Jurnal Kejuruteraan 37(8) 2025: 4065-4074
https://doi.org/10.17576/jkukm-2025-37(8)-34

Process Optimization of PLA/Wollastonite/Epoxidized Palm Oil Biocomposite Filament for Fused Deposition Modeling 3D Printing

Mohd Ikram Ramli[a*], Ong Chun Yao[a], Abu Bakar Sulong[b], Farrahshaida Mohd Salleh[c], Amir Arifin[d], Meor Ahmad Faris Meor Ahmad Tajuddin[e]

[a]*School of Engineering, University of Wollongong Malaysia,*
Jalan Kontraktor U1/14, Seksyen U1, 40150 Shah Alam, Selangor, Malaysia

[b]*Department of Mechanical and Manufacturing Engineering, Faculty of Engineering and Built Environment,*
Universiti Kebangsaan Malaysia, 43600 Bangi Selangor, Malaysia

[c]*Faculty of Mechanical Engineering, Universiti Teknologi MARA, 40450 Shah Alam, Selangor, Malaysia*

[d]*Department of Mechanical Engineering, Sriwijaya University, Indralaya 30662, Indonesia*

[e]*Faculty of Mechanical Engineering Technology,*
Universiti Malaysia Perlis (UniMAP), Pauh Putra, 02600 Arau, Perlis, Malaysia

**Corresponding author: ikram.r@uow.edu.my*

Received 15 March 2025, Received in revised form 26 August 2025
Accepted 26 September 2025, Available online 30 November 2025

ABSTRACT

The optimization of the extrusion process for biocomposite filaments derived from Polylactic Acid (PLA), reinforced with Wollastonite (WA), and plasticized using Epoxidized Palm Oil (EPO) is crucial for enhancing their performance in Fused Deposition Modeling (FDM) applications in three-dimensional printing. Although PLA is extensively utilized in 3D printing, it frequently exhibits inadequate strength and flexibility for rigorous applications, a limitation that can be mitigated through the incorporation of WA and EPO. This investigation delineates the optimal extrusion parameters that enhance the mechanical properties and consistency of the filaments. The findings indicate that an extrusion temperature of 170°C across both zones, a screw speed of 3 rpm, and a material composition comprising 90 wt.% PLA, 10 wt.% WA, and 3 vol.% EPO yield the highest filament density of 1.32 g/cm³, a tensile strength of 24.03 MPa, and an elongation at break of 1.43%. The screw speed emerged as the most significant variable affecting both filament density and tensile strength, while scanning electron microscopy (SEM) images validated the uniform distribution of WA particles within the PLA matrix, which contributes to the improved mechanical properties. This research substantiates the assertion that process optimization can markedly enhance the mechanical performance and quality of PLA/WA/EPO biocomposites, thereby positioning them as a viable material for high-quality 3D printing applications.

Keywords: Polylactic Acid (PLA); Wollastonite (WA); Epoxidized Palm Oil (EPO); Filament Extrusion; 3D Printing

INTRODUCTION

Polylactic Acid (PLA) is a biodegradable and biocompatible thermoplastic derived from renewable resources such as corn and sugarcane (Nhassa, Ben Khalifa & Snoussi 2024). While PLA has gained significant attention in the field of additive manufacturing due to its sustainability and ease of processing, it exhibits inherent brittleness and limited mechanical properties, which restrict its broader applications, especially in demanding fields such as 3D printing (Sultana et al. 2023). To overcome these limitations, researchers have explored the incorporation of various natural fibers and minerals as fillers, as well as the use of plasticizers to improve the mechanical properties of PLA-based composites. This has become increasingly important in light of the growing demand for more robust materials in advanced manufacturing, particularly for applications that require greater strength and flexibility. Recent studies indicate that the addition of Wollastonite and Epoxidized Palm Oil can significantly enhance the mechanical properties of PLA, making it more suitable for demanding 3D printing applications (Ramli et al. 2024; Poddar & Sarangi 2024).

Polymers like PLA are affordable and widely accessible for 3D printing; however, they may not possess the strength needed for fully functional applications. Recent advancements in material science have led to the development of PLA-based composites, combining PLA with materials such as ceramics, natural fibers, and graphene to improve both mechanical and functional properties (Valvez et al. 2020). PLA/Hydroxyapatite (HA) composites, for instance, are extensively utilized in biomedical fields due to HA's similarity to bone tissue. Scaffolds made from PLA with 15% HA and 30% porosity replicate the structure of trabecular bone, supporting cell and nutrient flow essential for bone regeneration (Omigbodun, Oladapo & Osa-uwagboe 2024).

The compatibility of materials is of paramount importance in the synthesis of composite materials. For instance, inadequate adhesion between short fibers and polylactic acid (PLA) may lead to heightened porosity and diminished mechanical integrity (Almeida et al. 2024). Additionally, PLA and wollastonite (WA) composites have been investigated, with injection-molded parts containing 90% PLA and 10% WA demonstrating optimal mechanical properties. However, higher WA content can decrease compatibility and overall performance (Saravana & Kandaswamy 2019). Moreover, the addition of WA to PLA improves its antibacterial characteristics, as shown by a decrease in Escherichia coli attachment when compared to pure PLA. These advancements render PLA/WA composites especially encouraging for use in medical device applications (Choudhary et al. 2022).

