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Thermal and Mechanical Characterization of Recycled LDPE/Sida acuta Fiber/Paper Pulp Composites for Sustainable Wall Panels

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Abstract: Plastic waste, especially low-density polyethylene (LDPE), poses a serious environmental challenge. This work develops wall panel composites by reinforcing recycled LDPE with *Sida acuta* (wire weed) fibers and recycled paper pulp. Panels were fabricated by melt mixing and compression molding (150–160 °C), with *S. acuta* fiber at 0–45 wt% and 5 wt% constant paper pulp (except the neat sample). Mechanical tests (tensile, flexural, impact, Rockwell hardness) and dynamic mechanical thermal analysis (DMTA) were conducted. Results show tensile strength of neat LDPE (33 MPa) declined with fiber addition to 21 MPa at 45 wt% fiber, while tensile modulus rose from 0.31 to 0.61 GPa (0-45 wt%). Flexural strength peaked at low fiber content (225 MPa at 5 wt%, vs. 209 MPa for neat) and then decreased to 189 MPa (45 wt%). In contrast, flexural stiffness roughly doubled (modulus 0.247-0.534 GPa at 45 wt%). Impact toughness and surface hardness improved continuously: impact energy increased with fiber (3.2 kJ/m² at 45 wt%), and hardness rose from 14.6 to 69.2 HRB (0-45 wt%). DMA showed that all composites retain dimensional stability up to 240 °C, with reinforced samples exhibiting lower damping (tan δ) and higher effective Tg than neat LDPE, indicating restricted polymer mobility. These findings demonstrate that valorizing LDPE waste with *Sida acuta* fiber and paper pulp yields composites with enhanced stiffness, toughness, and thermal stability. The composites' performance especially increased modulus and impact resistance suggests they show potential for non-load-bearing interior partition applications in indoor partitions.

Keywords: Recycled LDPE; *Sida acuta* fiber; Paper pulp; Natural fiber composites; Mechanical properties; Thermal stability

1 INTRODUCTION

Rapid growth in plastic production and inadequate recycling have led to an accumulation of plastic waste, particularly low-density polyethylene (LDPE) from single-use packaging (Nayanathara Thathsarani Pilapitiya & Ratnayake, 2024). LDPE is durable but poorly biodegradable, so converting it into high-performance composites offers a circular-economy solution (Debele et al., 2024). Natural fibers are attractive reinforcements because of their low density, biodegradability, and good specific properties (Elfaleh et al., 2023). In construction, lightweight wall panels demand materials that are moisture-resistant yet mechanically robust. Previous studies have shown that recycled polyolefins can be combined with agricultural fibers to produce cladding or partition materials (Das et al., 2026). For example, Kumi-Larbi *et al.* (2018) demonstrated that recycled LDPE can bind sand to form partition blocks with sufficient strength (Kumi-Larbi et al., 2018).

However, many abundant plant fibers remain underutilized. *Sida acuta* (wire weed) is a perennial shrub with high cellulose content of 73% and intrinsic tensile strength of 627 MPa (Gopinath et al., 2022). These properties, along with thermal stability to 240 °C, suggest *S. acuta* fiber is promising as a composite reinforcement. Recycled paper pulp – rich in cellulose has also emerged as an eco-friendly filler that can improve stiffness and interface bonding (Pătrăucean-Patraşcu et al., 2025). To our knowledge, no prior work has combined *S. acuta* fiber and waste paper pulp in a recycled LDPE matrix for wall panels. This study fills that gap by fabricating LDPE/*S. acuta*/paper pulp composites and evaluating their mechanical and thermal properties. The objective is to identify optimal fiber loading and demonstrate the material's potential for sustainable interior panel applications.

2 MATERIALS AND METHODS

2.1 Materials

The overall experimental methodology, illustrated in Figure 1, was structured into five sequential and interrelated stages which are

(i) raw material collection
(ii) material preparation
(iii) composite formulation and panel fabrication
(iv) mechanical and thermal characterization, and
(v) (v) benchmarking against relevant standards and conventional wall partition materials. Each stage was designed to ensure material consistency, reliable processing, and accurate performance evaluation of the developed recycled LDPE/*Sida acuta*/paper pulp composite panels.

