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Investigation of Mechanical, Thermal, and Biodegradation Properties of Starch-Based Biopolymer Composites Reinforced with Natural Fibres

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Abstract--- Biopolymers made up of starch are suitable alternatives to petroleum-based plastics due to their renewability, cost-efficiency, and biodegradability, although their brittleness, moisture sensitivity, and low thermal stability limit their application. Fibre reinforcement is commonly cited as the solution to such limitations while maintaining biodegradability. This paper provides an evidence-based analysis of how fibre reinforcement influences the mechanical, thermal and biodegradation characteristics of starch-based composites. An analytical framework connecting the formulation factors, interface mechanisms, and outcomes is suggested, and fifteen scientific studies published between 2021 and 2026 are synthesized. Quantitative evidence on a completely characterized thermoplastic cassava starch/candelilla wax composite with 0-60 wt% Pennisetum purpureum fiber reinforcement reveals that density, equilibrium moisture absorption, and water solubility were reduced by 17.3%, 53.7%, and 55.1%, respectively, at 60 wt%, while soil burial weight loss decreased from 67.4% to 43.4The mechanical performance of the composite is optimal around 50 wt% fibre until void formation and agglomeration start to dominate. Thermal performance increases with the temperature at which the material starts to decompose. Biodegradation is reduced but not prevented. The study provides guidelines on the loading range from 40 to 50 wt% and research needs.

Keywords--- Thermoplastic Starch, Natural Fibre, Biocomposite, Mechanical Properties, Thermal Stability, Soil-Burial Biodegradation.

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I. Introduction

The rise of environmental pollution from petroleum-based plastics has led to an increased effort in researching renewable materials that biodegrade. One of such materials is starch, a bio-based polymer which has been researched in depth for applications in engineering and packaging due to its renewability, low cost and biodegradable properties. However, native starch is hydrophilic, brittle, and thermally sensitive. Through glycerol plasticization, native starch is transformed to Thermoplastic Starch (TPS), which is thermo-plasticizable but still retains poor stability and high sensitivity to moisture (Schutz et al., 2024; Wang et al., 2023).

There are two methods used in the practice that predominate. One involves use of micro- and nanocellulose as reinforcing material in melt blended TPS, which offers high interfacial surface and effective stress transfer (Cataño et al., 2023). Second one and the theme of this paper involves using macroscopic lignocellulosic fibres that are cheap, low density and are available as agricultural wastes. Since both starch and cellulose contain plenty of hydroxyl group in their structure, the possibility of forming hydrogen bonding between the fibre and matrix can be expected to improve the adhesion and hinder the chain mobility, which forms the base of the stiffness and dimensional stability reported in literature (Surendren et al., 2022; Kibet et al., 2025). Thermoplastic starches and biodegradable composites are currently seen as viable replacements for single-use packaging and mechanical studies of natural fibre starch biocomposites have been conducted.

Studies on experiments have expanded the spectrum of fibres studied. Cassava starch reinforced by 10–60 wt% Cymbopogon citratus fibres has displayed better thermal stability and reduced biodegradation rates when

compared with neat matrix (Kamaruddin et al., 2022). Also, 10–60 wt% Cymbopogon citratus fibres have enhanced the physical and impact properties of a cassava starch/palm wax matrix (Kamaruddin et al., 2023). In recent times, the structure–property relationship and moisture resistance of thermoplastic cassava starch/candelilla wax matrix reinforced by Pennisetum purpureum (Napier grass) have been investigated, while the other study has discussed the dimensional stability and soil burial behavior of the same matrix system (Diyana et al., 2024). Moisture resistance has been the major concern in natural-fiber composites (Mohammed et al., 2023). Hybrid fibres have expanded the mechanical property designs space (Nurazzi et al., 2021). Other researches on fiber reinforced starch films and wax blended starch films have shown moisture sensitivity, while the biodegradation of the starch-based packaging materials has been well reviewed (Hazrati et al., 2021; Diyana et al., 2021; Su et al., 2023). Additional treatment of fibres changes their adhesive and mechanical behavior (Asyraf et al., 2022).

With these emerging studies, however, there is no unified understanding since there is no standardisation in terms of fibre types, plasticiser amounts and test methods. Therefore, the aims of this paper are (i) to present a conceptual model, (ii) to present some recent studies on mechanical, thermal and biodegradation properties and (iii) to quantify the compromises made using a complete data set.

