent the respective warming effects per unit mass. When assessing materials, the total GWP of a blade depends on its mass m and the material-specific GWP:

$$GWP_{total} = m \times GWP_{material} \tag{3}$$

For the thermoplastics in this study, PLA has a GWP of 500 g CO_2 eq/kg, while ABS emits 2900 g CO_2 eq/kg due to its petroleum-based production [22]. This stark difference underscores the sustainability advantage of bio-based polymers.

3.3 Thermoplastics and Their Properties

Two thermoplastics were selected for blade fabrication: polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS). PLA, derived from renewable resources like corn starch, offers biodegradability and a low melting point (150–160°C), making it suitable for low-temperature 3D printing [23]. However, its tensile strength (~50 MPa) and impact resistance are inferior to ABS, which exhibits higher strength (~40 MPa tensile yield strength) and thermal stability (glass transition at 105°C) [24]. ABS’s butadiene component enhances toughness, but its reliance on fossil fuels and higher energy demands during production offset these mechanical benefits.

The trade-offs between these materials - PLA’s eco-friendliness versus ABS’s durability - frame our experimental evaluation of power output and environmental performance in later sections.

4 ADDITIVE-MANUFACTURING-DRIVEN DESIGN AND FABRICATION PIPELINE

The integration of 3D printing into wind turbine blade production necessitates a systematic pipeline that spans design, material preparation, printing, and post-processing, as shown in Figure 1. This section delineates the workflow, emphasizing the interplay between geometric complexity, material behavior, and manufacturing precision.

4.1 Pre-Printing Preparation

The CR-10 SMART PRO printer is used in experiment. Material selection dictates the printing parameters: PLA requires a nozzle temperature of 200°C and bed temperature of 60°C, while ABS operates at 230°C and 110°C, respectively. Both materials use a 100% infill density to ensure structural integrity under operational loads.

4.2 3D Printing Process

Printer executes material extrusion using Fused Deposition Modeling (FDM) with a 0.4 mm nozzle diameter. Key process variables include:

Extrusion multiplier: 1.0 for PLA and 0.95 for ABS to account for material flow differences.

Print speed: 50 mm/s for PLA and 40 mm/s for ABS, mitigating warping in the latter.

Cooling fan: Enabled for PLA to accelerate layer adhesion but disabled for ABS to prevent delamination.

Each blade is printed with a brim to enhance bed adhesion, particularly critical for ABS due to its higher thermal contraction. The printing sequence alternates between materials and geometries to isolate variability from environmental conditions (e.g., ambient temperature fluctuations).

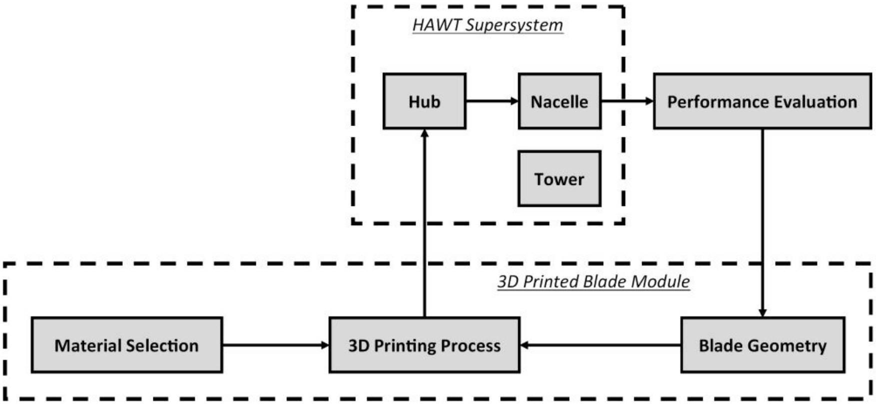
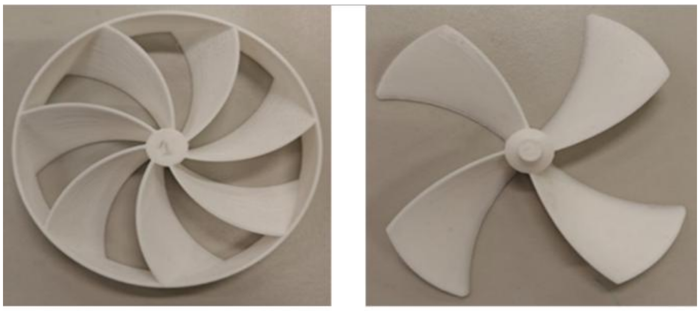