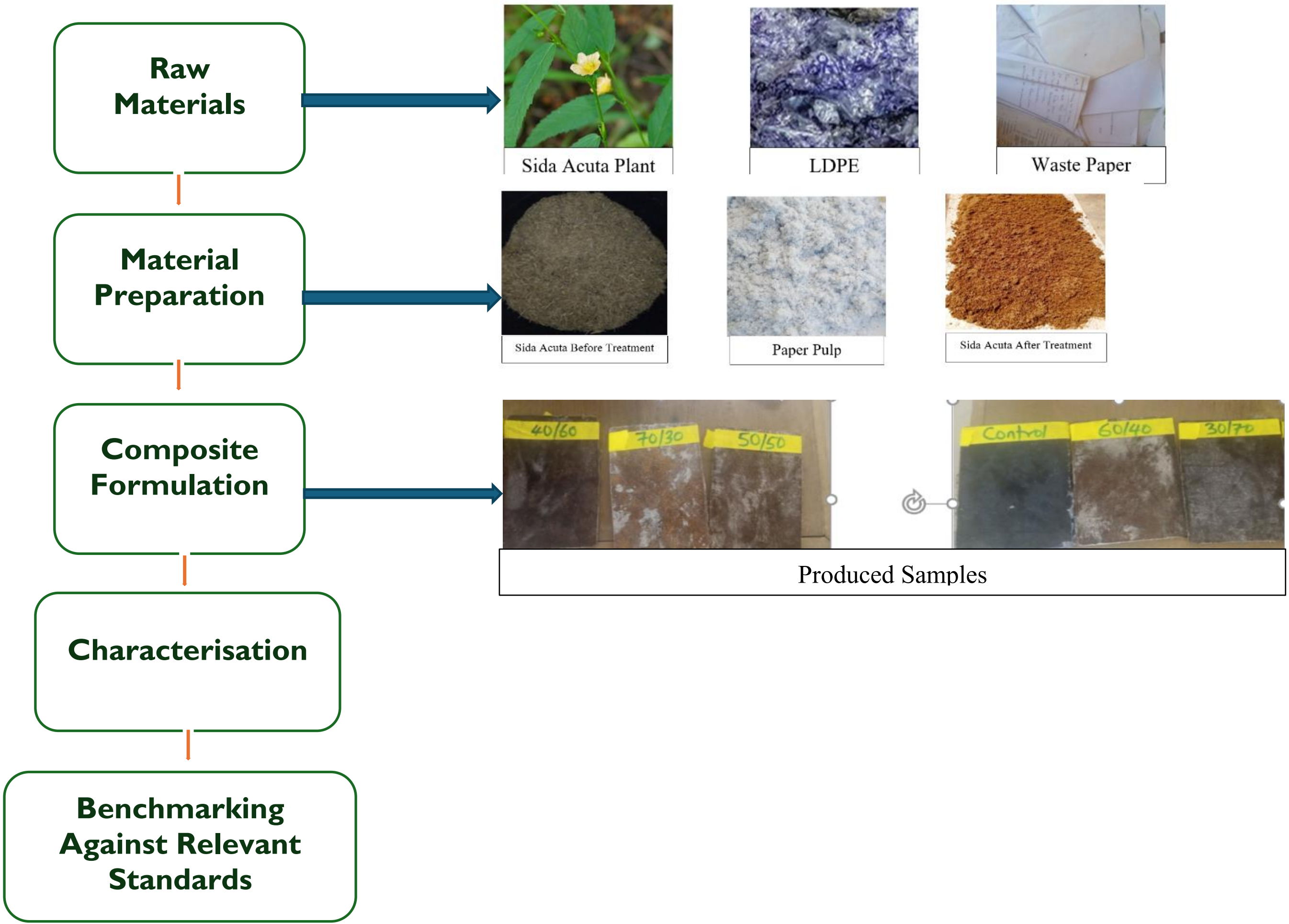

***Figure 1:** Experimental framework*

Recycled LDPE pellets (from used sachet water bags) served as the polymer matrix. *S. acuta* fibers were collected from mature stems, cleaned, alkali-treated (5% NaOH), and dried to <5% moisture. Recycled paper pulp (cellulosic waste) was used as a secondary filler. All materials were locally sourced and processed as described by standard protocols (Amaechi et al., 2026).

2.2 Material Preparation

LDPE pellets, treated *S. acuta* fibers, and paper pulp were dry-mixed in a twin-screw mixer at 160 °C (50 rpm). The paper pulp content was held constant at 5 wt% in all formulations with the exception of the neat sample which had 0% reinforcement. Fiber loadings of 0, 5, 15, 25, 35, and 45 wt% (*i.e.* samples W0–W50) were produced (Table 1). The homogenized blends were then compression-molded at 150–160 °C under 5 MPa pressure for 10 min, followed by 2.5 MPa cooling for 3 min, into 150×100×3 mm panels.

