PERFORMANCE ANALYSIS OF PLA BASED HYBRID FILAMENT COMPOSITES REINFORCED WITH SPF/WTR FOR 3D PRINTING

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

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A thesis submitted
in fulfillment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "Performance Analysis of PLA Based Hybrid Filament Composites Reinforced with SPF/WTR for 3D Printing." is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : Nur Batrisyia Binti Norhazlin

Date : 27 July 2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Mechanical Engineering

Signature	:...
Supervisor Name	:Ts. Dr. Mohd Adrinata bin Shaharuzaman
Date	: 8 August 2025

DEDICATION

In the name of Allah, all praises are due to the Prophet Muhammad (S.A.W.). Alhamdulillah, Haza Min Fadhli Rabbi, I completed my research project and thesis writing.

I would like to express my deepest appreciation to my family for their unwavering support, encouragement, and sacrifices throughout this journey. Their guidance and belief in me have been invaluable. May Allah reward them with goodness and prosperity for their kindness.

ABSTRACT

Fused Deposition Modeling (FDM) is a widely used 3D printing method due to its cost-efficiency and material flexibility. Presently, synthetic and carbon fibers are the predominant reinforcements. However, concerns regarding their environmental impact have prompted a shift towards more sustainable options. To address these issues, this research has proposed utilizing natural and recycled materials as a composites filler. Polylactic acid (PLA), a biopolymer derived from renewable sources like corn starch and sugarcane, accounts for over 60% of bio-based plastics globally. While PLA is biodegradable and offers environmental benefits, it has limited thermal and mechanical strength, restricting its broader use in functional applications. This study aims to enhance the performance of PLA by incorporating sugar palm fiber (SPF) that has high stiffness and renewability and waste tyre rubber (WTR) that offers superior impact resistance, flexibility, and energy absorption, which compensates for the brittleness of PLA and rigidity of SPF as reinforcements to develop hybrid composite filaments suitable for 3D printing. The primary objectives of this research include investigating the effects of filler loading on the mechanical and thermal properties of the composites. Three filler ratios (75% SPF: 25% WTR, 50% SPF: 50% WTR, and 25% SPF: 75% WTR) were evaluated. The second objective of this research was to examine the effect of infill density on the mechanical properties, morphology and surface quality which is three infill density (50%, 70% and 100%) were evaluated. The composites were analyzed for mechanical testing including tensile, flexural and impact, thermal analysis in Thermogravimetric analysis (TGA) and Differential scanning calorimetry (DSC), morphological analysis, and surface quality properties. For the first objective, the 75% SPF: 25% WTR composition showed the highest tensile 37.89 MPa and flexural strength 54.40 MPa, while the 25% SPF: 75% WTR combination recorded the greatest impact strength 4.30 kJj/m^2. Thermal analysis on the TGA show that 75% SPF: 25% WTR has a great thermal stability while on the DSC show that 25%SPF:75%WTR has better heat resistance and dimentianal stability. For the second objective results on the mechanical testing, in terms of tensile strength, the 75% SPF: 25% WTR composite with a 50% infill density demonstrated superior strength compared to other configurations. For flexural strength, the 75% SPF: 25% WTR composite with a 100% infill density exhibited the highest performance, while the 25% SPF: 75% WTR composite with 100% infill density achieved the best impact resistance. Morphological analysis indicated that composites with higher SPF content and increased infill density exhibited more uniform internal structures. Increased infill density, particularly at 100% at 75% SPF: 25% WTR, contributed to smoother surface finish and enhanced load distribution, which correlated with improved tensile strength. These results indicate that SPF/WTR reinforced PLA composites could promote sustainable alternatives for material development in additive manufacturing.