Wollastonite (WA), a naturally occurring calcium silicate mineral, has shown promise as a reinforcing filler in PLA-based composites due to its high strength, low thermal expansion, and bioactive properties (Saravana & Kandaswamy 2019). Its ability to enhance the mechanical properties of PLA while maintaining its biodegradability makes it an ideal candidate for use in biomedical applications, such as tissue repair and engineering. Wollastonite, typically produced through the thermal metamorphism of limestone, can also enhance the material's resistance to thermal degradation and increase its dimensional stability, making it suitable for high-performance applications (Gotlib et al. 2021). The addition of WA to PLA not only improves its strength but also imparts desirable characteristics such as improved toughness and resistance to thermal degradation, which are critical for the successful application of PLA in more demanding environments (Tazibt et al. 2023).

In addition to wollastonite, Epoxidized Palm Oil (EPO) has been employed as a plasticizer in PLA-based composites to address the material's brittleness and improve its flexibility. EPO, derived from palm oil, is an eco-friendly and renewable material that enhances the flexibility, processability, and thermal stability of PLA while maintaining its biodegradability (Awale et al. 2018). The introduction of EPO into PLA composites improves elongation at break and overall mechanical performance, making the material more suitable for a wider range of applications (Ali, Anuar & Fakhruldin 2016). EPO's ability to reduce phase separation in composite materials further enhances its suitability for use in PLA-based biocomposites, particularly in 3D printing (Anuar et al. 2023).

Fused Deposition Modeling (FDM) is one of the most widely used 3D printing techniques, relying on thermoplastic filaments that are extruded through a heated nozzle and deposited layer by layer to build three-dimensional objects (Krishnanand & Taufik 2021). The quality of the filament used in FDM printing is critical, as it directly influences the mechanical properties of the printed part, including its strength, flexibility, and dimensional accuracy. The filament extrusion process itself is complex, involving precise control over several parameters, including extrusion temperature, screw speed, spooling speed, and material composition. The optimization of these parameters is essential to guarantee that the filament maintains a uniform diameter and possesses suitable mechanical characteristics. Inadequate extrusion conditions may result in anomalies such as voids, suboptimal interlayer adhesion, and dimensional discrepancies, all of which can adversely affect the functionality of the resultant printed object (Damayanti & Muttaqin 2024).

Processing plays a crucial role in determining the performance of PLA-based biocomposites. The choice of extrusion parameters, such as temperature, screw speed, and material composition, directly influences the homogeneity of the mixture, the dispersion of reinforcing fillers like Wollastonite (WA), and the final mechanical properties of the filament. (Hartig et al. 2021). For instance, higher extrusion temperatures can improve material flow but may compromise the strength of the material due to reduced polymer chain bonding (Das et al. 2020). Conversely, lower temperatures may result in inadequate mixing and poor dispersion of fillers, leading to compromised mechanical properties. Therefore, a careful balance of these parameters is essential for optimizing the performance of PLA-based biocomposites in 3D printing applications.

Additionally, screw speed affects the shear forces within the extruder, which influences the mixing of PLA with other materials, ensuring a uniform blend or leading to poor filler dispersion if not optimized properly (Kaczor et al. 2022). Screw speed also significantly affects the extrusion process. A higher screw speed increases shear forces (Kast & Bonten, 2016), leading to more thorough mixing of the PLA matrix with fillers like Wollastonite (WA) and Epoxidized Palm Oil (EPO). While this can improve the homogeneity of the biocomposite and enhance the dispersion of the fillers, it can also result in a decrease in the material's density due to higher air entrapment and reduced bonding between filler particles and the PLA matrix (Sardar et al. 2024). Conversely, lower screw speeds may reduce shear forces, which can affect the uniform distribution of the fillers and result in lower-quality filaments with inconsistencies in both mechanical properties and filament diameter.

Density is another critical factor in the performance of 3D printed parts. The density of the filament directly impacts its mechanical properties, such as tensile strength and elongation at break (Oviedo et al. 2020). A higher filament density indicates better material compaction, which generally leads to stronger and more durable printed parts. Inadequate density, often caused by poor extrusion parameters or improper mixing, can result in voids or air pockets in the filament, which weaken the final printed part and reduce its performance (Ghorbani et al. 2022). Therefore, optimizing both extrusion temperature and screw speed is essential for achieving the desired density, which in turn contributes to improved strength, flexibility, and overall performance of the PLA/WA/EPO biocomposite filament.

In this framework, it is imperative to examine the ramifications of these processing conditions on the efficacy of PLA/WA/EPO biocomposites. For instance, augmenting the ratio of Epoxidized Palm Oil (EPO) bolsters the flexibility of the filament; however, it may concurrently diminish its rigidity and tensile strength if not meticulously calibrated. Similarly, the optimization of the extrusion process through stringent regulation of these variables can yield a substantial enhancement in both the mechanical attributes and the printability of the filament, thereby rendering it appropriate for high-caliber 3D printing applications (Shaqour et al. 2021).

Fused Filament Fabrication (FFF) is a widely utilized 3D printing technique that works with materials such as Polylactic Acid (PLA), thermoplastic polyurethane (TPU), and polyvinyl alcohol (PVA), while engineered plastics like acrylonitrile butadiene styrene (ABS) are commonly employed in professional and industrial applications (Dey, Eagle & Yodo 2021). The process involves the horizontal movement of the nozzle to deposit each layer, followed by vertical movement along the Z-axis until the part is fully formed as depicted in Figure 1. Several parameters influence the mechanical properties of the printed part, including nozzle temperature, raster angle, raster width, and build orientation (Attoye, Malekipour & El-Mounayri 2019). These parameters affect the build quality and overall behavior of the printed component. The strength of the printed part relies on proper interlayer adhesion, which is influenced by factors such as the heating and remelting of already deposited layers. Higher temperatures enhance interlayer bonding by promoting polymer chain diffusion and bead fusion. Conversely, lower temperatures can hinder adhesion by reducing molecular mobility. Since viscosity plays a critical role in the flow and bonding properties of the material, temperature has a significant effect on bead formation (Mundada, Yang & Chen 2022).