***Table 1:** Composition of the Samples*

Sample ID	*Sida acuta* Fiber (wt.%)	Paper Pulp filler (wt.%)	Recycled LDPE (wt.%)
W 0	0	0	100
W 10	5	5	90
W 20	15	5	80
W 30	25	5	70
W 40	35	5	60
W 50	45	5	50

2.3 Characterisation

3.1 mechanical characterisation

3.1.1. Tensile

Tensile tests were performed per ASTM D638-76 using a Shimadzu Universal Testing Machine (AG-X Series, Japan). Five specimen dumbbell shaped (Figure 2), each with dimensions of 120 mm × 20 mm × 3 mm and a gauge length of 80 mm, were tested at a crosshead speed of 5 mm/min. For each test, five replicates were prepared, and the average values reported.

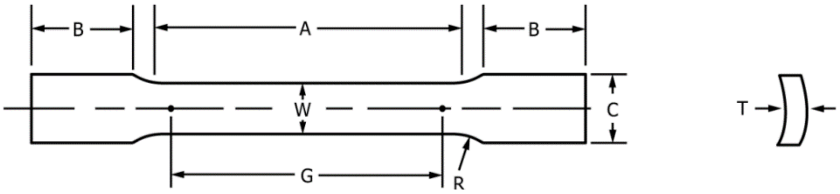

Figure 2: *Tensile Specimen Geometry*

Where, A – Reduced section length: 40 mm
B – Grip section length (each side): 20 mm
C – Overall width at grip section: 15 mm
G – Gauge length: 30 mm
R – Fillet radius: 5 mm
W – Reduced section width: 5 mm
T -Thickness: 3 mm
Each specimen had an overall length of approximately 120 mm. Testing was performed at a crosshead speed of 5 mm/min.

$$\text{Tensile Strength} = \frac{Force}{Area}$$

$$\frac{F}{WT} \ (\text{MPa}) \qquad (3.1)$$

Where,
F = Maximum tensile load
W = Sample thickness
T = Sample width

$$\text{Strain} = \frac{\Delta L}{L} \qquad (3.2)$$

Where,
ΔL = Extension
L = Gauge Length

$$Modulus = \frac{Stess}{Stain} \ (MPa) \qquad (3.3)$$

3.1.2. Impact Strength

Impact energy absorption was determined using an Izod impact tester (Model: XC-50 Pantec, 22 J hammer) in accordance with ASTM D256. Five specimens (60.25 × 12.7 × 3 mm) were tested to evaluate resistance under sudden load conditions using a weighted pendulum, and the average energy absorption values were recorded.

3.1.3. Hardness

Hardness of the composites was evaluated using a Rockwell B (Instron hardness tester A654R, Serial No.: 97345603) according to ASTM D785. Specimens with dimensions of 25 mm in diameter and 20 mm in length were tested for Rockwell-B hardness (HRB) based on the moderate hardness range and composite composition, and the average values were documented.

3.1.4. Flexural Test

Flexural properties were determined using a three-point bending configuration in accordance with ASTM D790 (Figure 3). The tests were conducted using a Shimadzu Universal Testing Machine (AG-X Series, Japan) at room temperature. Rectangular specimens with dimensions of 100 mm × 12.7 mm × 3 mm were prepared from the fabricated composite panels. The support span was set at 48 mm (corresponding to a span-to-depth ratio of 16:1). Loading was applied at the midspan at a crosshead speed of 2 mm/min until specimen failure. For each composite formulation, five specimens were tested and the average flexural strength and flexural modulus were reported.

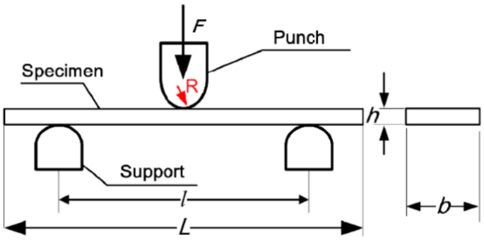

Figure 3: *Flexural Geometry*

Flexural strength was calculated using:

$$(\sigma_f) = \frac{3\mathrm{FL}}{2\mathrm{bh}^2}\left({}^{N}/_{mm^2}\right) \qquad (3.4)$$

Modulus of elasticity (MOE)/Flexural Modulus (E_f)

$$(E_f) = \frac{FL^3}{4bd^3D}\left({}^{N}/_{mm^2}\right) \qquad (3.5)$$

where *F* is the maximum load (N), *L* is the support span (mm), *b* is the specimen width (mm), and *d* is the specimen thickness (mm).
The flexural modulus was determined from the slope of the initial linear portion of the load–deflection curve.
For specimens with thickness 3 mm:
Length (L): 100–127 mm
Width (b): 12.7 mm
Thickness (h): 3 mm
Support span (S): 16 × thickness
S = 16 × 3 mm = 48 mm