II. Conceptual Framework

Figure 1 presents the conceptual framework which splits the study into three related layers. The first layer consists of input factors which can be manipulated by the material engineer: the type of the starch feedstock and amylose content; type of the plasticiser and additive (such as glycerol and wax); fibre types and pre-processing; fibre loading; processing method. The second layer is the combination of the physical and chemical processes which govern the conversion of the above input parameters into behaviour: interfacial hydrogen bonding; stress transmission and matrix constraint; the barrier effect provided by lignin and surface waxes; the development of voids and agglomerations in the case of high loadings; and the stability of the crystalline cellulose and lignin during degradation (Schutz et al., 2024; Jumaidin et al., 2023; Diyana et al., 2024).

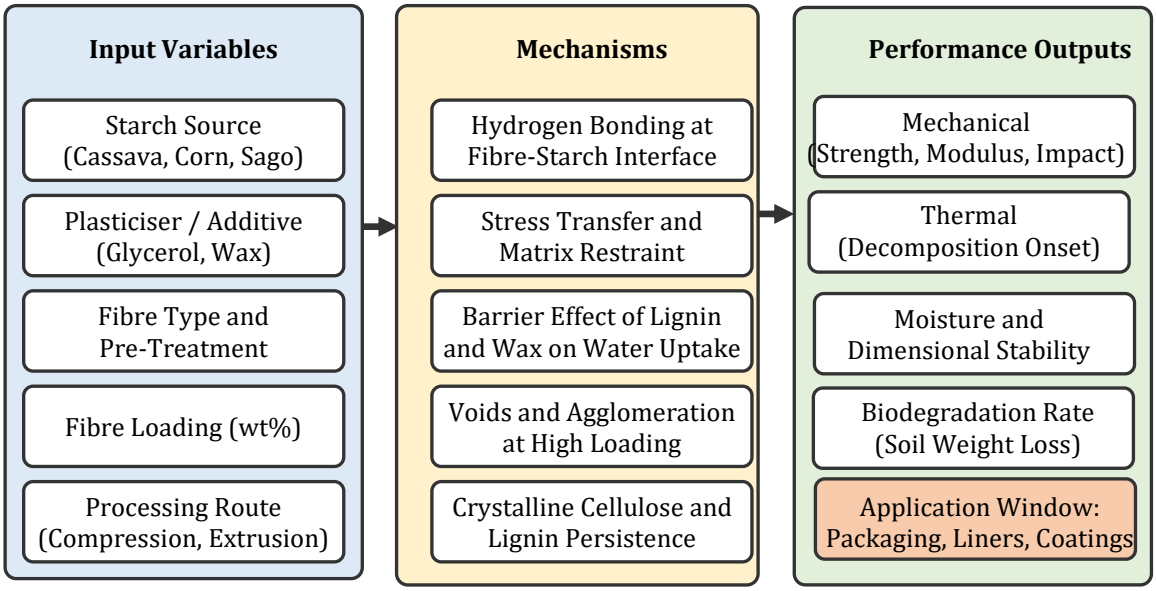


Figure 1: Conceptual Framework Linking Formulation Variables, Interfacial Mechanisms and Performance Outputs of Natural-Fibre-reinforced Starch Composites

A crucial aspect of the model is that the outputs are dependent on each other and not independent. Fibre reinforcement increases the strength of the matrix and decreases the percentage of hygroscopic starch; this increases the stiffness, heat, and moisture resistance but reduces the percentage of starch that quickly decomposes; hence reducing the rate of weight loss in the soil Kamaruddin et al., (2022) and Diyana et al., (2024). In the high loading case, incomplete wetting of the material causes the formation of voids, which cause stress concentrations and serve as routes for water and microbes to penetrate (Jumaidin et al., 2023; Diyana et al., 2024).

Working Hypotheses

The four testable hypotheses that can be formulated on the basis of the theory are presented below and their validity is checked with respect to the data obtained in Sections 4–7. H1: Strength and stiffness will increase with increasing fiber content up to an optimum, above which presence of defects will affect the properties adversely. H2: Onset of thermal degradation will increase with increasing fiber content because lignocellulosic material is thermally more stable than plasticized starch. H3: Moisture sorption, solubility and swelling will decrease monotonically with increasing fiber content because diffusion channels become blocked. H4: the degradation rate determined through soil burial is lower at higher fibre concentrations, but biodegradability persists shows in below table 1.

