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Printability of Pineapple Leaf Fibre/Polylactic Acid (PLAF/PLA) Filament in Fused Deposition Modelling (FDM) using Taguchi Method

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Abstract

Fused Deposition Modelling (FDM) is particularly valued for its cost-effectiveness and operational simplicity. There is a widely adopted 3D printing technology for enterprise additive manufacturing and rapid prototyping. This technique is applicable to various thermoplastic polymers, including the environmentally sustainable polylactic acid (PLA). Recently, natural fibres (NFs), such as kenaf, abaca, sugar palm fibre, and pineapple leaf fibre (PALF), have gained recognition as reinforcing agents in FDM filaments due to the advantageous properties, low cost, and wide availability. This research uses the Taguchi method to examine the effect of printing method parameters on the mechanical performance of PALF/PLA composites. The experimental model was organized into three stages of printing parameters: layer thickness, printing speed, and infill density. The outcomes indicate that the optimal parameter combination for achieving superior mechanical properties in PALF/PLA composites comprises a layer thickness of 0.1 mm, a printing speed of 25 mm/s, and a 100% infill density. Therefore, infill density was the most significant factor affecting mechanical strength. The enhanced mechanical performance of PALF/PLA composites was achieved with consistent optimal printing parameters. These findings highlight the need for sustainable product design, particularly in the automotive, aerospace, and consumer goods sectors, given the potential of PALF/PLA composites for structural and load-bearing applications.

Keywords: - Polylactic Acid (PLA), Pineapple Leaf Fibre (PALF), Fused Deposition Modelling (FDM)

1. Introduction

FDM is a 3D printing method that employs polymers to manufacture final products, prototypes, or samples (Wojtyła et al., 2017; Rahim et al., 2019 & Deb et al., 2021). Polylactic acid (PLA) is employed in additive manufacturing due to its excellent processability, biodegradable origin, and favorable mechanical properties. Findings indicate that the mechanical, thermal, and physical properties of 3D-printed composites increase when PLA is reinforced with bio-derived materials (Muthe et al., 2022). Lately, natural fibres (NF) have been incorporated into FDM filaments as reinforcement. A high superior natural fibre-occupied thermoplastic composite requires absolute mixing of the biofilter with the polymeric matrix, involving coupling and hardening agents (Mazzanti et al., 2019). Combining fibres with polymers can increase brittleness and reduce durability, potentially leading to filament fracture or melting within the nozzle (Kamran et al., 2016). Fibre reinforcement raises polymer viscosity, and excessive fibre saturation may inhibit material flow. Still, poor diffusion of natural fibres can result in non-uniform composite flow, indicating irregular printing or nozzle stumbling block (Lee et al., 2021). In FDM 3D printing, temperature and speed significantly influence the strength and structural reliability of composite filaments. Contrasts in natural fibre forms, such as wood, bamboo, and cork, may influence composite properties due to their separate structures (Zaman et al., 2019). To avoid nozzle blockages, a consistent filament diameter of 1.75 mm is essential. Improving process parameters enhances product quality and cost-effectiveness, thereby increasing production efficiency. Trade-offs must be considered, such as reduced build time and potentially weakened parts (Mazur et al., 2022). Therefore, to achieve desirable mechanical and physical properties in the additive manufacturing of natural fibre composites, it is crucial to understand the relationship between printing parameters and material properties. This study examines the effects of printing process parameters on the mechanical properties of PALF/PLA composites using the Taguchi method. The Taguchi Method is primarily used as a robust statistical tool for parameter optimization to enhance the printability and mechanical performance of the filament (Ahmad et al., 2022 & Refat et al., 2025). To improve manufacturing processes by enhancing toughness while maintaining adaptability, the Taguchi method has been widely utilized for statistical optimization, yielding a robust engineering approach (Astner et al., 2015). The basis of this method is the orthogonal array procedure for systematically evaluating multiple factors and interactions (Kam et al., 2023). The Taguchi methodology is used to enhance mechanical and physical properties by optimizing process parameters to produce high-quality components at reduced costs (Saini, 2019 & Radhwan et al., 2020).