3.2. Thermal Characterisation

Thermal characterisation gives us the information about the stability and serviceability of composites under different temperature conditions (Barra et al., 2023; Neto et al., 2021; Reis et al., 2025). The thermal performance of the recycled LDPE/Sida acuta/paper pulp composites was tested in this study in order to ascertain their dimensional stability and applicability to building projects like wall partitioning. Viscoelastic response of the composites was studied by Dynamic Mechanical Thermal Analysis (DMTA), specifically the storage modulus (E), the loss modulus(E 2), and damping factor ($tan\ d$). The findings indicated that the storage modulus declined steadily with temperature which revealed the change of the glassy state to the rubbery state which is characteristic of polymeric systems. The E' values of reinforced composites were slightly lower than that of neat LDPE, which showed the effect of fiber and filler on the polymer chain mobility. Nonetheless, the formulations with $40 - 50\ wt$ percent of fibers ensured the balance between stiffness and damping, and it was recommended to be used in the interior housing in terms of thermal stability. The tan d and the loss modulus profiles also verified that the reinforcement did not only change the relaxation behavior of the polymer matrix but also decreased the energy loss of the polymer matrix but increased its dimensional stability at high temperatures. The findings of these observations demonstrate how Sida acuta fibers and paper pulp inhibited chain movement and enhanced the thermo-loading structural integrity of the composites.

3.RESULTS AND DISCUSSION

3.1 Tensile Properties

Tensile tests showed that adding *S. acuta* fiber (with 5 wt% pulp) to LDPE reduced ultimate strength. Neat LDPE (W0) had the highest tensile strength (33 MPa) (B et al., 2024) With increasing fiber, strength declined to 26 MPa $(5 - 15\ wt\%)$, reaching 21 MPa at $45\ wt\%$ fiber (W50), a 36% decrease. This inverse strength–stiffness relationship is typical in natural fiber composites: rigid fibers create stress concentrations and imperfect bonding, so load transfer to fibers is limited. Indeed, untreated fiber surfaces and residual impurities can weaken the interface, leading to premature failure (as also reported for other lignocellulosic fibers in polyolefins.

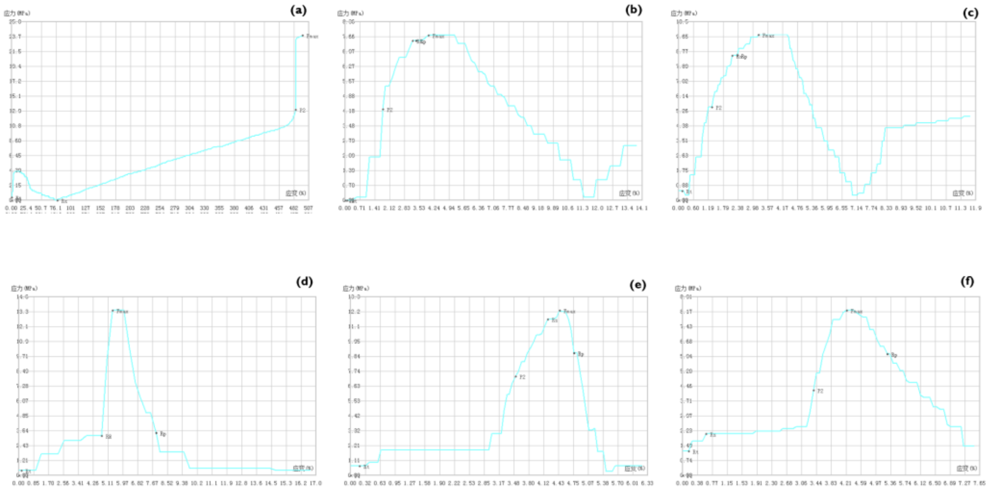

Figure 4: ***(a)*** *Tensile strength for Control* ***(b)*** *Tensile strength for Wall 30* ***(c)*** *Tensile strength for Wall 40* ***(d)*** *Tensile strength for W50* ***(e)*** *Tensile strength for Wall 60* ***(f)*** *Tensile strength for W30*

In contrast, the tensile modulus increased markedly with fiber. Figure 4b shows a nearly linear rise in tensile modulus from 0.309 GPa for neat LDPE (W0) to 0.605 GPa for W50. The added *S. acuta* fiber (stiff, cellulose-rich) stiffens the matrix. Similar trends were reported by Arrakhiz *et al.* (2013), who observed increased modulus when adding natural fibers to an LDPE matrix (Arrakhiz et al., 2013). Thus, although ultimate strength fell, the composites became much stiffer: the polymer's deformation under load is greatly reduced by the rigid fiber network. The trade-off between strength and stiffness is characteristic of biocomposites (Okumura, 2015).

