JOURNAL OF ENGINEERING AND SCIENCE
E-ISSN: 2828-805X, P-ISSN: 2828-8106
Volume 4 Number 1, June 2025, pp 48-55.
DOI: https://doi.org/10.56347/jes.v4i1.267.

KAWANAD Institute

Fatigue Performance of Sugar Palm Fibre-Reinforced Thermoplastic Polyurethane Composites with Varying Fibre Content

Dandi Bachtiar [a*], Januar Parlaungan Siregar [b], Suhaeri [c], Masri [d], Zulfadhli [e]
[a*,c,d,e] Department of Mechanical and Industrial Engineering, Universitas Syiah Kuala, Banda Aceh City, Aceh Province, Indonesia.
[b] Faculty of Mechanical and Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, Pekan 26600, Pahang Darul Makmur, Malaysia.

ABSTRACT
This study investigates the fatigue behavior of sugar palm fibre (SPF)-reinforced thermoplastic polyurethane (TPU) composites with varying fibre contents (10 wt%, 20 wt%, and 30 wt%). The composites were fabricated using extrusion followed by hot press moulding. Tensile tests were conducted in accordance with ASTM D638 to determine the ultimate tensile strength (UTS), and fatigue tests were performed under stress levels of 80%, 70%, 60%, and 50% of the UTS, following ASTM D7791. The results indicate that an increase in fibre content leads to a reduction in both tensile strength and fatigue life, likely due to poor interfacial bonding and fibre agglomeration. Fatigue life was found to be significantly higher at lower stress levels across all fibre contents. These findings provide valuable information about the potential and limitations of SPF/TPU composites for applications involving cyclic loading, particularly in lightweight and sustainable material applications.

ARTICLE HISTORY
Received 3 February 2025
Accepted 20 June 2025
Published 30 June 2025

KEYWORDS
Sugar Palm Fibre; Thermoplastic Polyurethane; Fatigue Behavior; Natural Fibre Composites; Tensile Strength.

1. Introduction

The increasing demand for sustainable and eco-friendly materials has led to growing interest in natural fibre-reinforced polymer composites. These materials offer several advantages over synthetic fibre composites, including biodegradability, low density, cost-effectiveness, and reduced environmental impact (Mohanty *et al*., 2002; Faruk *et al*., 2012). Among the various natural fibres, sugar palm fibre (SPF), derived from the Arenga pinnata tree, is gaining attention due to its good durability, availability in tropical regions, and resistance to seawater (Mukhtar *et al*., 2019; Imraan *et al*., 2023). Despite these advantages, the widespread industrial adoption of natural fibre composites remains limited. This is primarily due to their inherent drawbacks, such as high moisture absorption, poor interfacial adhesion with polymer matrices, and limited thermal stability (Uyanik & Erturk, 2023; Musa & Onwualu, 2024). Consequently, further research is needed to better understand their mechanical performance under various loading conditions, particularly in real-world applications.

One critical aspect that remains underexplored is the fatigue behavior of natural fibre composites. Fatigue failure is a common mode of degradation in structural components subjected to repeated loading, especially in automotive, marine, and consumer product applications (Fotouh *et al*., 2014; Bhowmik *et al*., 2023). While several studies have investigated the tensile and flexural properties of SPF composites (Bachtiar *et al*., 2008; Bachtiar *et al*., 2010), limited data are available on their endurance performance under cyclic loading (Bachtiar *et al*., 2024).

CONTACT Dandi Bachtiar dandibachtiar@usk.ac.id Department of Mechanical and Industrial Engineering, Universitas Syiah Kuala, Banda Aceh City, Aceh Province, Indonesia.

This study aims to investigate the tensile and fatigue properties of sugar palm fibre-reinforced thermoplastic polyurethane (TPU) composites at varying fibre contents (10 wt%, 20 wt%, and 30 wt%). TPU was selected as the matrix due to its flexibility, toughness, and recyclability (Khalifa *et al*., 2020). Tensile strength was measured to determine the baseline mechanical performance, while fatigue tests were conducted at different stress levels relative to the ultimate tensile strength. The outcome of this study is expected to contribute to a better understanding of the mechanical durability of SPF/TPU composites and their suitability for cyclic loading applications.