Table 1: Sources Included in the Evidence Synthesis and their Focus

Ref.	Year	Type	Focus
Schutz et al., (2024)	2024	Review	Starch-Based Biocomposites Reinforced with Plant Fibres
Wang et al., (2023)	2023	Review	Recent Advances and Engineering Applications of Starch-Based Biocomposites
Cataño et al., (2023)	2023	Review	Thermoplastic Starch Reinforced with Micro- and Nano-Cellulose Using Melt Blending
Surendren et al., (2022)	2022	Review	Biodegradable Thermoplastic Starch, Blends and Composites for Single-Use Packaging
Kibet et al., (2025)	2025	Review	Effects Of Natural Fibre Reinforcement on the Mechanical Properties of Starch Biocomposites
Kamaruddin et al., (2022)	2022	Experimental	Cassava Starch–Lemongrass Fibre Composites: Mechanical, Thermal and Biodegradation Properties
Kamaruddin et al., (2023)	2023	Experimental	Effect of Lemongrass Fibre on Physical and Impact Properties of Thermoplastic Cassava Starch/Palm Wax Composites
Jumaidin et al., (2023)	2023	Experimental	Durian Peel Fibre-Reinforced Thermoplastic Cassava Starch: Mechanical, Thermal and Biodegradation Properties
Diyana et al., (2024)	2024	Experimental	Pandanus Amaryllifolius Fibre-Reinforced Cassava Starch/Beeswax Composites: Physical, Mechanical, Thermal and Biodegradation Properties
Mohammed et al., (2023)	2023	Review	Water Absorption Behaviour and Challenges in Natural Fibre-Reinforced Polymer Composites
Nurazzi et al., (2021)	2021	Review	Mechanical Performance of Hybrid Natural Fibre-Reinforced Polymer Composites for Structural Applications
Hazrati et al., (2021)	2021	Experimental	Preparation And Characterization of Starch-Based Biocomposite Films Reinforced with Dioscorea Hispida Fibres
Diyana et al., (2021)	2021	Experimental	Thermal, Mechanical and Moisture Absorption Properties of Thermoplastic Starch/Beeswax Blends
Su et al., (2023)	2023	Review	Biodegradation Behaviour and Digestive Properties of Starch-Based Food Packaging Films
Asyraf et al., (2022)	2022	Experimental	Chemical Treatment of Sugar Palm Fibres and Mechanical Properties of Fibre-Reinforced Polymer Composites

Reference Formulation and Characterisation Protocols

The reference data set employs a matrix of TPCS/CW comprising 65 wt% of cassava starch, 30 wt% of glycerol and 5 wt% of candelilla wax containing 0–60 wt% Pennisetum purpureum fibres and formed through compression moulding at 150 °C and pressure of approximately 7.55 MPa. The fibres were water-retted, dried and reduced to 1 cm long before dry blending. The characterisation procedures involved in this study are illustrated in table 2 below, and reflect those generally employed in starch-based biocomposites literature. Specimen samples were subjected to oven drying at 105 °C before conducting tests, and five specimens per each formulation were used. Differences were tested using one-way analysis of variance at 5%.

Table 2: Characterisation Protocols Used to Generate the Quantitative Dataset

Property	Method / Standard	Key Conditions
Density	ASTM D1895; Mass/Volume with Densimeter	10 × 10 × 3 Mm, Dried At 105 °C For 24 H
Moisture Content	Oven-Drying Mass Loss	105 °C, 24 H, Five Specimens
Water Absorption and Thickness Swelling	Immersion; ASTM D5229-Based	Distilled Water, 23 ± 1 °C, 2 H
Equilibrium Moisture Uptake	Climate Chamber	25 ± 2 °C, 75 ± 2% RH, 7 Days
Water Solubility	Immersion And Re-Drying	30 Ml Water, 24 H Agitation
Biodegradation	Soil-Burial Weight Loss	26 ± 4 °C, 76 ± 4% RH, Ph ≈ 6.5; 2 And 4 Weeks
Morphology	Field-Emission SEM Of Fracture Surfaces	10 Kv, Gold-Coated