2. Literature Review

The Taguchi method provides a systematic approach to identifying the optimal combination of 3D printing parameters to minimize process variation and maximize product quality (Turkoglu & Kilinc, 2025). In the context of PLAF/PLA composites, its use involves the following key components:

i. **Experimental Efficiency through Orthogonal Arrays**: Instead of testing every possible combination of variables (which would be time-consuming), researchers use Orthogonal Arrays (e.g., L9 or L18) to conduct a minimal number of strategic experiments (Ahmad et al., 2022 & Turkoglu & Kilinc, 2025). This allows simultaneous evaluation of multiple printing factors, such as nozzle temperature, layer thickness, print speed, and infill density (Refat et al., 2025).

ii. **Signal-to-Noise (S/N) Ratio Analysis**: The method uses S/N ratios to measure how much the response (quality characteristic) deviates from the desired value. For PLAF/PLA printability, researchers typically aim for "Larger-is-Better" for tensile strength and flexural modulus (Ahmad et al., 2022 & Refat et al., 2025) and "Smaller-is-Better" for surface roughness and dimensional deviation (Refat et al., 2025).In modern times, the combination of topology optimization with additive manufacturing (AM) is expected to revolutionize the fabrication of dense, bio-inspired, and multi-gauge structures that were previously impossible to produce (Wu et al., 2021). The current study is increasingly focused on Multiphysics challenges, such as fluid-thermal connections and electromagnetic effects, and on integrating machine learning to reduce the substantial computational costs conventionally associated with iterative optimization sequences (Alexandersen & Andreasen, 2020 & Shin et al., 2022).

By applying Analysis of Variance (ANOVA) to Taguchi results, researchers can statistically determine which parameter has the greatest impact on the final printed part (Ahmad et al., 2022 & Turkoglu & Kilinc, 2025). For example, studies often find that layer thickness or build orientation are the most influential factors in determining the strength of fibre-reinforced PLA (Ahmad et al., 2022 & Turkoglu & Kilinc, 2025). Enhancing Interfacial Bonding: Because natural fibres like pineapple leaf are hydrophilic and PLA is hydrophobic, achieving a "printable" composite is challenging. The Taguchi method helps determine the optimal thermal and speed settings to ensure proper interfacial bonding between the fibre and the matrix, reducing voids and improving the mechanical integrity of the 3D-printed part (Refat et al., 2025 & Turkoglu & Kilinc, 2025).

Later, enhancing composite materials, embedding natural fibres in a polymer matrix is vital for improving the base polymer's mechanical, thermal, and physical properties, yielding Natural Fibre-Reinforced Polymer Composites (NFRPCs). NFRPCs' products are biodegradable and provide value by minimizing environmental pollution, whilst the use of bio-based sources reduces reliance on non-renewable fossil fuels (Rafiee et al., 2021). As safe, recyclable, and sustainable alternatives to conventional materials, natural materials in additive manufacturing are also gaining momentum (Jiang & Raney, 2019). The agricultural and forestry products, including reeds, peanut shells, rice husks, crop straws, bamboo, starch, pineapple leaf fibre, kenaf, and wood fibres, as the term "natural fibre" incorporates a wide range of (Jiang & Raney, 2019; Lee et al., 2021 & Bi et al., 2022). Due to their high specific stiffness, unique properties, processability, and cost-effectiveness, the fibres mentioned above are increasingly regarded as ideal reinforcements in plastic composites (Luhar et al., 2020). Natural fibres, obtained from renewable organic sources, can be recognized as a new initiative for reinforcing materials. In contrast to synthetic fibres, which exhibit lower strength, natural fibres can achieve mechanical performance comparable to synthetic fibres in specific applications (Ahmad et al., 2023; Rafiee et al., 2021). To determine their effects on mechanical and physical properties, PALF/PLA composites can be examined by varying selected printing process parameters. This project aims to identify optimal printing circumstances for manufacturing high-quality products with superior strength and surface finish for various purposes.