2. Materials and Methods

2.1 Materials

Sugar palm fibres (SPF), obtained from the mature trunks of Arenga pinnata, were selected as the reinforcement due to their availability, biodegradability, and promising mechanical properties. The fibres were manually extracted, washed thoroughly to remove impurities, and sun-dried for 48 hours to reduce moisture content. After drying, the fibres were cut into lengths of approximately 5–6 cm and mechanically crushed using a rotary crusher to produce particles in the size range of 0.5–1.0 mm. This size range was chosen to ensure adequate dispersion and fibre-matrix interaction during composite fabrication. Thermoplastic polyurethane (TPU) pellets, acquired from a commercial supplier, were used as the polymer matrix. TPU was selected due to its high elasticity, abrasion resistance, and good compatibility with natural fibres, making it suitable for applications involving cyclic loading.

2.2 Composite Fabrication

The composite fabrication process involved two main stages: melt compounding and compression moulding. The SPF and TPU pellets were dry-mixed in weight fractions of 10 wt%, 20 wt%, and 30 wt% fibre content to examine the effect of fibre loading on fatigue and tensile performance. The mixtures were processed using a Eurolab 16 co-rotating twin-screw extruder. The extrusion parameters were set to a temperature profile of 150 °C to 170 °C across the barrel zones, with a screw speed maintained at 100–150 rpm to ensure uniform melting and fibre dispersion. The extrudates were air-cooled and pelletized for further processing. Pelletized composite blends were then moulded into sheets using a hydraulic hot press. The mould size was 200 mm × 200 mm × 3 mm. The hot pressing was carried out at 160 °C under a pressure of 20 tonnes for 10 minutes, followed by a cold press stage to reduce residual thermal stresses and ensure dimensional stability. The cold pressing continued until the sheet temperature dropped below 70 °C .

2.3 Specimen Preparation

Test specimens were machined from the composite sheets using a fine-toothed jigsaw. To ensure accuracy and consistency in geometry, manual finishing using fine sandpaper was performed along the specimen edges. Tensile specimens were prepared according to ASTM D638-12 (Type I), while fatigue specimens adhered to ASTM D7791-12, which provides guidance for cyclic testing of plastics in tension-tension mode. Each batch included at least five specimens per testing condition to ensure statistical validity.

2.4 Tensile Testing

Tensile tests were conducted using a universal testing machine (Instron Model 5567) equipped with a 10 kN load cell. The crosshead speed was fixed at 5 mm/min, as recommended by ASTM D638-12. The primary output of the test was the ultimate tensile strength (UTS), which served as the reference value for determining the stress amplitudes in subsequent fatigue tests. Data acquisition software was used to record the stress-strain curves for further analysis.

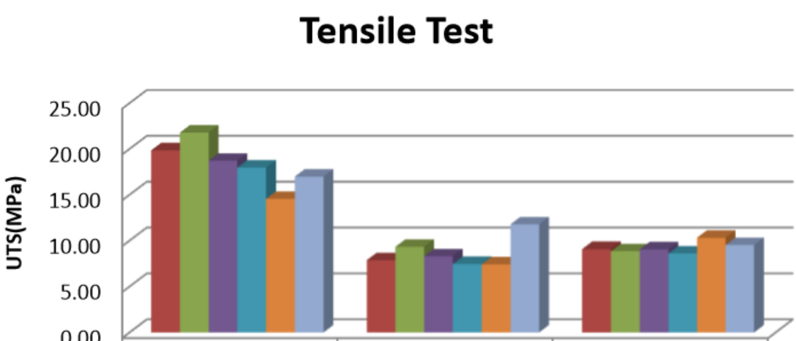
2.5 Fatigue Testing

Fatigue testing was performed on a servo-hydraulic testing machine (MTS Landmark 370) in tension–tension loading mode with a stress ratio R = 0.1. The cyclic load was sinusoidal, applied at a frequency of 5 Hz to minimize heat build-up and potential viscoelastic effects. For each fibre content, the specimens were tested at four different stress levels—80%, 70%, 60%, and 50% of their respective UTS values. Each test was terminated either upon specimen fracture or when the specimen reached a run-out limit of 1 million cycles without failure. The number of cycles to failure was recorded and used to construct S–N (stress–number of cycles) curves. All tests were performed under ambient laboratory conditions (23 ± 2 °C, 50 ± 5% RH).