3.2 Impact Strength

Impact resistance improved with fiber addition (Figure 5). Although quantitative values are not plotted here, the maximum impact energy was attained at the highest fiber content (3.2 kJ/m² for W50). This increase indicates that the fiber and pulp network effectively dissipates energy during crack propagation: fibers bridge and deflect cracks, while the paper pulp contributes micro-bridging and frictional dissipation. In other words, the composite becomes less brittle and more tough with fiber reinforcement, which is useful for applications where dynamic loads or sudden impacts occur.

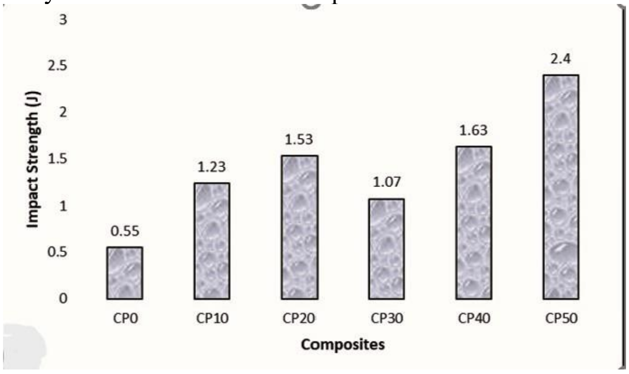

Figure 5: *Impact strength*

3.3 Hardness

Surface hardness also rose sharply with fiber (Figure 6). The Rockwell B hardness increased from 14.57 HRB for neat LDPE to 69.2 HRB at 45 wt% fiber[6] (roughly a fivefold gain). This reflects the stiff, interlocked internal structure formed by high fiber/pulp content[26]. Increased hardness implies better resistance to indentation and wear – again at the expense of ductility. This trend is consistent with other natural-fiber systems[6][27]. In summary, fiber-reinforcement significantly stiffens the surface and enhances toughness, but designers must balance this against flexibility needs.

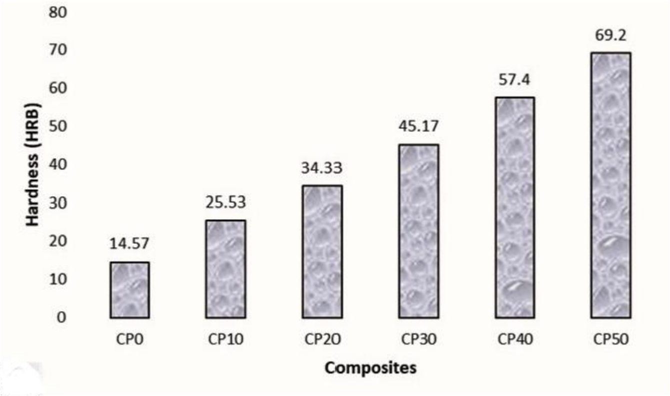

***Figure 6:** Hardness of recycled LDPE/Sida acuta composite*

3.4 Flexural Properties

The flexural strength (Figure 2a) exhibited a non-monotonic trend. A small fiber addition actually improved strength: W10 (5 wt% fiber) reached 225.4 MPa, about 8% higher than neat LDPE (209.2 MPa) (Pearson et al., 2022). This initial gain suggests that well-dispersed fibers and micro-scale pulp bridges can enhance load transfer in bending. However, beyond 15 wt% fiber, flexural strength declined steadily to 189.2 MPa at 45 $wt\%$ (W50) (Bhuiyan et al., 2026). The deterioration at high fiber content likely stems from agglomeration, fiber pull-out, and voids that weaken the composite under bending (Wang et al., 2025). Prior studies have similarly noted that excessive fiber can impair interfacial adhesion in thermoplastic matrices (Pearson et al., 2022). Although Various strategies, including nanoparticle incorporation, plasma surface modification, ozone treatment, and oxidative surface activation, have been employed to enhance fibre–matrix interfacial bonding in thermoplastic composites by increasing fibre surface polarity and improving compatibility with non-polar polymer matrices (Periasamy et al., 2023). However, these techniques often increase processing complexity and cost.