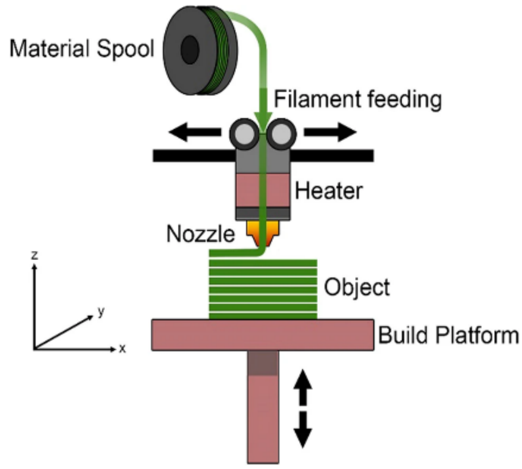

FIGURE 1. Working Mechanism of FFF (Rath et al. 2024)

Filament production for FFF requires feeding material pellets or granules into an extruder, where they undergo a staged heating process: softening in the feed zone, plasticizing in the transition zone, and fully melting in the metering zone. The molten material is then extruded through a die, cooled with a cold air gun, and solidified. The rate of cooling affects the quality of the filament, as faster cooling can lead to inconsistencies in the filament, which in turn impacts the print consistency and final part quality (Bhanuprakash & Kumar 2024). The process of extruding thermoplastic filaments is comparatively uncomplicated, as it does not necessitate any mixing; the materials are generally supplied in pellet form and can be directly introduced into the extruder. In contrast, composites necessitate supplementary procedures. The constituent materials are amalgamated in a heated mixer to achieve a uniform blend prior to being cooled and extracted. Subsequently, the mixture is subjected to the identical extrusion procedure as pure polymer pellets. (Parmar, Patel & Bhatia 2021).

To optimize the filament extrusion process, the Taguchi Method, a robust statistical experimental design approach, is widely used (Kam, Ipekçi & Şengül 2021). This method allows for the systematic evaluation of multiple factors with fewer experimental runs, making it both time-efficient and material-efficient. Taguchi's L9 orthogonal array is particularly effective in optimizing manufacturing processes, as it enables the identification of optimal levels for various extrusion parameters such as temperature, screw speed, and material composition (Mahajan 2018). The Taguchi Method minimizes the complexity of testing while maximizing experimental efficiency, which is crucial for the successful development of high-performance biocomposite filaments for 3D printing applications (Poddar & Sarangi 2024).

This research aims to investigate how these processing parameters affect the mechanical performance of PLA/WA/EPO biocomposites and provide insights into achieving optimal filament properties for Fused Deposition Modeling (FDM). The optimization of these parameters is crucial for enhancing the filament's density, tensile strength, and elongation at break, which are critical for their application in advanced manufacturing and 3D printing.

METHODOLOGY

MATERIALS

The medical-grade PLA pellets, which served as the base material for feedstock preparation, were supplied by Vistec Technology Sdn. Bhd. Wollastonite powder, with an average particle size of 8.7 µm, was sourced from CNPC Powder Material Co., Ltd. in China. The measured densities of the materials were 1.25 g/cm³ for PLA, 2.99 g/cm³ for Wollastonite (WA), and 0.94 g/cm³ for Epoxidized Palm Oil (EPO), which was purchased from Grunchem Tech Sdn. Bhd.

The formulation of the PLA/WA/EPO biocomposite was established at a ratio of 90:10 for PLA to Wollastonite, with the EPO concentration varying between 1% and 3% to assess its influence on both the mechanical characteristics and the processability of the filament. The incorporation of EPO is anticipated to augment the flexibility of the filament. Among the various EPO concentrations evaluated, 3% EPO emerged as the most effective loading, as it yielded the optimal blend of flexibility and uniformity in filament diameter when compared to the 1% and 2% EPO variants. Moreover, the interaction between EPO and the PLA/WA biocomposite facilitated enhancements in mechanical properties, as the filament produced with 3% EPO exhibited reduced brittleness and a diminished susceptibility to fracture compared to those with lower EPO concentrations.

The selection of 3 vol.% Epoxidized Palm Oil (EPO) was based on previous research by Chieng et al. (2014), which demonstrated that moderate EPO concentrations significantly enhance the flexibility and elongation at break of PLA-based biocomposites without compromising tensile strength or causing phase separation. This concentration was adopted to balance mechanical performance and processability in the filament extrusion process.

FEEDSTOCK PREPARATION

The raw materials are first placed in an oven at 80°C for at least 2 hours to remove excess moisture, as PLA is hydrophilic, and moisture content can negatively affect the mixing process. In addition, the wollastonite powder is sieved before mixing to ensure uniformity, as unsieved powder can lead to inconsistencies during the blending process (Oka et al. 2017). The prepared feedstock is then subjected to a blending process at a controlled temperature and torque to ensure a homogeneous mixture, which is critical for achieving optimal filament properties.