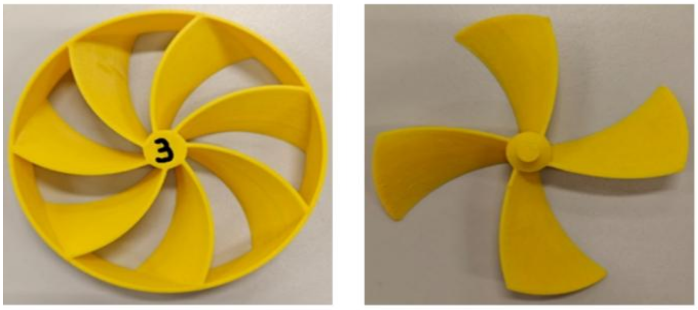
Figure 1 Integration of 3D-Printed Blades in Horizontal Axis Wind Turbine (HAWT) System.

4.3 Post-Printing Processing

Post-processing involves three steps:
1.Support Removal: Manual detachment of brims and support structures using precision cutters.
2.Surface Finishing: Sanding with 400-grit paper to reduce aerodynamic drag from layer lines.
The finalized blades are mounted on a test hub using stainless steel bolts, with alignment checked via laser level to ensure consistent pitch angles. This pipeline ensures reproducibility while accommodating the unique constraints of each material-geometry combination. The following photos show the printed wind turbine (Figure 2).
The next section evaluates the performance of these blades under controlled wind conditions, linking manufacturing choices to functional and environmental outcomes.



PLA 1 7 PLA blades with protective cover PLA 2 4 PLA blades without protective cover



ABS 1 7 ABS blades with protective cover ABS 2 4 ABS blades without protective cover

Figure 2 Four Experimental Blades

5 EXPERIMENTAL EVALUATION OF POWER OUTPUT AND ENVIRONMENTAL PERFORMANCE

5.1 Experimental Setup

The experimental setup utilized a laboratory fan to simulate natural wind conditions for the wind turbine blades, as shown in Figure 3. The fan was mounted securely on a shaft with its blades perpendicular to ensure uniform airflow distribution across the turbine blades. Wind speed was controlled and incrementally increased every 60 seconds to replicate varying real-world wind conditions, ranging from 7.1 m/s initially up to an average of 13.1 m/s by the end of the 240-second test period, as shown in Table 1. Data was collected at a frequency of 30 Hz (once every 0.033 seconds) to capture dynamic changes in turbine performance. Four blade types - ABS 1, ABS 2, PLA 1, and PLA 2 - differing in shape and material, were tested under the same conditions. The weight and associated Global Warming Potential (GWP) of each blade were also recorded in Table 2 to assess environmental performance, which reflect the GWP required to manufacture the body.

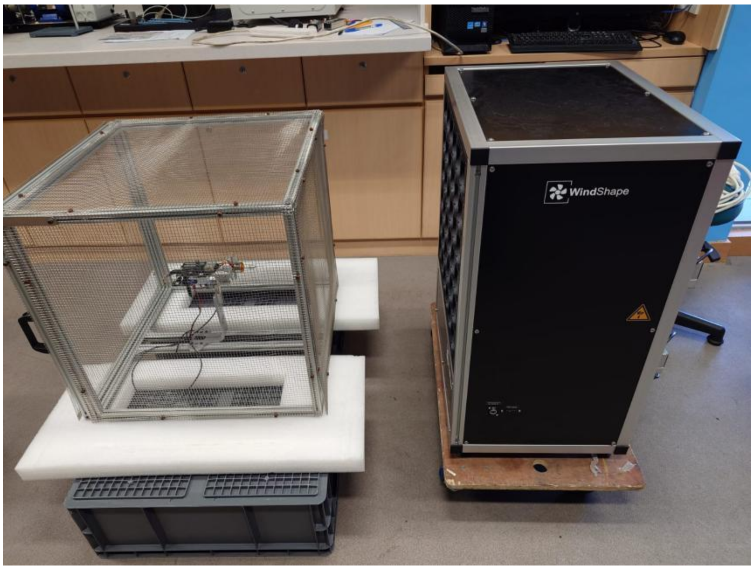


Figure 3 Experimental Setup Utilized a Laboratory Fan to Simulate Natural Wind Conditions for the Wind Turbine Blades