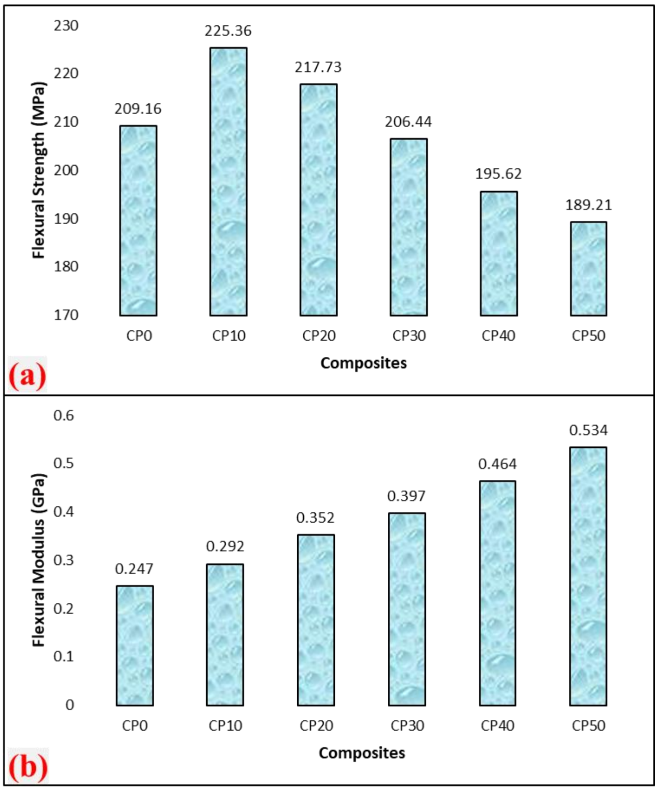

***Figure 7:** (a) Flexural strength and (b) modulus of recycled LDPE/Sida acuta composite*

Flexural stiffness increased with fiber (Figure 7b). The flexural modulus rose from 0.247 GPa (W0) to 0.534 GPa at 45 wt% fiber, more than doubling. This stiffening is again attributed to the rigid lignocellulosic fiber and pulp structure. The behavior aligns with expectations for fiber reinforcement: even as flexural strength drops, the panel’s resistance to bending (modulus) is greatly enhanced

(Yang et al., 2025). In practice, this means the panels are much less prone to deflect under load, a desirable property for partitions. The apparent “optimal” strength at low fiber content (W10) followed by increased stiffness at high content suggests that moderate fiber loadings (10–20 wt%) yield balanced performance, whereas 35–45 $wt\%$ maximize rigidity.

3.5 Thermal and Viscoelastic Behavior (DMTA)

The storage modulus measures the materials ability to absorb and store elastic energy which implies its stiffness. For this study, the samples generally showed a decrease in storage modulus as the temperature increases which is a typic behavior of polymetric material that is transiting from glassy to rubbery form. Although the control sample exhibited a higher storage modulus at all temperature ranges which may be due to poor dispersion or weak interface. As expected, samples with higher fillers showed a decrease in storage modulus. The trend observed implies that increase in the quantity of reinforcement hinders the homogeneity and breaks the chain of the polymer leading to a reduction in load bearing capacity and transfer as well as the stiffness of the matrix. Additionally, the samples with W50 as well as 40/60 composition did not indicate a change in storage modulus meaning that there is a balance between the polymer matrix and reinforcement which is important for housing applications where mechanical integrity is required.