The materials are mixed using a VT Sigma Blade Mixer, set to 195°C to aid in the melting of PLA. To ensure consistency, small batches of PLA pellets are gradually added to the mixer, as adding a large quantity at once may cause clumping and uneven melting. Once the PLA is fully melted, wollastonite powder is slowly incorporated into the mixture. A spatula is used to evenly distribute the wollastonite powder in the sigma blade mixer, as adding too much at once could result in clumping or uneven dispersion.

Epoxidized Palm Oil (EPO), in liquid form, is the final material to be added. It is introduced slowly into the mixture since its liquid state allows for easier incorporation, but adding too much EPO at once could cause it to float above the PLA-WA mixture, leading to overflow from the mixer. The entire mixing process takes approximately 2-3 hours to ensure a thoroughly homogeneous blend. Once the mixture is fully blended, it is removed from the mixer and flattened into biscuit-like shapes before being processed in the crusher.

After mixing the material will need to be crushed to become feedstock which will be fed to the single screw extruder. The flattened material after mixing will be processed further to be suitable for extrusion. The crushing process turns the solid flat sheet into smaller uniform pellets which can be fed into the extruder. The crushed feedstock is then carefully introduced into the single screw extruder, where it undergoes controlled heating and melting to form the final filament.

FILAMENT EXTRUSION

A 3Devo Precision 450 Filament Maker was used for the extrusion of the filament. The extrusion process utilized two temperature zones, T1 and T2, with temperatures ranging from 170°C to 190°C. The screw speed was varied between 3 RPM and 5 RPM to optimize the extrusion process. Additionally, the internal fan speed was set to 20% to aid in the cooling and solidification of the extruded filament.

The temperature range of 170°C to 190°C was selected based on the thermal processing window of PLA, which typically melts between 160°C and 180°C (Pelin et al. 2023). This range ensures sufficient melting for homogenous mixing while avoiding thermal degradation of PLA and EPO. Similarly, the screw speed range of 3 to 5 RPM was chosen to balance shear mixing and residence time. Lower speeds promote better filler dispersion and reduce air entrapment, while higher speeds enhance throughput. These ranges were also informed by preliminary trials and existing literature on PLA-based composite extrusion (Ramli et al. 2024).

DESIGN OF EXPERIMENT

To optimize the extrusion process, a Design of Experiment (DOE) was conducted using the Taguchi method with an L9 orthogonal array. Three extrusion parameters—Temperature 1, Temperature 2, and Screw Speed—were selected as the control factors for optimization, as these parameters directly influence the quality and mechanical properties of the extruded filaments as shown in Table 1. The predetermined ranges for these factors were: Temperature 1 and Temperature 2, set between 170°C and 190°C, and Screw Speed, ranging from 3 RPM to 5 RPM. The density of the extruded filaments was measured as the primary response using a Sartorius BSA224S-CW weighing balance, employing the buoyancy method.

In addition, tensile strength, Young's Modulus, and elongation were measured as secondary responses. Tensile strength was determined using a Shimadzu Universal Testing Machine equipped with a 50 kN load cell. The testing speed was set at 0.5 mm/min, and a 9 cm sample length was used for the tensile test.

TABLE 1. Parameters for extrusion using Taguchi with L9 orthogonal array

Run	Temp. 1 (°C)	Temp. 2 (°C)	Screw Speed (rpm)
1	170	170	3
2	170	180	4
3	170	190	5
4	180	170	4
5	180	180	5
6	180	190	3
7	190	170	5
8	190	180	3
9	190	190	4

3D PRINTING

ASTM 638 Type V tensile bar specimens will be 3D printed to evaluate the printing properties of the filament produced with the optimized extrusion parameters. These specimens are selected for their standardized shape, which allows for a detailed analysis of the filament's mechanical properties, such as tensile strength, elongation, and overall printability. By testing these samples, the performance of the filament under real-world printing conditions can be accurately assessed, ensuring that the optimized extrusion parameters lead to consistent and high-quality printed parts.

RESULTS AND DISCUSSION

DENSITY OF PLA/WA/EPO FILAMENTS

Density is a crucial parameter for determining the quality and performance of 3D printed parts. Higher filament density generally leads to improved mechanical properties, such as tensile strength and elongation at break, and also reduces the occurrence of voids or defects in the printed part. In this study, filament density was measured as the primary response, and the results were influenced by variations in extrusion temperature and screw speed.

The average densities of the extruded filaments, measured based on the L9 experimental parameters, are as shown in Table 2. All extruded filaments had a diameter of 1.75 mm ± 0.10 mm. The density of the filaments varied according to the extrusion parameters, material distribution, and testing consistency. The manipulation of extrusion temperatures and speeds significantly influenced the density of filaments produced through 3D printing techniques. Elevated extrusion temperatures resulted in a diminished filament density, attributable to enhanced material flow and a concomitant decrease in viscosity (Butt, Bhaskar & Mohaghegh 2021). The highest recorded density was 1.321 g/cm³, achieved with extrusion parameters of T1 at 170°C, T2 at 170°C, and a screw speed of 3 RPM. The lowest density of 1.28 g/cm³ was recorded when T1 was 180°C, T2 was 170°C, and the screw speed was set to 4 RPM. The results highlight the critical influence of extrusion parameters on filament density, which is essential for achieving optimal mechanical properties in 3D printed components.