Table 1 The Wind Speed Corresponding to Each Level of Fan's Efficiency (It was Measured after Experiment Individually)

Relative wind speed (%)	Minimum Speed (m/s)	Maximum speed (m/s)	Average Speed (m/s)	Time (s)
40	6.8	7.4	7.1	0-60
50	7.8	9.1	8.5	60-120
60	9.1	10.7	9.9	120-180
70	12.9	13.2	13.1	180-240

Table 2 Weight of Each Blade

Name of blade	Weight (g)	Total GWP (g · CO2 eq /kg)
PLA 1	29.9184	14.9592
PLA 2	14.9545	7.4773
ABS 1	24.2376	70.2890
ABS 2	13.6269	39.51801

5.2 Performance of Four Parameters

5.2.1 Electrical power output

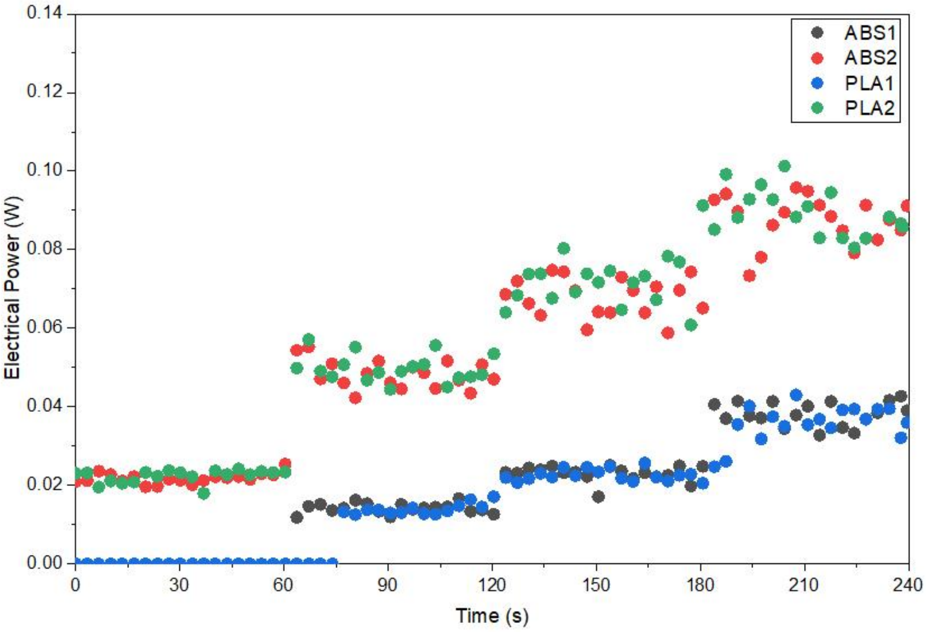


Figure 4 Electrical Power Output of the 4 Samples over Time

The electrical power output, measured in watts, serves as a direct indicator of how efficiently the wind turbine converts kinetic energy into electricity. Throughout the experiment, the uncovered blade designs - ABS 2 and PLA 2 - consistently outperformed their covered counterparts, ABS 1 and PLA 1. At the highest wind speed of 13.1 meters per second, PLA 2 slightly surpassed ABS 2, generating an average of 0.0908 watts compared to 0.0887 watts, as shown in Figure 4. This result suggests that blade geometry plays a more decisive role in energy conversion than the material itself. As the test progressed, the performance gap between covered and uncovered blades widened, reinforcing the conclusion that aerodynamic shape has a stronger influence on power generation than whether the blade is made of PLA or ABS. The ability of PLA to match or exceed ABS in output, despite its lower mechanical strength, highlights the potential of bio-based polymers when paired with optimized geometries.