Fibre Selection and Pre-Treatment

Classification of lignocellulosic fibers is based on their plant source (bast, leaf, grass, fruit and seed) and they are predominantly composed of cellulose, hemicellulose, lignin, waxes and extractives, in amounts that determine hydrophilic properties, rigidity and thermal characteristics of the fiber. For instance, grass fibers like Pennisetum purpureum exhibit rapid growth and medium levels of lignin and wax that have been attributed to favorable moisture characteristics in the starch matrix while leaf fibers like sugar palm and Cymbopogon citratus offer increased cellulose and have been widely explored as reinforcements in starch systems. Methods of pretreating the fibers like alkaline treatment, silane treatment, and acetylation may help in cleaning the surface of the fibers and in altering the hydrophilic and hydrophobic functional groups. While such treatment processes may contribute to improved interfacial interactions and mechanical strength, too much of fiber modification may limit hydrogen bonding sites, making the fibers incompatible with the starch matrix. In view of this, pretreatment conditions have to be carefully tailored to individual fiber-matrix combinations. This research mainly involves untreated and water retted natural fibers.

III. Mechanical Properties

Mechanical reinforcement of TPS using fibres occurs based on fibre concentration, aspect ratio, distribution, and interfacial adhesion. The high concentration of hydroxyl groups in cellulose allows for hydrogen bonding with starch and glycerol, thereby transferring any applied load from the soft matrix to the stiff fibres. Literature reviews of fibre-reinforced starch composite materials always show increased tensile modulus and tensile strength when compared to neat TPS and a decrease in elongation. In a hybrid system, the use of different stiffness fibres would widen the range of material properties, while chemically modifying the surface decreases hydrophilicity.

The most recent data on this issue relates to TPCS/candelilla wax modified by 0-60 wt% of Pennisetum purpureum fiber. Mechanical properties increased as a function of loading until 50 wt%, where they obtained optimal values. In fracture studies, fiber failure and pullout were noted, thus stress transfer was achieved; however, at 60 wt% the appearance of voids and fiber agglomeration was observed, which are stress concentration zones. This non-linear behavior, illustrated schematically in figure 2, is in accordance with the theory outlined in Section 2 as well as with loading dependent behavior in Cymbopogon citratus fiber. Table 3 provides the direction of changes of all mechanical properties.

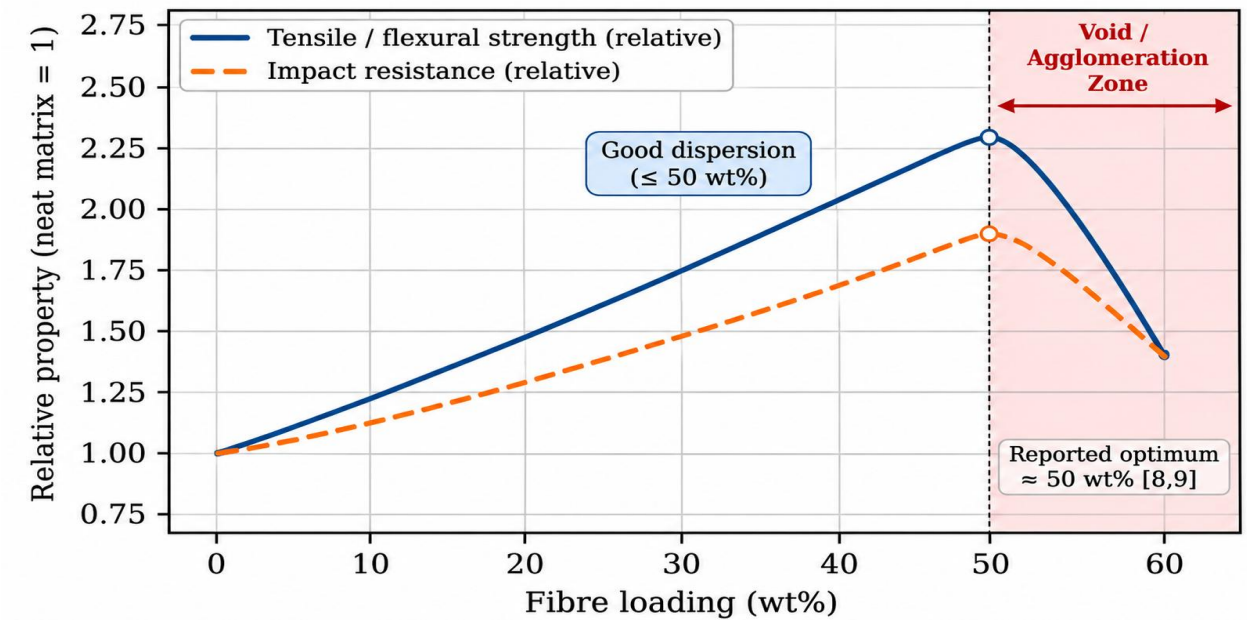


Figure 2: Schematic Trend of Relative Mechanical Properties Versus Fiber Loading, Presenting the Optimum Near 50 wt% and the Void/Agglomeration Zone Reported