TABLE 2. Density of PLA/WA/EPO filament

Run	Density 1 (g/cm³)	Density 2 (g/cm³)	Density 3 (g/cm³)	Average Density (g/cm³)
1	1.330	1.330	1.303	1.321
2	1.305	1.304	1.300	1.303
3	1.293	1.296	1.287	1.292
4	1.295	1.307	1.303	1.290
5	1.309	1.300	1.297	1.302
6	1.307	1.289	1.304	1.300
7	1.296	1.306	1.302	1.301
8	1.305	1.303	1.307	1.305
9	1.298	1.299	1.294	1.297

Lower density filaments may contain a higher number of voids or show inadequate filler dispersion, such as with the wollastonite, which can negatively affect the overall density (Andersson et al. 2021). Additionally, testing inconsistencies, such as trapped air bubbles during the immersion process can lead to variations in the recorded density values. Furthermore, the implications of optimizing filament properties extend beyond mechanical performance, potentially influencing the sustainability of 3D printing practices. As the demand for eco-friendly materials rises, the incorporation of biocomposites like PLA/WA/EPO not only enhances the functional characteristics of printed objects but also aligns with the growing trend towards sustainable manufacturing. The use of renewable resources such as Epoxidized Palm Oil contributes to a reduction in reliance on fossil fuels, thereby lowering the environmental footprint of 3D printing processes. Moreover, the improved mechanical properties of these biocomposites can facilitate their application in a wider range of industries, from medical devices to construction, where both strength and biodegradability are crucial (Damayanti & Muttaqin 2024). This multidimensional approach to material optimization underscores the potential for biocomposite filaments to play a pivotal role in advancing sustainable manufacturing technologies.

Figure 2 shows the average density of PLA/WA/EPO filaments at different extrusion temperatures and screw speeds. The highest average density (1.32 g/cm³) was recorded at T1 = 170°C, T2 = 170°C, and screw speed = 3 RPM, while the lowest average density (1.28 g/cm³) occurred at T1 = 180°C, T2 = 170°C, and screw speed = 4 RPM. These variations highlight the critical role of extrusion conditions in achieving optimal filament density.

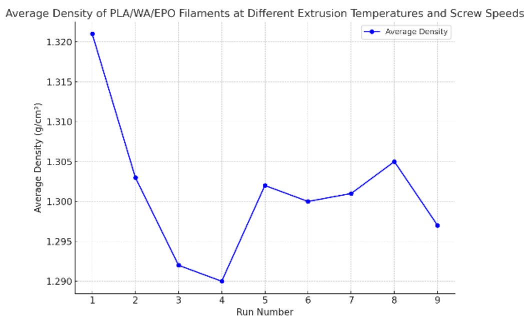

FIGURE 2. Average density of PLA/WA/EPO Filaments at different extrusion temperatures and Screw speeds

The observed density trends are closely related to the processing conditions and highlight the importance of optimizing both extrusion temperature and screw speed to ensure the production of high-quality filament. Higher density filaments are expected to demonstrate superior mechanical properties such as higher tensile strength and greater elongation at break. This is particularly relevant for applications in Fused Deposition Modeling (FDM) 3D printing, where material strength is crucial for producing functional and durable printed parts.

To determine the optimal extrusion parameters, the results obtained from the density tests were analyzed. The extrusion parameter with the greatest influence on density was the screw speed, followed by Temperature 1. Temperature 2 had the least effect on the filament density as showed in Table 3. The higher screw speeds tend to increase the shear forces within the extruder, which can enhance material mixing but may also lead to variations in density depending on the temperature settings (Lubis et al. 2024). Additionally, optimizing these parameters could lead to improved filament quality, indicating a clear relationship between processing conditions and the final product characteristics (Gupta & Taufik 2021).

It was observed that the highest density occurred at a screw speed of 3 RPM, with a noticeable decline in density at 4 RPM, indicating that the filament density is particularly sensitive to variations in screw speed. These findings emphasize the importance of optimizing extrusion parameters to enhance not only the mechanical properties but also the sustainability of 3D printing practices.

TABLE 3. Response for mean density values

Level	Temperature 1	Temperature 2	Screw Speed
1	1.305	1.304	1.309
2	1.297	1.303	1.297
3	1.301	1.296	1.298
Delta	0.008	0.008	0.012
Rank	2	3	1

Temperature 1 showed a non-linear, U-shaped effect on density, with the highest density recorded at 170°C, followed by a decrease at 180°C, and an increase again at 190°C. On the other hand, Temperature 2 exhibited a weaker and more linear impact, with density decreasing steadily as the temperature increased from 170°C to 190°C. Based on the Signal-to-Noise (S/N) ratio for the density of the PLA/WA/EPO filament, the optimum extrusion parameters were determined to be Temperature 1 at 170°C, Temperature 2 at 170°C, and a screw speed of 3 RPM. These parameters were found to produce the highest filament density, confirming their effectiveness in achieving the desired material properties.

TENSILE PROPERTIES

Tensile testing provided a comprehensive analysis of the mechanical properties of the filaments, particularly in terms of tensile strength, Young's Modulus, and elongation at break as shown in Figure 5. Test 1 exhibited the highest tensile strength of 24.35 MPa, followed closely by Test 2 at 23.87 MPa and Test 5 at 22.68 MPa as shown in Figure 3. The high tensile strength observed in these tests indicates that the chosen extrusion parameters, particularly the screw speed and temperature settings, effectively promoted strong interlayer bonding and filler dispersion. In contrast, Test 9 displayed the lowest tensile strength of 16.96 MPa, which may be attributed to inadequate filler-matrix adhesion at higher extrusion temperatures. This insufficient bonding likely led to the formation of stress concentrators within the filament, reducing its overall strength. This observation aligns with findings from previous studies, where poor adhesion between filler particles and the polymer matrix has been shown to negatively affect the tensile strength of composites, particularly at elevated processing temperatures (Ahmed et al. 2024).