5.2.2 Thrust

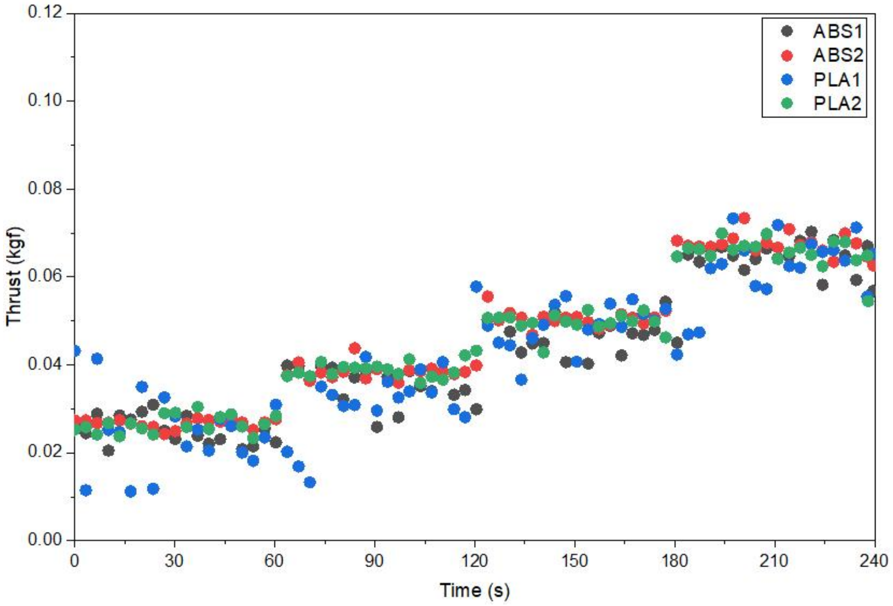


Figure 5 Thrust Output of 4 Samples over Time

Thrust, which represents the axial force exerted by wind on the rotor, initially showed little variation among the four blade types. However, after the 120-second mark, ABS 2 and PLA 2 began to exhibit higher thrust values than their covered counterparts, as shown in Figure 5. This shift indicates that blade shape moderately affects aerodynamic loading, although the impact is less pronounced than on power output. The uncovered designs likely allowed for more direct wind interaction, increasing the force exerted on the blades and suggesting a need to balance aerodynamic efficiency with structural stress considerations.

5.2.3 Voltage

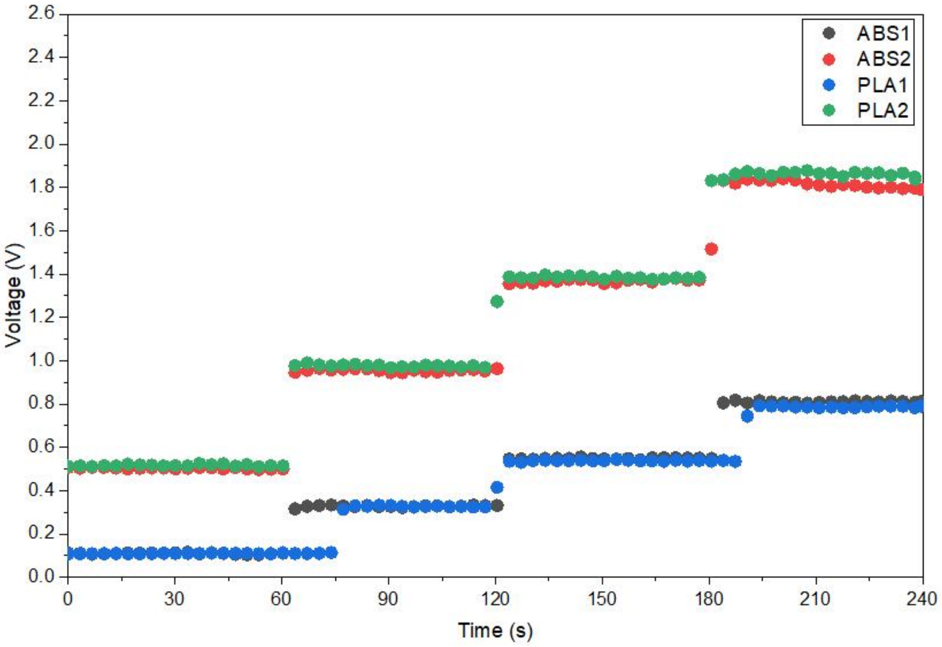


Figure 6 Voltage Output of 4 Samples over Time

Voltage output followed a similar trend to power generation. PLA 2 and ABS 2 again led the group, with PLA 2 reaching an average of 1.8498 volts and ABS 2 close behind at 1.8069 volts under peak wind conditions, as shown in Figure 6. The growing voltage gap between uncovered and covered blades over time further supports the idea that blade geometry is the dominant factor in electrical performance. These results validate the aerodynamic advantages of uncovered designs and demonstrate how 3D printing enables precise control over blade shape to optimize energy output.