In terms of biodegradability, environmental friendliness, and additive manufacturing compatibility, the NFRPCs show considerable promise for use in Fused Deposition Modelling (FDM) 3D printing across various manufacturing applications. The minimalism and cost-efficiency of FDM make it an ideal choice for rapid prototyping, particularly for consumer goods and toys (Khilji et al., 2023). In the healthcare sector, NFRPCs are being investigated for customizing goods, including biocompatible orthotics, prosthetics, implants, and drug-delivery systems, with FDM simplifying patient-precise solutions and functional replicas for medical exercise and surgical preparation (Nazir et al., 2023). In aerospace, the lightweight, high-strength properties of NFRPCs enable the design of fuel-efficient, reliable components (Balakrishnan et al., 2016). The automotive industry relies on extensive manufacturing consumption of natural fibres, with major producers such as NFRPCs incorporating cutting-edge vehicle components, including door panels and seats, to increase sustainability and reduce costs (Kamarudin et al., 2022 & Mohammed et al., 2015). Similarly, the construction sector's advantages in initiating NFRPCs for applications such as assembled panels and catastrophe-release structures. This includes the utilization of natural materials like bamboo, areca, and jute for their structural and acoustic properties (Nurazzi et al., 2022 & Kumar et al., 2019). Education and research also provide platforms for discovering material properties, optimizing FDM parameters, and developing new composites. This facilitates the transition and sustains broader acceptance of sustainable technologies. NFRPCs in FDM denote an enabling area for continued development and application in environmentally accountable manufacturing. (Ravindran et al., 2023)

The process parameters, such as nozzle and bed temperatures, printing speed, infill density, layer thickness, and raster pattern key, mainly require optimization to achieve high performance and cost-effective production. These parameters notably affect dimensional accuracy, surface finish, mechanical strength, and thermal properties. Combining materials and printing conditions can minimize waste, reduce build time, and improve product performance. The study exhibits that improper nozzle temperatures can indicate impoverished interlayer deformation. This makes layer thickness and printing speed influence fibre orientation and surface quality. Meanwhile, infill strategies also affect structural integrity, and bed levelling is key to confirming a robust base. For instance, Singh et al. emphasized that optimizing parameters in any manner increased the biocompatibility of PLA-hydroxyapatite scaffolds. These settings can enhance print quality and mechanical behavior (Bhagya et al., 2021; Triyono et al., 2020 & Lian et al., 2023). Furthermore, higher infill densities and finer layer heights lead to longer print times and greater material consumption. Consequently, the interplay between material properties and process parameters is vital for producing effective, precise, and robust FDM components, particularly when using composite filaments in advanced products. (Sangkharat & Techawinyutham, 2024). As illustrated in Fig. 1, the relationship between the composite filament characteristics and the printing process parameters is demonstrated.

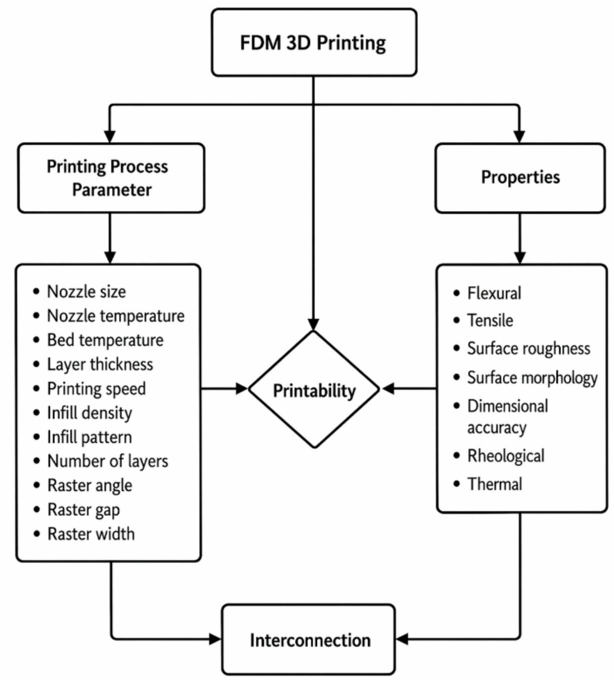

Fig. 1: The relationship between the printing process parameters and the properties (Sangkharat & Techawinyutham, 2024)