ANALISIS PRESTASI KOMPOSIT FILAMEN HIBRID BERASASKAN PLA BERTETULANG SPF/WTR UNTUK PERCETAKAN 3D

ABSTRAK

Permodelan Pemendapan Bersatu (FDM) merupakan kaedah percetakan 3D yang meluas digunakan kerana kosnya yang efisien dan fleksibiliti bahan. Pada masa ini, gentian sintetik dan gentian karbon merupakan bahan penguat yang dominan. Namun begitu, kebimbangan terhadap kesan alam sekitar telah mendorong kepada peralihan ke arah pilihan yang lebih mampan. Bagi menangani isu ini, kajian ini mencadangkan penggunaan bahan semula jadi dan bahan kitar semula sebagai pengisi dalam komposit. poly (asid laktik) (PLA), iaitu biopolimer yang berasal daripada sumber boleh diperbaharui seperti kanji jagung dan tebu, menyumbang lebih daripada 60% plastik berasaskan bio di seluruh dunia. Walaupun PLA boleh terbiodegradasi dan mesra alam, ia mempunyai kekuatan terma dan mekanikal yang terhad, sekali gus mengehadkan penggunaannya dalam aplikasi berfungsi. Kajian ini bertujuan untuk meningkatkan prestasi PLA dengan menggabungkan serat pokok enau (SPF) dan getah tayar terbuang (WTR) sebagai bahan penguat bagi menghasilkan filamen komposit hibrid yang sesuai untuk percetakan 3D. Objektif utama kajian ini adalah untuk menyiasat kesan peratusan gentian terhadap sifat mekanikal dan terma komposit. Tiga nisbah gentian yang berbeza telah dikaji, 75% SPF:25% WTR, 50% SPF:50% WTR, dan 25% SPF:75% WTR. Objektif kedua pula adalah untuk mengkaji kesan ketumpatan infill terhadap sifat mekanikal dengan menilai tiga tahap infill iaitu 50%, 70%, dan 100%. Komposit yang dihasilkan dianalisis melalui ujian mekanikal termasuk ujian tegangan, lenturan dan impak, serta analisis terma menggunakan analisis termogravometrik (TGA) dan kalori pengimbasan pembezaan (DSC), di samping analisis morfologi dan kualiti permukaan. Bagi objektif pertama, komposisi 75% SPF:25% WTR menunjukkan kekuatan tegangan 37.89 MPa dan lenturan tertinggi 54.40 MPa, manakala kombinasi 25% SPF:75% WTR mencatatkan kekuatan impak tertinggi 4.30 kJ/m^2. Analisis TGA menunjukkan bahawa komposisi 75% SPF:25% WTR mempunyai kestabilan terma yang baik, manakala DSC menunjukkan bahawa 25% SPF:75% WTR mempunyai rintangan haba dan kestabilan dimensi yang lebih baik. Bagi objektif kedua, hasil ujian mekanikal menunjukkan bahawa untuk kekuatan tegangan, komposit 75% SPF:25% WTR dengan infill 50% memperlihatkan kekuatan yang lebih tinggi berbanding konfigurasi lain. Untuk kekuatan lenturan, komposit 75% SPF:25% WTR dengan infill 100% memberikan prestasi tertinggi, manakala 25% SPF:75% WTR dengan infill 100% menunjukkan rintangan impak terbaik. Analisis morfologi menunjukkan bahawa komposit dengan kandungan SPF yang tinggi dan infill yang lebih padat mempunyai struktur dalaman yang lebih seragam. Ketumpatan infill yang lebih tinggi, terutamanya pada 100% pada 75% SPF:25% WTR, menyumbang kepada permukaan yang lebih licin dan agihan beban yang lebih sekata, yang berkait rapat dengan peningkatan kekuatan tegangan. Hasil kajian ini menunjukkan bahawa komposit PLA bertetulang SPF/WTR berpotensi sebagai alternatif mampan dalam pembangunan bahan untuk teknologi pembuatan tambahan (additive manufacturing).

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	-	3 Dimension
ABS	-	Acrylonitrile Butadienes
AM	-	Additive Manufacturing
ASTM	-	American Society For Testing And Materials
CAD	-	Computer-Aided Design
CF	-	Carbon Fiber
DMA	-	Differential Mechanical Thermal Analysis
DSC	-	Diferential Scanning Calorimetry
DTG	-	Difference Thermogravimetry
FDM	-	Fused Deposition Modeling
FFF	-	Fused Filament Fabrication
FTIR	-	Fourier Transform Infrared Spectroscopy
HFRPC	-	Hybrid Fiber Reinforced Polymer Composites
LOM	-	Laminated Object Manufacturing
NaOH	-	Sodium Hydroxide
NFRPC	-	Natural Fiber Reinfoced Polymer Composites
NR	-	Natural Rubber
OBJ	-	Objective
OPBA	-	Oil Palm Boiler Ash
PBS	-	Poly(Butylene Succinate)
PDLA	-	Poly-D-Lactide
PDLLA	-	Poly-DL-Lactide
PHB	-	Poly(3-Hydroxybutyrate
PLA	-	Poly-Lactic Acid