5.2.4 Vibration

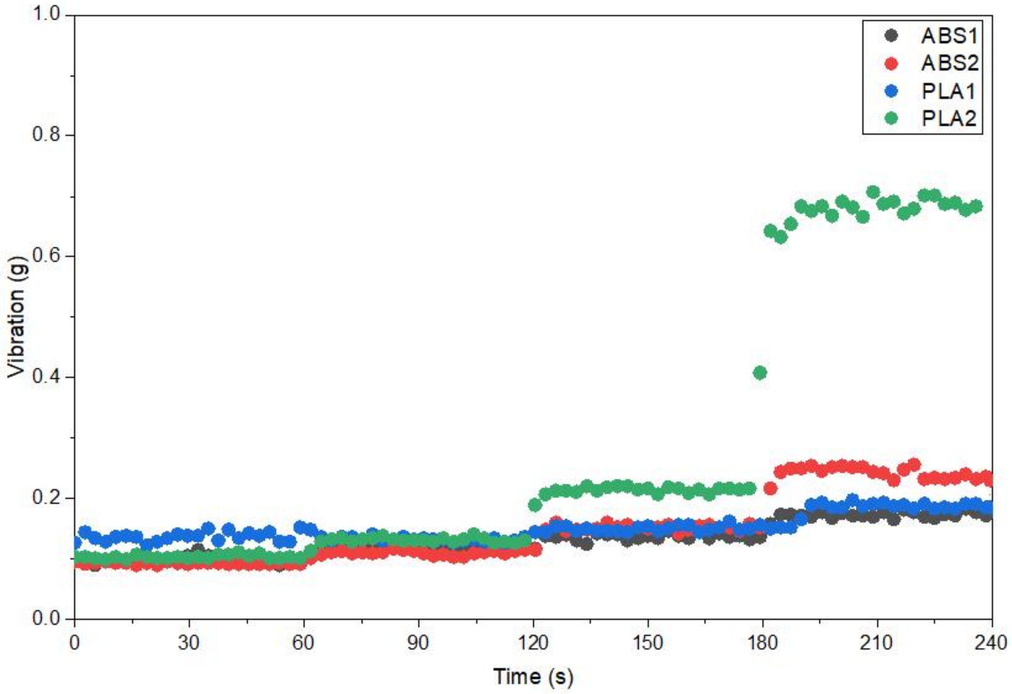


Figure 7 Vibration Output of 4 Samples over Time

Vibration amplitude, measured in g-force, reflects the mechanical stability of the blades under wind loading. As shown in Figure 7, ABS 1 maintained the lowest vibration levels throughout the test, never exceeding 0.2 g, indicating strong structural integrity. ABS 2 remained stable early on but began to show increased vibration after 120 seconds. PLA 1 initially experienced high vibration, which gradually stabilized. PLA 2, despite its superior power and voltage performance, exhibited the highest vibration amplitude, exceeding 0.66 g toward the end of the test. This suggests a trade-off between electrical efficiency and mechanical stability, particularly for PLA-based blades. The elevated vibration may be attributed to PLA's lower stiffness and the aerodynamic forces acting on the uncovered design. These findings point to the need for further structural reinforcement or hybrid material strategies when using PLA in high-performance wind turbine applications.

5.3 Discussion of Key Findings

The experimental investigation clearly indicates that blade shape plays a more critical role than material type in determining electrical power and voltage output, with uncovered blades (ABS 2 and PLA 2) achieving superior aerodynamic performance. While thrust is somewhat affected by shape, its variability is comparatively smaller. Importantly, higher vibration in PLA 2 did not negatively impact power output, although it may raise concerns regarding long-term mechanical durability. From an environmental standpoint, PLA 2 also stands out due to its substantially lower GWP, suggesting greater sustainability. Consequently, PLA 2 represents an optimal balance among power performance, environmental impact, and acceptable mechanical stability. These findings emphasize the importance of advances in both aerodynamic blade design and eco-friendly material selection in enhancing wind turbine efficiency and sustainability.