3. Results

3.1 Tensile Properties

The tensile strength of sugar palm fibre (SPF)/thermoplastic polyurethane (TPU) composites showed a decreasing trend with increasing fibre content, as depicted in Figure 1. The composite with 10 wt% SPF exhibited the highest ultimate tensile strength (UTS), while the 30 wt% fibre composite recorded the lowest UTS. Specifically, the 10 wt% sample demonstrated a UTS of approximately 18.3 MPa, which decreased to 8.7 MPa and 9.2 MPa for the 20 wt% and 30 wt% composites, respectively. These values represent the average results obtained from six test specimens for each composition. This inverse correlation between fibre content and tensile strength can be attributed to several interrelated factors. At lower fibre contents, the fibres are more uniformly dispersed within the matrix, enabling better stress transfer across the fibre–matrix interface. As the fibre content increases, however, the likelihood of fibre agglomeration, void formation, and poor wetting of the fibres by the matrix increases, thereby compromising the mechanical integrity of the composite. Similar observations have been reported by researchers who noted a decline in tensile strength with increased fibre loading in oil palm fibre-reinforced polyester composites due to reduced interfacial adhesion and non-uniform stress distribution (Zuhri *et al.*, 2009).



	10%	20%	30%
sample1	19.84	7.86	9.08
sample2	21.77	9.32	8.84
sample3	18.70	8.29	9.04
sample4	17.95	7.45	8.59
sample5	14.54	7.41	10.31
sample6	16.98	11.76	9.51

Figure 1. Ultimate Tensile Strength of Composites With Varying Fibre Contents

The reduction in tensile properties at higher fibre contents is also consistent with the findings of researchers who studied the effects of fibre loading on various natural fibre composites (Huzaifah *et al*., 2019). They reported that an optimal fibre loading exists beyond which the mechanical performance deteriorates due to insufficient matrix volume to effectively encapsulate the fibres. Regarding the modulus of elasticity, the composites followed a similar declining trend with increasing fibre content. Although natural fibres inherently possess higher stiffness compared to thermoplastic matrices, the expected enhancement in modulus was not realized at higher fibre loadings. This discrepancy can be explained by the non-uniform fibre alignment and the presence of microvoids, both of which reduce the load-bearing capacity of the composite. Moreover, excessive fibre content can lead to stress concentration zones, which initiate early matrix cracking under tensile load. In contrast, some studies have demonstrated improved tensile modulus with increasing fibre content, particularly when chemical treatments or compatibilizers are used to enhance fibre–matrix interaction. For instance, researchers showed that alkaline-treated sugar palm fibres in a polyester matrix resulted in significant increases in tensile modulus due to improved interfacial adhesion (Norizan *et al*., 2018). However, such treatments were not applied in this study, which may explain the overall reduction in both tensile strength and stiffness with increased SPF content. In summary, the mechanical performance of SPF/TPU composites under tensile loading is significantly influenced by the fibre loading level. While moderate fibre incorporation (around 10 wt%) enhances load transfer and maintains composite integrity, higher fibre contents introduce structural imperfections that degrade the tensile performance. This suggests that optimization of fibre content is critical in balancing mechanical properties for potential structural applications.

3.2 Fatigue Life Analysis

Fatigue tests were performed at four different stress levels—80%, 70%, 60%, and 50% of the ultimate tensile strength (UTS)—to assess the endurance performance of sugar palm fibre (SPF)-reinforced TPU composites under cyclic loading. The S–N curves (stress vs. number of cycles to failure) revealed a consistent trend: fatigue life decreased with increasing fibre content across all stress levels (Figure 2). The composite with 10 wt% SPF exhibited the longest fatigue life, while the 30 wt% variant showed the shortest.