Table 3: Direction of Change in Mechanical and Thermal Properties with Increasing Fibre Content in Starch-Based Composites

Property	Trend With Fibre Loading	Principal Mechanism	Source
Tensile / Flexural Strength	Increases To an Optimum (≈50 Wt% For P. Purpureum), Then declines	Stress Transfer; Voids and Agglomeration at Excess Loading	Kibet et al., (2025) and Jumaidin et al., (2023) and Diyana et al., (2024)
Modulus / Stiffness	Increases	Rigid Cellulose Network Restrains Starch Chains	Schutz et al., (2024) and Kamaruddin et al., (2022)
Elongation At Break	Decreases	Restricted Chain Mobility	Schutz et al., (2024) and Kibet et al., (2025)
Impact Resistance	Improves Up to Optimum	Fibre Pull-Out and Fracture Absorb Energy	Kamaruddin et al., (2023) and Jumaidin et al., (2023)
Decomposition Onset (TGA)	Shifts Higher	Thermally Stable Cellulose/Lignin; Lower Starch Fraction	Kamaruddin et al., (2022)
Residual Char / Ash	Increases	Higher Lignocellulosic Content	Kamaruddin et al., (2022)

IV. Thermal Properties

For fibre-filled thermoplastic starch, the thermogravimetry generally reveals a stepwise weight loss: desorption of water adsorbed and plasticizer volatilized at low temperature, followed by degradation of glycerol-rich starch regions and finally by decomposition of hemicellulose, cellulose and lignin at higher temperatures. Due to the high temperature of decomposition of lignocelluloses being equal to or higher than that of plasticized starch, the increase in fibre concentration results in an elevation of the temperature of decomposition initiation and ash content, as shown for cassava starch containing C. citratus fibre at 10–60 wt %. Hydrogen bonding between the phases inhibits the movement of the starch molecules, and addition of hydrophobic additives like waxes is beneficial.

There are two important caveats to note. One is that thermal advantages tend to be relatively small in absolute value since starch and fibre break down within the same range of temperature, and therefore the processing temperature must stay below the degradation point of the hemicellulose. The second one is that residual moisture and plasticizer level affect thermal behavior greatly, which makes sample preconditioning a necessary step prior to TGA or DSC analysis.

V. Moisture Resistance and Dimensional Stability

Absorption of water controls service life since it leads to plasticization of starch, swelling, and rapid microbe attacks. Table 4 and figures 3 and 4 show the whole series found for TPCS/candelilla wax composite reinforced by 0–60 wt% of P. purpureum fiber. There was a 17.3% decrease in density from about 1.33 to 1.10 g/cm3. This was due to the low density and presence of lumen in the fiber; about 10-20% has been found in banana, kenaf, and sisal composites. The moisture content was reduced from 8.6% to 5.0%, two hours water absorption from 52.2% to 31.8%, water solubility from 29.2% to 13.11%, and seven days equilibrium moisture absorption from 8.31% to 3.85%.

Table 4: Physical and Moisture-Related Properties of TPCS/Candelilla Wax Composites at 0 and 60 wt% P. Purpureum Fiber

Property	Neat Matrix	60 Wt% Fibre	Change (%)
Density (G/Cm^3)	1.33	1.10	−17.3
Moisture Content (%)	8.6	5.0	−41.9
Water Absorption, 2 H (%)	52.2	31.8	−39.1
Water Solubility (%)	29.2	13.11	−55.1
Equilibrium Moisture Uptake, 7 D (%)	8.31	3.85	−53.7
Soil Weight Loss, 2 Weeks (%)	51.6	34.9	−32.4
Soil Weight Loss, 4 Weeks (%)	67.4	43.4	−35.6

There are three possible explanations for the observed improvement. The first one is the presence of lignin and surface waxes that make the fiber hydrophobic to some extent. The second reason lies in the displacement of hygroscopic starch by fiber and consequent decrease in hydroxyl sites available for interaction. The third one is related to better interfacial bonding that makes the structure denser and decreases porosity. Such an effect was observed for C. citratus fiber in cassava starch matrices and beeswax-modified TPS.