3. Methodology

The experiment was initiated by organizations producing natural fibre/PLA composite filaments, establishing starting raw materials and fully advanced composite filaments. The printing process parameters, including layer thickness, infill density, and printing speed, were selected based on relevant literature. The number of experimental runs and the total sample size were determined using the Design of Experiments (DOE) approach within the Taguchi method. Consequently, the optimal nozzle and bed temperatures representing printing PALF/PLA composites were recognized. The printing procedure was performed within the Taguchi method's experimental design, with the following parameters recognized. The printed samples were tested at that time in accordance with ASTM standards to evaluate mechanical and physical properties, including tensile and flexural strengths, as well as surface roughness. This analysis associated the optimal levels of layer thickness, infill density, and printing speed. This statistical analysis explained the strength and tendency of the relationships between the printing parameters and the resulting properties.

3.1 Experimental Setup/ Materials Preparation

This study uses natural fibres, pineapple leaf fibre (PALF), and IngeoTM Biopolymer 2003D Pellets, which are 100% pure PLA, as reinforcements for PLA. The PLA and PLAF properties were tabulated in Table 1 (Zin et al., 2018; Afzaluddin et al., 2019 & Aloyaydi et al., 2020).

Table 1: The properties of PLA and PALF

Properties	PLA	PALF	Authors
Density (g/cm^3)	1.24	1.07	Zin et al., 2018; Afzaluddin et al., 2019 & Aloyaydi et al., 2020
Flexual Strength (MPa)	108	-	
Flexual Modulus (MPa)	2378	-	
Tensile Strength (MPa)	60	126.60	
Elongation at Break (%)	9	2.2	
Tensile Modulus (MPa)	3100	4405	

The production of natural fibre/PLA composite filament initiated through the formulation of the fibres preceding to combination with PLA. This formulation engaged a sequence of procedures, including cutting, grinding, and sieving. Initially, raw pineapple fibres, approximately 15–20 cm in length, were cut into 2–3 cm slices. The fibres were subsequently scraped into refined fragments using the DF-15 Hammerhead Still Mill Grinder. Subsequently, the field fibres underwent sieving using a Sieve Shaker to obtain a standardized particle size range of 125–250 µm, resulting in a fine powder, as illustrated in Fig. 2. The processed fibres were then combined with PLA in an internal mixer to form a composite material. The resultant composite was pelletized, hooked onto small granules, and ultimately extruded to produce the composite filament.

Fig. 2: Structure of PLAF after the sieving process

3.2 Composites Filament Preparation

During the mixing procedure of NF/PLA composites, natural fibres were mixed with PLA at a fibre content of 5wt%, as testified by Mohamad et al. (2024). Research on diverse fibre loadings of advanced PALF/PLA composite filaments indicates that increasing fibre content increases the composite's mechanical strength. Thus, 5 wt% fibre demonstrated the highest mechanical strength among the compositions tested, including 1 wt% and 3 wt% fibre loadings. For each mixing cycle, 40 grams of PALF/PLA composite material were prepared to determine the internal mixer volume. Prior to extrusion, the fibre volume portion was consumed to calculate the composite's weight composition. Table 2 presents the specified weight composition of PALF/PLA. The PALF/PLA mixtures were weighed according to their specified compositions and placed in small zip-lock bags, as illustrated in Fig. 3. The mixing was conducted at 180 °C and 50 rpm to confirm an equal distribution of the fibres within the PLA matrix. The final form of the composites after mixing is depicted in Fig. 4.

Table 2: Details of PALF/PLA weight composition

Composite	Weight (500g total composite)		Weight (40g total composite)	
PALF/PLA	PALF	21.55	PALF	1.72
	PLA	478.45	PLA	38.28

(a) (b)

Fig. 3: The mixing process of PLA with NF (a), a weighted composite total of 40 g, and (b) packing in a small zip-lock bag

Fig. 4: xxxxx

The PALF/PLA composites underwent a crushing step followed by mixing to transform the modelled particle material into small, crystallized pellets, as illustrated in Fig. 5.

Fig. 5: The structure of composites after the crushing process, PALF/PLA

The last stage of the process involved extruding the composites into filament form. The extrusion was conducted at a constant temperature of 160 °C throughout the three heating zones. To confirm the applicable filament pattern, screw speeds of 320-360 rpm were used for the PALF/PLA composites. A laser detection system insisted on a precise filament diameter of 1.75 mm. The developing PALF/PLA composite filaments were effectively produced and precisely manufactured, as shown in Fig. 6.

