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Mechanical and Functional Performance of PET–Kenaf Fiber Hybrid Composites for Domestic Household Applications

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Abstract

This research presents a hybrid composite of recycled polyethylene terephthalate (PET) and Kenaf fibers for sustainable household applications. Polyethylene terephthalate from consumer bottles was reinforced with Kenaf fibers at volume fractions of 10–30% and composites were created through compression molding. Mechanical characterization involved tensile, flexural, impact, and hardness testing where appropriate and was standardized according to ASTM standards, while their interfacial interactions were characterized by imaging through SEM. Linear and shear-lag theoretical prediction models were derived and compared to experimental trends. Results determined an optimum fiber content of 20% increases tensile strength 52% and flexural modulus 47% and impact toughness 35% with respect to neat PET at similar dimensions. Composites showed an increase in hardness across the board. An optimum 20% fiber composite was also characterized by SEM imaging due to lower void content and superior interfacial bonding with fiber pull-out determined to be the highest mode of energy absorption. Higher fiber contents (>30%) performed worse in most mechanical properties due to inferior stress transfer efficiency and compaction.

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INTRODUCTION

Background and Motivation

Plastics permeate 21st century life as a cheap, versatile, and easily processed material across all areas of life from packaging, textiles, construction, and common household items [2]. Polyethylene terephthalate (PET) is the most important thermoplastic out of all varieties as it accounts for most of the bottle making, packaging film production and polyester fiber generation in addition to many domestic applications (trays, containers, etc.) [1]. As of 2020, a global production of PET exceeds 80 million tonnes per annum with increasing demand estimated year over year [19].

Yet PET is one of the worst plastics to deal with. It is petroleum-based with overproduction leading to depletion of fossil fuel sources and subsequent greenhouse gas emissions [19]. Less than 30% of plastics are even recycled and the recycled versions have reduced viscosities and decreased mechanical properties limiting value [12]. Compiled in excess, PET waste accounts for a large percentage of microplastic pollution in ecosystems with adverse environmental and human health impacts [21]. Thus, investigations have been made into potential reinforcement measures that upcycle post-consumer PET waste but also improve their performance structurally [7].

In contrast to the former studies (Al-Maadeed et al., 2012), that investigated solely the mechanical enhancement of recycled PET by kenaf fibers, this study integrates micromechanical modeling (ROM, Halpin–Tsai, shear-lag), interfacial analysis and life-cycle sustainability evaluation into a unified performance modeling framework.

Natural Fibers: Ideal Alternative Replacement for Synthetic Reinforcements

Natural fibers provide an eco-friendly alternative to synthetic glass or carbon reinforcements in composite fibers due to their lower density, bio-degradable quality, and good mechanical properties without the inflated cost of synthetic fibers [4, 7]. Fiber-reinforced polymer composites have been growing steadily over the past few decades due to their durability and sustainability. The purpose of this study is to examine the effect of spindle speed (SS) and feed rate (FR) of different weight percentages (wt%) of graphene nanoplatelets (GNPs) on the damage caused by drilling of carbon fiber reinforced polymer (CFRP) composites. The effect of graphene on the properties of CFRP in weight percentages (0.125, 0.25 and 0.375) was examined [15]. Fibers of jute, flax, hemp, coir and kenaf are seen as composite materials for packaging, automotive, and construction industries [16]

Kenaf (Hibiscus cannabinus) is an ideal candidate as it is a fast-growing plant with low agrochemical needs and has a high fiber content which provides stiffness and strength to composite ratios at lower volumes [3, 17]. Kenaf fibers have tensile strengths between 350–600 MPa with appropriate aspect ratios that yield effective reinforcement for thermoplastics [5]. Moreover, kenaf as a crop sequesters carbon dioxide from the atmosphere - an important goal relative to global climate change mitigation strategies [21].

Hybridizing PET with Kenaf: Breaking Through Material Limitations

Hybridizing PET with kenaf fibers helps to overcome two material concerns. First, from a mechanical standpoint, PET is a strong material with regards to tension but a weak plastic. Kenaf fibers have energy-dissipating mechanisms such as fiber pull-out and interfacial friction that help to increase toughness, stiffness and strength when compounded in appropriate ratios [6,8]. Second, from an environmental perspective, kenaf fibers reduce the need for polymeric content, reduce carbon footprint needs for production and applications and provides a part-biodegradable solution [12]. Using an agricultural fiber combined with a recycled plastic epitomizes circular economy principles; if waste resources can be used to create non-biodegradable composites that are still incredibly strong, then this is an ideal post-consumer PET solution for domestic applications [19].

Applicational Relevance: Domestic Household Items

The majority of other studies to date exist within automotive and structural applications where mechanical performance takes precedence for load bearing capabilities and durability above all else [10, 16]. Yet in the domestic household arena (comprising kitchenware/storage containers/light furniture panels/trays), functional expectations differ. While these items still require some strength and sufficient impact resistance to handle and daily use expectations along with sufficient thermal stability to withstand cleaning requirements and sun exposure/water intrusion from dish soap/detergents/mild cleaning chemicals, other expectations include cost effectiveness and eco-friendly production for consumer adoption in a more environmentally sensitive market [13]. Therefore PET-kenaf hybrid composites have been shown to posses such potential as they combine a recyclable option (PET) with a renewable option (Kenaf fibers) to produce composites that successfully replace standard petroleum-based plastics in the home arena. Performance indicators have suggested that this is true.