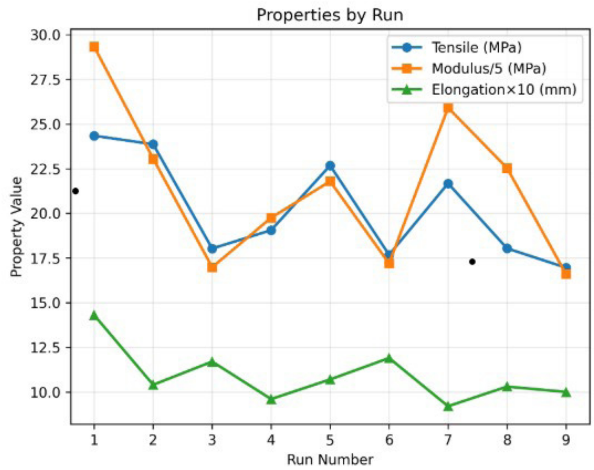

FIGURE 3. Mechanical properties of PLA/WA/EPO composite filament

YOUNG'S MODULUS OF PLA/WA/EPO FILAMENTS

Young's Modulus is an indicator of the stiffness of the material, reflecting its resistance to deformation under stress. The higher the modulus, the stiffer the material, which is important for applications requiring rigidity and structural integrity in the printed part.

Figure 3 shows the Young's Modulus values across the different experimental runs. The highest Young's Modulus (146.64 MPa) was recorded in Test 1, with extrusion parameters of T1 = 170°C, T2 = 170°C, and screw speed = 3 RPM, indicating a relatively stiff filament. This result supports the idea that lower screw speeds can lead to better filler dispersion, enhancing the composite's rigidity. In contrast, Test 9, with T1 = 190°C, T2 = 190°C, and screw speed = 4 RPM, showed the lowest Young's Modulus (82.99 MPa). This suggests that the higher processing temperature and screw speed likely reduced the filler-matrix bonding, leading to lower rigidity. These results are consistent with previous research indicating that the incorporation of reinforcing fillers, such as wollastonite, generally enhances the stiffness of PLA-based composites by providing additional structural support (Choudhary et al. 2022). However, the degree of reinforcement is highly dependent on the dispersion and bonding of the fillers within the polymer matrix.

The data indicate that increasing the screw speed tends to lower the modulus, likely due to increased shear forces that may cause excessive filler dispersion or weaken the bond between the PLA matrix and the reinforcing

Wollastonite (WA) particles. This effect highlights the trade-off between flexibility (elongation) and stiffness (Young's Modulus) depending on the extrusion conditions.

ELONGATION AT BREAK OF PLA/WA/EPO FILAMENTS

Elongation at break is a measure of the ductility of the material, indicating its ability to deform under stress before breaking. The elongation values are important for understanding the flexibility and toughness of the filament, which are crucial properties for 3D printed parts that must withstand stress and deformation.

As shown in Figure 3, the highest elongation at break (1.43 mm) was observed in Test 1, which had extrusion parameters of T1 = 170°C, T2 = 170°C, and screw speed = 3 RPM. This indicates that these conditions promoted better molecular mobility, allowing the filament to elongate more before failure. The addition of 3% Epoxidized Palm Oil (EPO) likely contributed to this increased flexibility, as EPO acts as a plasticizer, reducing the brittleness of PLA-based composites (Chieng et al. 2014). Conversely, Tests 4 and 7 showed the lowest elongation at break values (0.96 mm and 0.92 mm, respectively). These results suggest that lower EPO content, or variations in temperature or screw speed, reduced the flexibility of the filament, leading to more brittle behavior. This aligns with previous research indicating that higher EPO concentrations can improve elongation by reducing brittleness in PLA composites (Abd. Rashid et al. 2019).

These findings are consistent with the broader body of research on PLA-based composites, where the addition of plasticizers such as EPO is known to enhance the material's toughness and flexibility while maintaining adequate tensile strength (Jabbar & Mohammed 2024). However, it is important to note that the incorporation of plasticizers also introduces trade-offs, such as a reduction in stiffness, which must be carefully balanced depending on the desired application of the filament.

CONCLUSION

In conclusion, this study successfully optimized the extrusion parameters for PLA-based biocomposite filaments reinforced with Wollastonite (WA) and plasticized with Epoxidized Palm Oil (EPO), targeting enhanced performance in Fused Deposition Modeling (FDM) 3D printing. Using the Taguchi L9 orthogonal array, the optimal settings were identified as 170°C for both temperature zones and a screw speed of 3 RPM, with a material composition of 90 wt.% PLA, 10 wt.% WA, and 3 vol.% EPO. These parameters yielded the highest filament density (1.32 g/cm³), tensile strength (24.03 MPa), and elongation at break (1.43 mm), demonstrating significant improvements in mechanical performance and printability. The screw speed was found to be the most influential factor affecting filament quality, while SEM analysis confirmed uniform dispersion of WA particles within the PLA matrix. Furthermore, the use of renewable materials such as EPO contributes to the sustainability of the filament, aligning with eco-friendly manufacturing goals. Overall, the PLA/WA/EPO biocomposite filament shows promise for advanced 3D printing applications where mechanical reliability and environmental responsibility are critical.