Fig. 6: The composite filament produced after the extrusion process PALF/PLA

3.3 Testing Materials Setup

The filament was extruded to test tensile and flexural strength. The 3D printer parameters were configured with the nozzle temperature set to 170 °C, and the composite is consistent through this temperature. The bed temperature was maintained at 80°C, since PLA polymer does not require high temperatures. Additionally, the printing speed affected the performance of the printed samples. The nozzle speed was changed according to the specified parameters throughout printing. Fig. 7 indicates a schematic of 3D printing the composite filament.

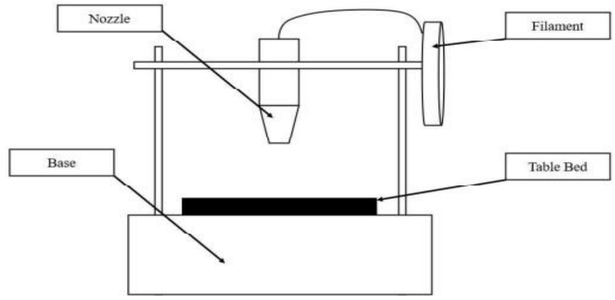

Fig. 7: Schematic diagram of 3D printing (FDM)

Table 3 presents the mechanical testing results (tensile and flexural strengths) obtained from the assessment, using the specified specimen and testing machine.

Table 3: Mechanical testing (tensile strength, flexural strength) versus specimen standard and machine used

Testing	Specimen Standard	Testing
Tensile	ASTM D638 Standard 	UTM 
Flexural	ASTM D790 Standard 	

ASTM = American Society for Testing and Materials
UTM=Universal Testing Machine

3.4 DOE Using the Taguchi Method

Research focuses on three printing parameters: layer thickness, printing speed, and infill density, each with three levels. The details are shown in Table 4, and other printing process parameters remained constant.

Table 4: The different levels of printing process parameters (Cho et al., 2019; Taborda Ríos et al., 2020 & Ahmad et al., 2022)

Printing Process Parameters	**Levels**		
	1	2	3
Layer Thickness (mm)	0.1	0.15	0.2
Printing Speed (mm/s)	25	50	100
Infill Density (%)	25	50	100

There will be 27 experiments for PALF/PLA, with three factors and three levels each. This research is devoted to the DOE Taguchi Method, using an L9 orthogonal array to fit three factors at three levels each. The L9 orthogonal array requires only nine experimental runs, thereby reducing the usual 27. The arrays were made using Minitab statistical software. The arrangement of the factors and their levels according to the L9 orthogonal array is shown in Table 5.

Table 5: Experimental plan based on L9 orthogonal array

Run	Layer Thickness (mm)	Printing Speed (mm/s)	Infill Density (%)
1	0.1	25	25
2	0.1	50	50
3	0.1	100	100
4	0.15	25	50
5	0.15	50	100
6	0.15	100	25
7	0.2	25	100
8	0.2	50	25
9	0.2	100	50

Minitab statistical software was utilized to analyze the results and identify the optimal 3D printing process parameters to achieve the highest mechanical and physical performance of PALF/PLA composites. The key parameters identified were layer thickness, printing speed, and infill density. The samples were printed in accordance with ASTM D790 for flexural properties and ASTM D638 for tensile properties.

4. Result

This section describes the mechanical results for NFRPCs and examines how printing process parameters affect the mechanical properties of PALF/PLA composites. The Taguchi technique was used to optimize the printing parameters to enhance the flexural and tensile properties of the NFRPCs.

Table 6 describes the median mechanical properties of PALF/PLA composites, including flexural strength, flexural modulus, tensile strength, and tensile modulus. Overall, experimental Run 3 exhibits the highest flexural strength and modulus, measured at 56.282 MPa and 3.263 GPa, respectively. However, run 7 boasts the highest tensile strength and modulus, at 37.097 MPa and 1.383 GPa, respectively. The outcome designates the arrangement of printing process parameters in Runs 1 and 7. It exhibits favorable mechanical characteristics, unlike the other experimental runs.