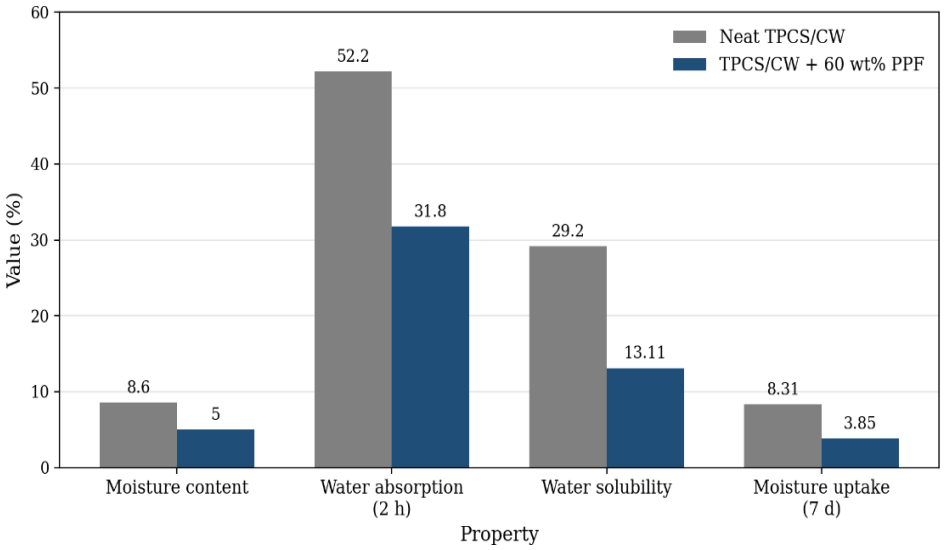


Figure 3: Absolute Moisture-Related Properties of the Neat TPCS/CW Matrix and the 60 wt% P. Purpureum Fibre Composites

VI. Biodegradation Behaviour

In laboratory tests, soil burial is the most common method for determining the biodegradability of starch composite materials, with the mass loss being due to the combined impact of microorganisms, water absorption, and the removal of soluble components. As seen from figure 4, neat TPCS/CW matrix material experienced 51.6% and 67.4% mass losses within two and four weeks, respectively, compared to 34.9% and 43.4% mass loss of the 60 wt% composite material. Hence, the presence of fibres just delays degradation. It can be compared with C. citratus fibres in cassava starch.

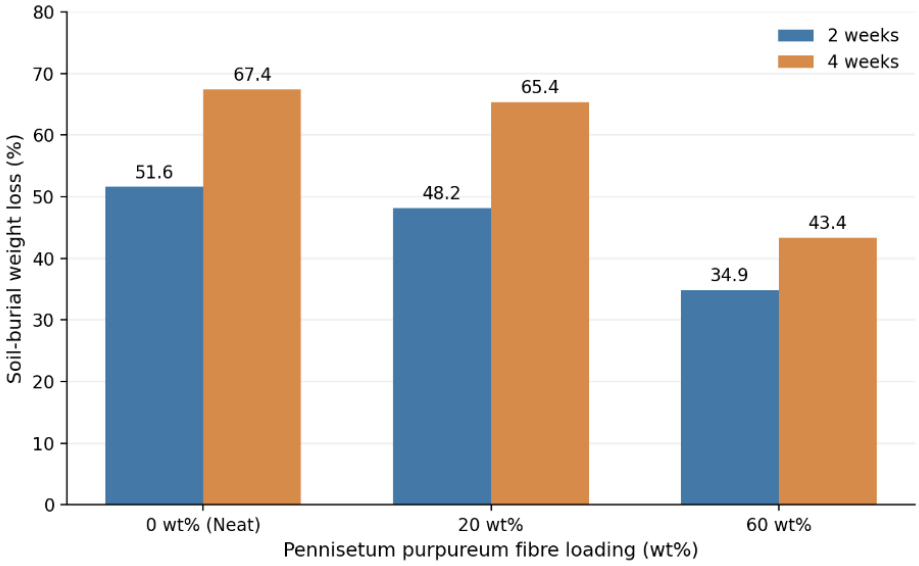


Figure 4: Soil-Burial Weight Loss of Neat and Fibre-Reinforced TPCS/CW Composites After 2 and 4 Weeks

This phenomenon occurs due to the reduction in the proportion of starch that easily undergoes hydrolysis, coupled with the degradation of crystalline cellulose and lignin occurring over a period of time. It is significant to note here that the phenomenon is not always monotonic; for example, the 20% by weight composite material exhibited a loss of 65.4% in just four weeks, similar to the neat matrix material, owing to void spaces in the interface that allow water and microorganisms in.