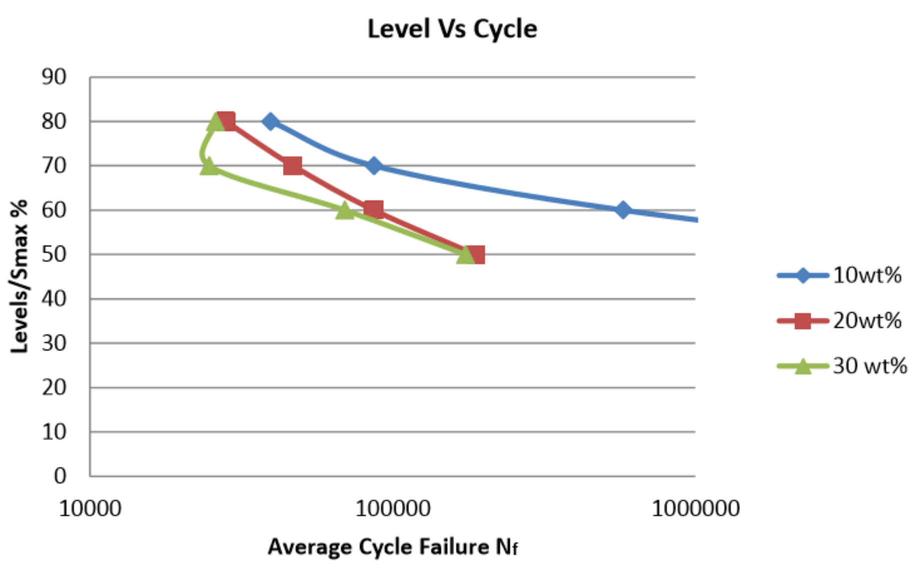


Figure 2. S–N curves for sugar palm fibre/TPU composites at different fibre contents

This trend suggests that while moderate fibre addition may help bridge microcracks and delay crack propagation, excessive fibre loading introduces defects such as fibre agglomeration, interfacial debonding, and microvoids, which act as stress concentrators. These defects facilitate early crack initiation and unstable crack growth, thereby reducing the number of cycles the composite can withstand before failure. Similar conclusions were reported by researchers who found that natural fibre composites exhibit reduced fatigue endurance at high fibre volume fractions due to poor fibre–matrix adhesion and void inclusions (Fotouh *et al*., 2014). Another contributing factor is the semi-random orientation of short SPF within the matrix. Unlike continuous or aligned fibre composites, short-fibre composites often suffer from non-uniform load distribution, which exacerbates localized stress accumulation and leads to premature failure under cyclic conditions. This observation is supported by researchers who demonstrated that orientation and aspect ratio of fibres play critical roles in determining fatigue resistance in natural fibre composites (Bhowmik *et al*., 2023). In addition to fibre content, fatigue performance was heavily influenced by the applied stress level. As expected, lowering the stress from 80% to 50% of UTS dramatically increased the fatigue life for all composite groups. For instance, the 10 wt% composite could endure over 10^4 cycles at 50% UTS, compared to fewer than 10^3 cycles at 80% UTS. This exponential improvement at reduced stress levels aligns with classical fatigue theory, particularly Basquin's Law, which describes the logarithmic relationship between stress amplitude and fatigue life for ductile polymers. Comparable fatigue trends have been observed in hemp and flax fibre composites, underscoring that natural fibres are more effective in sustaining cyclic loads at lower stress amplitudes (Shah *et al*., 2013; Liang *et al*., 2012).

4. Discussion

The experimental results demonstrate that the relationship between fiber content and mechanical properties in SPF/TPU composites is more intricate than initially anticipated. The decline in tensile strength from 18.3 MPa at 10 wt% to approximately 8.7-9.2 MPa at higher loadings challenges the conventional assumption that increased fiber content invariably enhances composite strength. This phenomenon can be understood through composite micromechanics and interfacial science analysis. The superior performance of the 10 wt% composite indicates an optimal balance between reinforcement efficiency and matrix integrity. At this loading level, the TPU matrix can effectively wet and encapsulate individual fibers, establishing efficient stress transfer pathways. The thermoplastic nature of TPU, with its inherent flexibility and processing characteristics, appears to work synergistically with moderate SPF content to maintain composite cohesion.

The deterioration observed at 20 wt% and 30 wt% loadings suggests a transition from fiber-dominated reinforcement to defect-dominated failure mechanisms. Formation of fiber clusters and agglomerations at high concentrations creates weak zones within the composite structure. These regions become preferential sites for crack initiation due to stress concentration effects and inadequate matrix penetration between tightly packed fibers. The role of fiber-matrix interface quality proves crucial in this context. Unlike synthetic fibers with tailored surface chemistries, natural fibers such as SPF possess hydrophilic surfaces that may not achieve optimal adhesion with hydrophobic polymer matrices without surface modification. The absence of chemical treatments in this study likely contributed to the observed performance degradation, as untreated fibers tend to form weak interfacial bonds that fail under mechanical stress.