Table 6: The average of the mechanical properties of PALF/PLA composites

Run	Flexural Strength (MPa)	Flexural Modulus (GPa)	Tensile Strength (MPa)	Tensile Modulus (GPa)
1	47.438	2.825	17.879	0.791
2	55.934	2.992	20.694	0.917
3	56.282	3.263	34.968	1.290
4	50.745	3.291	21.313	0.955
5	51.711	3.038	35.219	1.358
6	49.725	2.441	17.601	0.752
7	46.926	3.068	37.097	1.383
8	41.690	2.125	18.010	0.721
9	50.300	2.763	20.228	0.816

5. Discussion

The data in Table 7 show that the optimal layer thickness, which maximizes flexural strength and flexural modulus, is 0.1 mm. On the contrary, the highest tensile strength is attained, including a layer thickness of 0.2 mm and the tensile modulus peaks at 0.15 mm. Nearly all mechanical properties are optimized at 25 mm/s regarding the print speeds. An infill density of 100% generally yields the best mechanical performance. Flexural strength and surface roughness have been optimized at lower infill densities of 50% and 25%, respectively. Overall, the optimal printing parameters for developing the mechanical and physical characteristics of PALF/PLA composites include a layer thickness of 0.1 mm, a printing speed of 25 mm/s, and a 100% infill density. All 3 parameters align with previous studies, which report that thinner layers and higher infill densities improve interlayer bonding and load distribution, both of which are important for excellent tensile and flexural properties (Gómez-Gras et al., 2018 & Domingo-Espin et al., 2015). Furthermore, lower printing speeds increase material deposition and adhesion, thereby enhancing mechanical strength (Chacón et al., 2017).

Table 7: PALF/PLA parameter optimization based on properties results

Properties / Printing Parameters	Layer Thickness (mm)	Printing Speed (mm/s)	Infill Density (%)
Flexural Strength (MPa)	0.1	100	50
Flexural Modulus (GPa)	0.1	25	100
Tensile Strength (MPa)	0.2	25	100
Tensile Modulus (GPa)	0.15	25	100

6. Conclusion

Due to its cost-effectiveness and simple operating principle, Fused Deposition Modelling (FDM) is widely adopted in contemporary additive manufacturing (AM) across several industries. This 3D printing method has been evaluated primarily for its ability to process multiple polymers and composites, which are ideal for generating prototypes and complex products. The fundamental principle of FDM is to extrude a heated thermoplastic filament through a nozzle and deposit it layer by layer onto a build platform. This research employed the FDM method to fabricate natural fibrereinforced polymer composites (NFRPCs) using precisely fabricated PALF/PLA composite filaments.

Pineapple leaf fibre (PALF), as a natural fibre, offers an abundance, ease of processing, and compatibility with polymer matrices. These NFRPCs are increasingly incorporated into numerous products for their environmental benefits and performance advantages. This research combined PALF as a reinforcing agent with a polylactic acid (PLA) matrix, a biodegradable polymer known for its advanced mechanical properties. The PALF fibres underwent a series of pre-processing steps, including cutting, grinding, and sieving, before being blended with

PLA pellets. The subsequent mixture ensued, then crushed and extruded into composite filaments of PALF/PLA.

The Taguchi technique managed experimental design towards examine the consequences of FDM printing parameters, which are layer thickness, printing speed, and infill density, towards the mechanical and physical properties of the printed composites. The optimal printing conditions for mechanical properties, including flexural and tensile strength, are considered.

The outcomes indicate that the optimal FDM printing parameters for PALF/PLA composites are a layer thickness of 0.1 mm, a printing speed of 25 mm/s, and an infill density of 100%, resulting in the desired mechanical performance. In conclusion, the mechanical characteristics of the composite material vary depending on the type of natural fibre used. This reveals the promise of cutting-edge FDM 3D printing for PALF/PLA composites. The situation demonstrates printability, in addition to the mechanical reactions below, by emphasizing its suitability for cutting-edge, numerous industrial products.

Author Contributions: The research study was carried out successfully with contributions from all authors.

Conflicts of Interest: The authors declare no conflict of interest.

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