ACKNOWLEDGEMENT

The authors would like to thank University of Wollongong Malaysia for their financial support under the grant UOWMKDURG/2023/006.

DECLARATION OF COMPETING INTEREST

None.

REFERENCES

Abd. Rashid, S. M. S., Anuar, H., Mohd Apandi, S. N. E., Buys, Y. F., & Hasan, N. A. 2019. Effects of plasticizer on mechanical properties of durian skin fiber reinforced polylactic acid biocomposite. *AIP Conference Proceeding* 2068: 020007

Ahmed, W., ElHassan, A., Siraj, S., Al Mazrouei, N., Zaneldin, E., & Al Marzouqi, A. H. 2024. Investigating recycled 3D printing filament waste-based composites reinforced by fillers. *Academia Materials Science* 1(2): 1-14.

Ali, F., Anuar, H., & Fakhruldin, H. 2016. Plasticizing poly(lactic acid) using epoxidized palm oil for environmental friendly packaging material. *Malaysian Journal of Analytical Science* 20(5): 1153-1158.

Almeida, V. H. M., Jesus, R. M., Santana, G. M., & Pereira, T. B. 2024. Polylactic Acid Polymer Matrix (Pla) Biocomposites with Plant Fibers for Manufacturing 3D Printing Filaments: A Review. *Journal of Composites Science* 8(2): 67.

Andersson, H., Örtegren, J., Zhang, R., Grauers, M., & Olin, H. 2021. Variable low-density polylactic acid and microsphere composite material for additive manufacturing. *Additive Manufacturing* 40: 101925.

Anuar, H., Abd Rahman, N. A., Manshor, M. R., Alli, Y. A., Alimi, O. A., & Suhr, J. 2023. Novel soda lignin/PLA/EPO biocomposite: A promising and sustainable material for 3D printing filament. *Materials Today Communications* 35:106093.

Attoye, S., Malekipour, E., & El-Mounayri, H. 2019. Correlation Between Process Parameters and Mechanical Properties in Parts Printed by the Fused Deposition Modeling Process. *Mechanics of Additive and Advanced Manufacturing* 8(1):8.

Awale, R. J., Ali, F., Azmi, A. S., Puad, N. I. M., Anuar, H., & Hassan, A. 2018. Enhanced Flexibility of Biodegradable Polylactic Acid/Starch Blends Using Epoxidized Palm Oil as Plasticizer. *Polymers* 10(9): 977.

Bhanuprakash, L., & Kumar, H. 2024. A Review of Thermoplastic Filament Extruder Design and Fabrication Technologies. *Journal of Physics: Conference Series* 2837: 012083.

Butt, J., Bhaskar, R., & Mohaghegh, V. 2021. Investigating the effects of extrusion temperatures and material extrusion rates on FFF-printed thermoplastics. *The International Journal of Advanced Manufacturing Technology* 117: 2679-2699.

Chieng, B. W., Ibrahim, N. A., Then, Y. Y., & Loo, Y. Y. 2014. Epoxidized vegetable oils plasticized poly(lactic acid) biocomposites: mechanical, thermal and morphology properties. *Molecules*. 19(10): 16024-16038.

Choudhary, R., Bulygina, I., Lvov, V., Zimina, A., Zhirnov, S., Kolesnikov, E., Leybo, D., Anisimova, N., Kiselevskiy, M., Kirsanova, M., & Senatov, F. 2022. Mechanical, structural, and biological characteristics of polylactide/wollastonite 3D printed scaffolds. *Polymers* 14(3932).

Damayanti, A. M., & Muttaqin, K. I. 2024. Optimization in extrusion process for polypropylene and high-density polyethylene pellets in additive manufacturing of 3D printing filament. *Engineering And Technology Journal* 9(11): 5544–5548.

Das, A., Chatham, C. A., Fallon, J. J., Zawaski, C. E., Gilmer, E. L., Williams, C. B., & Bortner, M. J. 2020. Current understanding and challenges in high temperature additive manufacturing of engineering thermoplastic polymers. *Additive Manufacturing* 34: 101218.

Dey, A., Eagle, I. N. R., & Yodo, N. 2021. A review on filament materials for fused filament fabrication. *Journal of Manufacturing and Materials Processing* 5(3):69.

Ghorbani, J., Koirala, P., Shen, Y.-L., & Tehrani, M. 2022. Eliminating voids and reducing mechanical anisotropy in fused filament fabrication parts by adjusting the filament extrusion rate. *Journal of Manufacturing Processes* 80: 651-658.

Gotlib, E. M., Tverdov, I., Phuong, H. T. N., & Sokolova, A. 2021. The impact of production temperature of synthetic wollastonite filled with rice husk on its composition and modifying effect. *IOP Conference Series: Materials Science and Engineering* 1030: 012004.

Gupta, A. K., & Taufik, M. 2021. Effect of process variables on performances measured in filament and pellet based extrusion process. *Materials Today: Proceedings* 47(15): 5177-5184.

Hartig, S., Hildebrandt, L., Fette, M., Meyer, T., Musienko, E., Redlich, T., & Wulfsberg, J. P. 2021. Process parameter determination for small recycling plants for the production of filament for FFF printing using the Taguchi method. *Progress in Additive Manufacturing* 7: 87-97.

Jabbar, F. H., & Mohammed, F. M. 2024. Epoxidized olive oil as a sustainable plasticizer to polylactic acid. *Iraqi Journal of Science* 65(2): 616-622.