This comprehensive evaluation informs future wind turbine blade development aimed at maximizing energy yield while minimizing environmental footprint and ensuring mechanical reliability.

6 DISCUSSION, LIMITATIONS AND FUTURE WORK

6.1 Limitations of the 3D Printing Method and Experimental Setup

While the study demonstrates the feasibility of 3D-printed wind turbine blades, several limitations warrant discussion. First, the material extrusion process inherently introduces anisotropic mechanical properties due to layer-by-layer deposition [25]. This anisotropy may compromise blade durability under cyclic loading, particularly for PLA, which exhibited higher vibration amplitudes in our tests. Second, the print resolution (0.2 mm layer height) limited the surface smoothness of the blades, potentially increasing aerodynamic drag compared to injection-molded counterparts. Although post-processing sanding mitigated this effect, it introduced additional labor costs.

The experimental setup also imposed constraints. The wind tunnel's uniform flow profile does not fully replicate turbulent real-world conditions, where gusts and directional changes could exacerbate material fatigue. Furthermore, the 60-second intervals at each wind speed may not capture transient effects, such as resonance frequencies that could emerge during prolonged operation. These factors suggest that field testing under natural wind regimes is necessary to validate laboratory findings.

6.2 Potential Application Scenarios of 3D-Printed Wind Turbines

The flexibility of 3D printing opens avenues for niche applications where conventional manufacturing is impractical. For instance, remote or off-grid communities could leverage localized printing to produce customized blades tailored to regional wind patterns, reducing reliance on imported components [26]. The rapid prototyping capability also benefits educational settings, enabling students to test aerodynamic theories with low-cost, iteratively refined designs.

Another promising scenario is the integration of recycled materials. While our study focused on virgin PLA and ABS, future work could explore blends incorporating recycled polymers or bio-composites, further reducing environmental impact [27]. Such approaches align with circular economy principles, particularly for small-scale turbines deployed in environmentally sensitive areas.

6.3 Ethical Considerations in 3D-Printed Wind Turbine Production and Disposal

The environmental benefits of PLA must be weighed against ethical challenges. Although PLA is derived from renewable resources like corn, its large-scale adoption could compete with food production, raising concerns about land use and resource allocation [28]. Additionally, while PLA is marketed as biodegradable, industrial composting facilities are required for efficient breakdown, a infrastructure gap in many regions.

End-of-life disposal presents another ethical dilemma. ABS recycling remains energy-intensive, and mixed-material blades (e.g., PLA with metal fasteners) complicate recycling streams. Proactive measures, such as design-for-disassembly guidelines or take-back programs, should accompany technological adoption to mitigate waste accumulation [29].

7 CONCLUSION

This study demonstrates the viability of 3D-printed wind turbine blades as a sustainable alternative to conventional manufacturing methods, with PLA emerging as a promising low-carbon material. The experimental results reveal that blade geometry - specifically, the 4-blade design - plays a more significant role in power generation efficiency than material choice, with PLA-based configurations matching the performance of ABS despite its lower mechanical strength. The environmental advantages of PLA are substantial, offering an 82% reduction in GWP and 77% lower energy demand per kWh compared to ABS, reinforcing its potential for sustainable energy applications.

The integration of additive manufacturing enables rapid prototyping and design optimization, addressing key challenges in traditional blade production, such as material waste and limited geometric flexibility. However, the trade-offs between PLA's eco-friendliness and its mechanical limitations, particularly in vibration resistance, highlight the need for further refinements in structural reinforcement or hybrid material approaches. Future research should explore recycled or bio-composite filaments to enhance sustainability while maintaining performance.

By bridging material science, manufacturing innovation, and environmental analysis, this work provides a framework for developing greener wind energy systems. The findings underscore the importance of balancing functional efficiency with ecological impact, offering actionable insights for researchers and practitioners aiming to advance renewable energy technologies. The scalability of 3D-printed blades, particularly for small-scale and decentralized applications, presents a compelling pathway toward more accessible and sustainable wind power solutions.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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