PLLA	-	Poly-L-Lactide
PTA	-	Purified Terephthalic Acid
RA	-	Average Roughness Value
RF	-	Reinforced Fiber
RZ	-	Average Maximun Height
SBR	-	Styrene-Butadiene Rubber
SDL	-	Selective Deposition Lamination
SEM	-	Scanning Electron Microscope
SLA	-	Stereolithography Apparatus
SLS	-	Selective Laser Sintering
SPF	-	Sugar Palm Fiber
STL	-	Stereolithography
Tc	-	Crystalization Temperatre
TGA	-	Thermogravimetric Analysisis
Tg	-	Glass Transition Temperature
Tm	-	Melting Temperature
TPU	-	Thermoplastic Polyurethane
UV	-	Ultraviolet
WTR	-	Waste Tyre Rubber

LIST OF SYMBOLS

%	-	Percent
°C	-	Degree Celsius
wt%	-	Weight Percent
$\mathcal{E}$	-	Strain
σ	-	Strength
A	-	Area
b	-	Width
d	-	Depth
E	-	Elongation
F	-	Force
g	-	gram
g	-	Acceleration Gravity
GPa	-	Gigapascal
H	-	Height
J	-	Joules
kN	-	kiloNewton
kg	-	kilogram
kJ/m^2	-	kilojoules Per Square Meter
Kv	-	V-Notch Impact Energy
L	-	Length
m	-	Mass
m^2	-	Meter Square
mm	-	Millimetre
μm	-	Micrometer

mm/s	-	Milimetre Per Second
min	-	Minutes
mg	-	miligram
MPa	-	Megapascal
P	-	Force
Pa	-	Pascal
RPM	-	Rotation Per Minute

LIST OF APPENDICES

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

Norhazlin, B., Shaharuzaman, M.A. and Razali, N., 2025. Characterization Of Pla-Based Hybrid Composites: Mechanical And Morphological Properties. *Malaysian Journal of Microscopy*, 21(1), pp.274-285.

Norhazlin, N.B., Razali, N., Shaharuzaman, M.A., Mustafa, Z., Fadzullah, S.H.S. and Rashid, B., 2025. The Effect of Fibre Loadings on the Mechanical and Thermal Properties of Sugar Palm/Waste Tyre Rubber Reinforced Polylactic Acid hybrid Composites via Fused Deposition Modelling. *Journal of Advanced Research Design*, 133(1), pp.44-59.

Norhazlin, B., Shaharuzaman, M. A., Razali, N., & Koinkar, P. (2025). Mechanical, Thermal and Surface Roughness Properties of PLA-Based Hybrid Composite Filament for Fused Deposition Modelling. *Journal of Advance Research Fluid Mechanic & Thermal Science*, 133(2), pp. 106–125.

Norhazlin, N. B., Razali, N., Shaharuzaman, M. A., & Koinkar, P. (2025) A review: Poly(lactic acid) Hybrid Filament For Fused Deposition Modeling. *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 134*(2), pp. 171-195.

CHAPTER 1

INTRODUCTION

1.1 Background

The increasing awareness of the environmental impact of petroleum based materials has sparked significant concern in recent years. The extraction, processing, and combustion of fossil fuels contribute to greenhouse gas emissions, air pollution, and ecological degradation. Oil refineries are major sources of harmful emissions, including carbon dioxide and volatile organic compounds, which exacerbate climate change and pose health risks to surrounding communities. As a result, there is a pressing need to explore sustainable alternatives that reduce reliance on these materials and mitigate their harmful effects on the environment (Liu et al., 2019).

Composites are materials made from two or more constituent components that exhibit different physical or chemical properties (Bahl, 2020). They typically consist of a matrix and reinforcement (Knight et al., 2022). The matrix is the continuous phase that binds the composite together, providing shape and support, while the reinforcement is embedded within the matrix to enhance its mechanical properties. This combination allows composites to achieve superior strength, stiffness, and durability compared to their individual components.