Kaczor, D., Bajer, K., Domek, G., Madajski, P., Raszkowska-Kaczor, A., & Szroeder, P. 2022. Influence of extruder plasticizing systems on the selected properties of PLA/graphite composite. *Acta Mechanica et Automatica*. 16(4): 316-324.

Kam, M., Ipekçi, A., & Şengül, Ö. 2021. Taguchi optimization of fused deposition modeling process parameters on mechanical characteristics of PLA+ filament material. *Scientia Iranica*. 29(1): 79-89.

Kast, O., & Bonten, C. 2016. Influence of a grooved melting zone on high-speed single screw extrusion. *AIP Conference Proceeding*. 1779: 030004.

Krishnanand & Taufik, M. 2021. Fused Filament Fabrication (FFF) Based 3D printer and its design: A review. *Advanced Manufacturing Systems and Innovative Product Design*. 497-505.

Lubis, A. M. H. S., Kudus, S. I. A., Amran, A., Mustafa, N., Taha, M. M., & Shaharuzaman, M. A. 2024. Flow analysis and shear rate comparison of counter-rotating and co-rotating intermeshing twin-screw extruders for filament extrusion of polypropylene-based biocomposites. *Pertanika Journal of Science and Technology* 32(S2): 1-20.

Mahajan, Y. 2018. A review of taguchi optimization techniques in additive manufacturing techniques. *International Journal for Research in Applied Science and Engineering Technology* 6(3): 2517-2520.

Mundada, P. S., Yang, C., & Chen, R. K. 2022. Investigation of the effects of a pre-deposition heating system on the interfacial temperature and interlayer bonding strength for fused filament fabrication. *Rapid Prototyping Journal* 29(1): 9-18.

Nhassa, G., Ben Khalifa, R., & Snoussi, A. 2024. Impact of 3D printing settings on polylactic acid filament mechanical behaviors based on the taguchi method. *Recent Patents on Mechanical Engineering* 18(5):649-659.

Oka, S., Sahay, A., Meng, W., & Muzzio, F. J. 2017. Diminished segregation in continuous powder mixing. *Powder Technology* 309: 79-88.

Omigbodun, F. T., Oladapo, B. I., & Osa-uwagboe, N. 2024. Exploring the frontier of Polylactic Acid/ Hydroxyapatite composites in bone regeneration and their revolutionary biomedical applications – A review. *Journal of Reinforced Plastics and Composites*.

Oviedo, A. M., Puente, A. H., Bernal, C. R., Bernal, C. R., Pérez, E., & Pérez, E. 2020. Mechanical evaluation of polymeric filaments and their corresponding 3D printed samples. *Polymer Testing* 88: 106561.

Parmar, K., Patel, J. K., & Bhatia, D. 2021. Production of nanocomposites via extrusion techniques. *Emerging Technologies for Nanoparticle Manufacturing.* 99-108.

Pelin, G., Pelin, C.-E., Botan, M., Stefan, A., Cristea, G. C., & Panait, A. A. M. 2023. Thermo-mechanical properties of fused filament fabricated PLA at elevated temperatures. *INCAS Bulletin* 15(1): 59-70.

Poddar, M. K., & Sarangi, S. K. 2024. An experimental analysis of Poly-Lactic Acid (PLA) filament manufacturing for the 3D printer using taguchi and Analysis of Variance (ANOVA). *SSRG International Journal of Mechanical Engineering* 11(3): 1-10.

Ramli, M. I., Choudhury, A. M., Choong, D. L. J., Jun, T. J., Royan, N. R. R., & Faris, M. A. 2024. PLA/ wollastonite composite filaments for 3D printing application: Rheological properties and extrusion. *Jurnal Kejuruteraan* 36(5): 2097-2106.

Saravana, S., & Kandaswamy, R. 2019. Investigation on the mechanical and thermal properties of PLA/ calcium silicate biocomposites for injection molding applications. *Silicon* 11: 1143-1150.

Sardar, M. S., Gide, K. M., Stuart, A., Rostobaya, V., Zarrabinia, K., Beheshti, A., & Bagheri, Z. S. 2024. Evaluating mixing methods for FFF-printed PLA-HA composites: Towards high-performance composites and advancements in additive manufacturing. *The International Journal of Advanced Manufacturing Technology*. 136: 1267-1280.

Shaqour, B., Shaqour, B., Abuabiah, M., Abdel-Fattah, S., Juaidi, A., Abdallah, R., Abuzaina, W., Qarout, M., Verleije, B., & Cos, P. 2021. Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: A review. *The International Journal of Advanced Manufacturing Technology*. 114: 1279-1291.

Sultana, J., Rahman, Md. M., Wang, Y., Ahmed, A., & Chen, X. 2023. Influences of 3D printing parameters on the mechanical properties of wood PLA filament: An experimental analysis by Taguchi method. *Progress in Additive Manufacturing* 9: 1239-1251.

Tazibt, N., Kaci, M., Dehouche, N., Ragoubi, M., & Atanase, L. I. 2023. Effect of filler content on the morphology and physical properties of poly(lactic acid)-hydroxyapatite composites. *Materials*. 16(2): 809.

Valvez, S., Santos, P., Parente, J. M., Silva, M. P., & Reis, P. N. B. 2020. 3D printed continuous carbon fiber reinforced PLA composites: A short review. *Procedia Structural Integrity*. 25: 394-399.