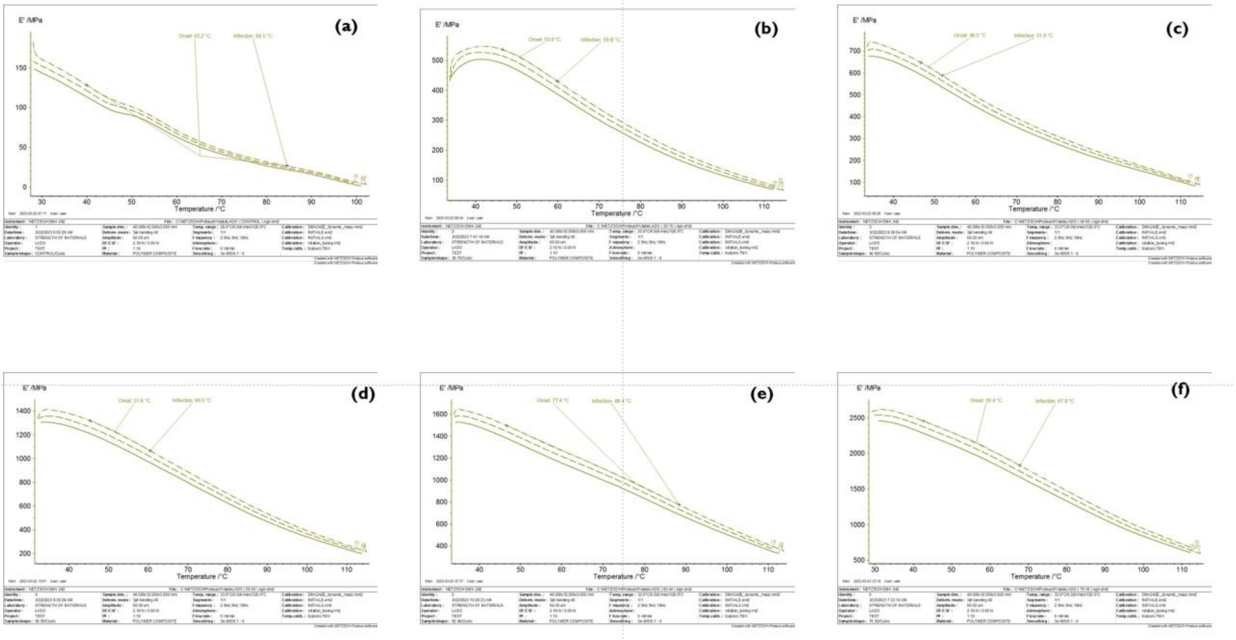

__Figure 8__: Storage Modulus (E') of (a) Control sample, (b) Wall 30, (c) Wall 40, (d) Wall 50, (e) Wall 60, (f) Wall 70

4.5.2 Loss Modulus (E")

This is the ability of a material to dissipate heat when applied to it. during the peak period of loss modulus, its curve and that of its glass transition region corresponds and at this region, the chain of the polymer molecule gains some amount of mobility. For the tested samples, the control showed a unique peak around the region of T_g indicating that as a result of molecular motion, there is active dissipation of energy. When the amount of filler is increased, the loss modulus peak varies in value with reduced intensity particularly in samples such as (W30). This implies a restriction in the mobility of chain as a result of the interference from the filler which reduces the flow and loss of energy. The shifting and broadening of E″ peaks across the composites imply that reinforcement alters the relaxation dynamics of the polymer chains, influencing the thermal transition behavior and potentially enhancing dimensional stability at elevated temperatures.

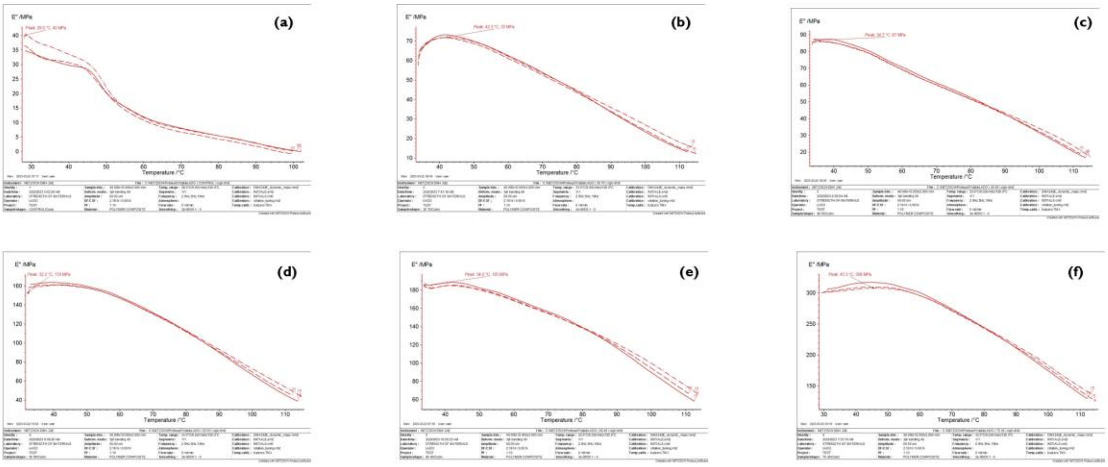

Figure 9: *Loss Modulus (E") of (a) Control sample, (b) Wall 30, (c) Wall 40, (d) Wall 50, (e) Wall 60, (f) W30*

4.5.3 Tan Delta (δ)

Tan delta is an important parameter used to identify the glass transition temperature as well as assessment of the damping properties of materials. It is the ratio of the storage to loss modulus and when high signifies a viscoelastic response that is high and the ability of the material to dissipate energy.