VII. Integrated Discussion

Section 4-7 Integration shows that fibre loading is used as the main design variable, although its impact varies across the material properties (Table 5). While mechanical properties reach the optimal point around 50 wt%, moisture resistance and density keep increasing up to 60 wt %, while the biodegradation rate steadily reduces. The consequence of this is that the optimal loading is different for various applications. In the case of packaging liners and coatings where increased moisture resistance is required, fibres' loading in the range of 40-50 wt% is ideal. This is because it provides an appropriate combination of mechanical strength and moisture resistance without reaching the defect-dominated region for 60 wt % loading. On the other hand, applications that need higher biodegradation rates would benefit from either low loading of fibres or proper fibre pre-treatment to ensure access of microorganisms.

Table 5: Integrated Design Guidance and Recommended Characterisation Practice for Fibre-Reinforced Starch Composites

Aspect	Design Implication	Recommended Practice	Source
Fibre Loading	Optimum ≈40–50 Wt% for Strength; Moisture Gains Continue To 60 Wt%	Test At Least Five Loadings Including a Neat Control	Jumaidin et al., (2023) and Diyana et al., (2024)
Interface	Treatments And Hydrophobic Additives Improve Adhesion and Water Resistance	Report Fibre Treatment, SEM of Fracture Surfaces	Diyana et al., (2021) and Asyraf et al., (2022)
Moisture	Largest Single Determinant of Durability	Standardised Conditioning and Immersion/Humidity Protocols	Diyana et al., (2024) and Mohammed et al., (2023)
Thermal	Directional Gain in Decomposition Onset	Equalise Moisture/Plasticiser Before TGA/DSC	Schutz et al., (2024) and Kamaruddin et al., (2022)
Biodegradation	Moderated, Not Eliminated, By Fibre	Soil Burial Plus Longer, Mineralisation-Based Tests	Diyana et al., (2024) and Su et al., (2023)

The application mapping comes directly out of table 5. Films, liner papers and coated papers for packaging are concerned with moderate moisture barriers, stability and degradability but not the very low permeability offered by the usual plastic films, which are consistent with the properties of the high fibre TPS blends. Rigid and light weight items like trays and containers can take advantage of the 10-20% reduction in density of starch composite films loaded with fibers, while hybrid fibre systems could be used when more structural strength is needed. However, water exposure or barrier needs that require high water barriers cannot be met by pure starch blends and will have to use coating or blends. The above statements are subject to some limitations. All the quantitative information contained herein relates to one particular blend of matrix-fiber, and extrapolations to other matrices, plasticisers and fibers should be made cautiously since the amylose content, granule structure and fiber properties all play important roles in the interactions.

VIII. Challenges and Future Directions

Four key priorities arise. The first is the requirement for standardized testing procedures for moisture conditioning, soil burial, and thermal analysis to allow the compilation of data generated from different laboratories. The second is the use of interfacial engineering techniques, such as gentle fiber modification, compatibilizers, and hydrophobic modifiers, to expand the practical loading range. The third priority is the testing of processability techniques other than compression molding, such as extrusion and injection molding, for highly filled blends. Finally, life-cycle and end-of-life evaluation, including composting and ecotoxicity,

needs to be done together with optimization of properties to validate biodegradability claims. Formulation by design based on the model of figure. 1 is one way of doing this efficiently.

IX. Conclusions

This study established a theoretical framework and reviewed recent findings related to natural fiber-reinforced starch-based composites. Fiber addition enhances mechanical properties to an optimum value around 50 wt% in the best-understood composite, raises the thermal degradation onset point, and significantly enhances hydrophobicity, lowering the water solubility and equilibrium moisture absorption to 55% and 54%, respectively, at 60 wt%. Biodegradation is slowed down, reducing the four-week soil loss value from 67.4% to 43.4%, but all compositions still degrade. The loading range of 40-50 wt% represents a balanced performance in terms of application in packaging. Future research should focus on standardizing testing procedures and optimizing fiber/matrix interfaces.

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