Fatigue analysis provides deeper insights into the long-term durability of these bio-composites under service conditions. The correlation between static tensile strength and fatigue life demonstrates that factors affecting quasi-static properties also influence cyclic performance, albeit with additional complexity introduced by damage accumulation mechanisms. The superior fatigue resistance of the 10 wt% composite across all stress levels reinforces the concept of optimal fiber loading. During cyclic loading, this composition appears to maintain structural integrity longer due to better load distribution and reduced stress concentration sites. The ability to sustain over 10^4 cycles at 50% UTS represents promising performance for applications requiring moderate cyclic loading.

The dramatic reduction in fatigue life at higher stress amplitudes (80% UTS) reflects the sensitivity of natural fiber composites to loading severity. This behavior is particularly relevant for design considerations, as it suggests that SPF/TPU composites are better suited for low-to-moderate stress applications rather than high-performance structural roles. The semi-random orientation of short SPF fibers introduces additional complexity in fatigue behavior. Unlike unidirectional composites where crack propagation follows predictable paths, the random fiber architecture creates multiple potential failure modes. While this can provide some damage tolerance through crack deflection and bridging mechanisms, it also introduces variability in fatigue response.

These findings have significant implications for sustainable composite material development. The identification of 10 wt% as optimal loading provides practical guidance for formulators seeking to balance performance with material cost and environmental benefits. This relatively low fiber content also offers processing advantages, as higher loadings often lead to increased melt viscosity and processing difficulties in thermoplastic systems. The fatigue data suggests that SPF/TPU composites could find applications in automotive interior components, consumer goods, or packaging applications where moderate mechanical properties and good fatigue resistance are required. However, for structural applications requiring high strength or fatigue endurance, surface treatments or hybrid reinforcement strategies may be necessary.

The environmental implications are noteworthy as well. The ability to achieve reasonable mechanical properties with relatively low natural fiber content means that a significant portion of the composite remains recyclable TPU, potentially facilitating end-of-life processing and circular economy principles. Future research should focus on surface modification techniques such as alkaline treatment, silane coupling, or plasma treatment to potentially improve fiber-matrix adhesion and shift optimal loading to higher values. Additionally, compatibilizers or coupling agents specifically designed for natural fiber-thermoplastic systems warrant exploration. Hybrid reinforcement strategies combining SPF with small amounts of synthetic fibers or nanofillers might address limitations observed at higher loadings while maintaining sustainability benefits of natural fibers.

5. Conclusions

This study comprehensively investigated the tensile and fatigue performance of sugar palm fibre (SPF)-reinforced thermoplastic polyurethane (TPU) composites at varying fibre contents (10 wt%, 20 wt%, and 30 wt%). The experimental results clearly demonstrate that the incorporation of SPF significantly influences the mechanical behavior of the composites under both static and cyclic loading conditions. The 10 wt% SPF composite exhibited the most favorable mechanical properties, characterized by the highest tensile strength and the longest fatigue life across all tested stress levels. In contrast, increasing the fibre content to 20 wt% and 30 wt% led to a progressive decline in both tensile and fatigue performance. This degradation is primarily attributed to fibre agglomeration, void formation, and poor interfacial adhesion, which collectively hinder efficient stress transfer and promote early crack initiation under repeated loading. These findings underscore the critical importance of optimizing fibre content in the formulation of natural fibre-reinforced composites to achieve a balance between stiffness, strength, and endurance. For applications where cyclic loading is prominent—such as automotive interiors, consumer goods, or lightweight semi-structural parts—maintaining a moderate fibre content is key to ensuring long-term mechanical reliability. Furthermore, the study highlights several areas for future research, including the application of surface treatments or compatibilizers to improve fibre–matrix bonding, the exploration of fibre alignment techniques to enhance load transfer efficiency, and the assessment of long-term durability and environmental aging effects. These strategies have the potential to unlock broader industrial applications for SPF/TPU composites, aligning with the global pursuit of sustainable, high-performance materials derived from renewable resources.

Acknowledgement

The authors would like to express their sincere gratitude to Muhammad Muhsin bin Ahmad Baker for his valuable assistance in conducting the laboratory testing and data acquisition for this research. His support and dedication during the experimental phase significantly contributed to the successful completion of this study.

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