While the reinforced samples showed a lower value of the tan delta especially the samples W30 and W40, indicating a reduced damping implying that the filler increment reduced the network of polymer. the control sample showed the highest value of the tan δ indicating it outstanding damping value property of the material sample. The sharp peak observed around the T_g indicates a satisfactory chain mobility and structural limitation of the material. Additionally, The shift of Tg to slightly higher temperatures in these samples also supports the hypothesis of enhanced thermal stability due to restricted chain motion. Furthermore, the wall 40 and wall 50 samples showed intermediate tan δ behaviors, thus balancing the damping performance with thermal and structural stability which makes them potentially suitable for applications that requires a moderate flexibility, reduced vibrational transmission, and improved mechanical strength.

The DMTA obtained thus shows the extent of the influence of filler content on the thermal-mechanical performance of the LDPE composites. While the control sample provides superior stiffness and damping due to an unaltered polymer matrix, increased reinforcement modifies both the elastic and viscous responses. Composites with moderate reinforcement levels (e.g., 40/60 and W50 appear to offer a good compromise between stiffness, damping, and thermal stability. In contrast, highly filled systems W40 and W30 may suffer from excessive rigidity and reduced energy dissipation, though they benefit from improved dimensional and thermal stability.

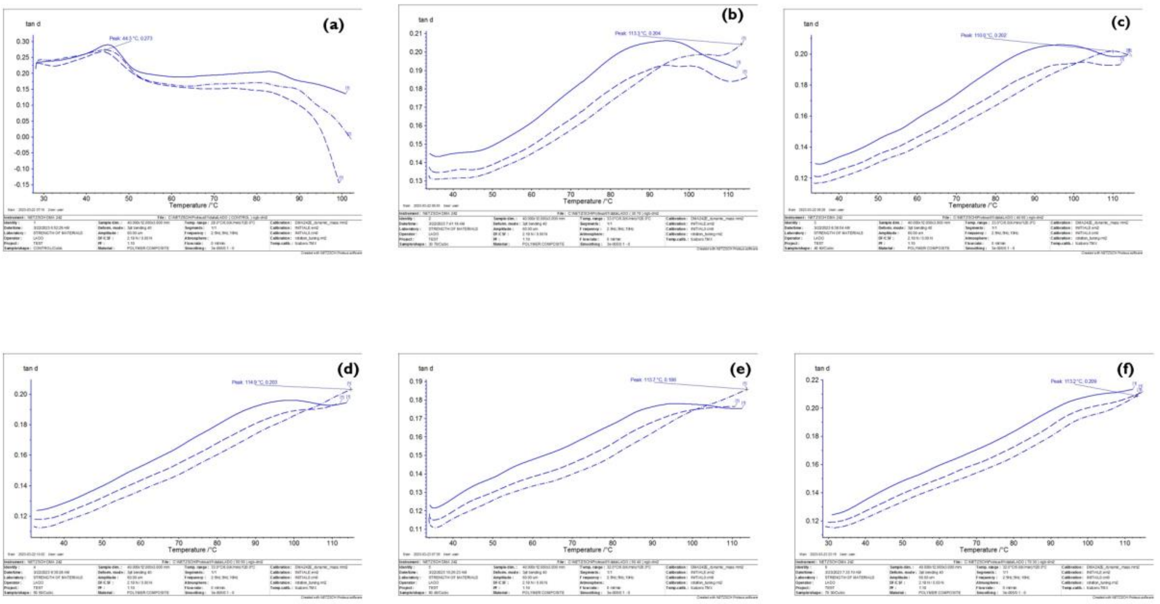

Figure 10: *Tan Delta (δ) of (a) Control sample, (b) Wall 30, (c) Wall 40, (d) Wall 50, (e) Wall 60, (f) Wall 70*

4 CONCLUSION

Recycling LDPE into composites with *Sida acuta* fiber and paper pulp yields materials with promising properties for building applications. In our study, moderate fiber contents ($5 - 15\, wt\%$) slightly enhanced flexural strength, while higher contents ($35 - 45\, wt\%$) dramatically increased stiffness, hardness, and impact resistance. Tensile strength decreased with fiber, but the composite modulus was greatly improved. DMA showed that the reinforced composites have lower damping and higher effective Tg, confirming improved thermal stability. These dual-reinforced LDPE composites thus transform plastic waste into panels that are lightweight, moisture-resistant, and structurally robust. By valorizing two waste streams (plastic and paper) in a circular design, this work demonstrates a novel route toward eco-efficient partition materials. Future work may optimize fiber treatments and explore long-term durability.

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