Polylactic Acid (PLA) is a biodegradable thermoplastic polymer derived from renewable resources such as corn starch or sugarcane. One of the renewable and biodegradable base polymers in the polyester group is PLA (Mazzanti et al., 2020). As a matrix material, PLA offers several advantages that make it particularly appealing for composite applications, but due to their disadvantages which are lower in thermal stability and strength, some applications might not be applicable (Manral and Bajpai, 2020). Its biodegradability ensures that PLA decomposes naturally at the end of its life cycle, reducing environmental impact compared to conventional petroleum based polymers. Being a thermoplastic, PLA can be easily processed using various techniques such as extrusion and injection molding, facilitating efficient production of composite materials. Moreover, PLA exhibits good mechanical performance, making it suitable for various applications when reinforced with natural fibers or other materials (Ilyas et al., 2022).

Natural fibers serve as an effective reinforcement in composite materials due to their favorable properties. Compared to synthetic fibers like glass fiber, natural fibers offer several advantages that enhance their appeal in sustainable material development. Other than that, the characteristics between natural fibers and synthetic fibers are quite similar, such as low density, high stiffness, and good mechanical properties (Bambach, 2020). They are renewable and biodegradable, contributing to lower environmental impact throughout their lifecycle. Additionally, the production of natural fibers generally requires less energy than synthetic fibers, resulting in reduced greenhouse gas emissions. Natural fibers are often more economical than glass fibers while providing competitive mechanical properties and being lightweight but tends to absorb moisture and exhibit poor interfacial bonding with hydrophobic PLA. Incorporating waste tyre rubber into hybrid composites with natural fibers presents an innovative solution for enhancing material performance while addressing waste management issues. According to Suriani et al. (2021), hybridisation in composite area is a method of the combination of different resources and processes with different properties for the improvement of existing material. Waste tyre rubber adds flexibility and impact resistance to composites, improving their overall toughness (Islam et al., 2022). The recycling process of waste tyres can solve two problems which are efficiently reducing the number of tyres that are disposed of and making resources accessible (Zedler et al., 2022). The combination of natural fibers and rubber not only enhances mechanical properties but also promotes sustainability by recycling waste materials that would otherwise contribute to environmental pollution.

The use of polymer hybrid composites in environmentally friendly Fused Deposition Modelling (FDM) technology has gained traction among industries and researchers alike. FDM allows for the efficient production of complex geometries using thermoplastic materials. Acrylonitrile butadiene styrene (ABS) and (PLA) are popular because they are stable. The most frequent thermoplastic that had been produced in this technology is PLA (Jamadi et al., 2023). The implementation of hybrid composites in FDM filaments as a replacement for traditional fillers has attracted considerable interest from competitors and market platforms. This shift towards sustainable practices not only aligns with environmental goals but also opens new avenues for innovation in composite manufacturing.

1.2 Problem Statement

PLA is widely used in FDM due to its biodegradability and ease of processing. However, its inherent limitations such as low thermal stability, brittleness, and reduced impact strength restrict its application in load bearing or functional components (Mazzanti et al., 2020; Manral and Bajpai, 2020). To overcome these deficiencies, natural fibers and recycled materials have been explored as reinforcements. Sugar palm fiber (SPF), with good tensile strength and renewability, suffers from hydrophilicity, which can cause poor interfacial bonding with hydrophobic polymer matrices and lead to moisture absorption and mechanical degradation (Atiqah et al., 2019). Waste tyre rubber (WTR), while beneficial in improving flexibility and impact resistance, presents challenges due to its poor dispersion, and weak interfacial adhesion in the polymer matrix (Islam et al., 2022). To reduce these limitations, surface treatment of SPF and WTR is often required to improve compatibility with the PLA matrix. In this study, treatment is applied as a preparation step to enhance filler matrix bonding, though the main objective is to investigate how different filler loadings and printing parameters affect composite performance. If the compatibility issues and mechanical limitations are not addressed, the resulting PLA composites may exhibit low strength, poor thermal resistance. Inadequate dispersion or interfacial bonding may cause stress concentrations, reducing durability of the printed parts.

Although hybridization in material has been proposed in recent studies, most focus on individual fillers or do not fully explore the synergy between SPF and WTR in a PLA matrix. Furthermore, there is limited research evaluating how different fiber loadings and FDM specific parameters such as infill density influence the composite's mechanical, thermal, and surface performance. This study aims to fill this gap by systematically evaluating the effect of green material SPF/WTR ratio and infill density on the performance of PLA hybrid composite filaments. By optimizing filler composition and printing parameters, this research supports the development of more durable, sustainable, and application ready hybrid composite materials for 3D printing.