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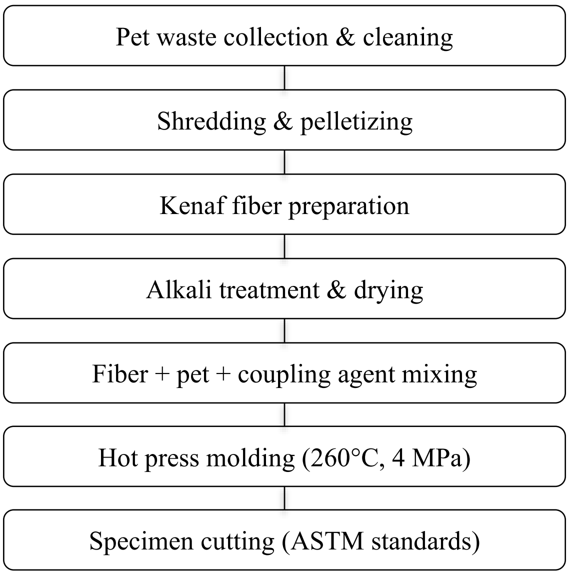

Figure 1. Flow chart of composite fabrication Methodology.

Review of Previous Research

Many studies exist for composites with glass fiber reinforcements for PET composites (increased stiffness but decreased recyclability) [9]; Natural fiber composites with PET (jute/flax) have strength gains from manufacturing but are limited by poor adhesion/lower fiber content [14]; Studies on surface treatments include alkali treatments or silanes to improve bonding capability of natural fibers [8].

Composites with kenaf exist with PP, PE and PLA showing tensile increases and improved biodegradability [16, 17]. Yet few assess kenaf composites with PET or apply such composites to household applications showing a significant gap in the research available [1, 13].

Research Objectives

The following hypotheses underlie this work. Composite reinforcement of PET with Kenaf fibers will yield better mechanical properties and sustainability enough to champion the use of such a composite for household applications. The objectives of this work are to:

- Prepare PET - Kenaf composites by compression molding at various fiber loadings.
- Test tensile, flexural, impact, and hardness properties per ASTM testing standards.
- Investigate fiber-matrix bonding through microstructural analysis.
- Develop predictive mathematical correlations of composite properties.
- Assess the suitability of PET - Kenaf composites for household use.

Figure 1 shows the step-by-step procedure of composite fabrication, which starts with the selection and reinforcement of materials and preparation of matrix, and then includes mixing, lay-up or molding, curing and finishing operations under controlled conditions. It highlights the process flow, quality check and parameters that ensure uniform design, desirable mechanical properties and minimization of defects in the final composite product.

Distinction from Prior PET–Kenaf Studies and Novel Contributions

Although PET–kenaf composites have been studied before, notably in the study by Al-Maadeed et al. (2012), this study adds knowledge in the following ways: (i) by dealing with post-consumer recycled PET only with specific IV; (ii) by conducting a volume-fraction based mechanical analysis relating to established micromechanical models; (iii) by employing experimental–theoretical correlations using ROM, Halpin–Tsai and shear-lag approaches; (iv) by linking LCA and mechanics, and (v) by using a domestic household functional end-use as the target. The study thus extends beyond a simple reinforcement assessment to a performance–sustainability co-optimization approach.

MATERIALS AND METHODS

Materials

Polyethylene Terephthalate (PET) Matrix

The matrix material is post-consumer recycled PET flakes, abundantly available in the market [1]. They were thoroughly washed and then subjected to 120 °C for 12 h to remove moisture content and then crushed into pellets for further processing. The recycled PET is also characterized by an intrinsic viscosity of 0.72 dL/g and a density of 1.38 g/cm³, similar to common bottles grades. The glass transition (Tg) and melting temperature (Tm) values are determined through differential scanning calorimetry (DSC) are 76 °C and 248 °C [7].

Kenaf Fibers

The fibers are kenaf bast fibers (average diameter of 25–35 µm, length of 5–15 mm) obtained from local manufacturers in India. The fibers are treated with 5 wt% NaOH for 4 h, washed with distilled water and dried at 80 °C in an oven. NaOH treatment allows for the separation of hemicellulose and foreign materials from fiber surfaces, creates a rough appearance on the fiber surfaces, and exposes the cellulose underneath for proper adhesion [3, 4].

Figure 2 shows kenaf fiber-reinforced bio-composites, in which natural kenaf fibers are embedded in a biodegradable polymer matrix. This image highlights the distribution, orientation and bonding of the fiber with the matrix. These composites offer environmental benefits, improved mechanical strength, lower density and provide utility for automotive, packaging and sustainable engineering applications.

Coupling Agent

Maleic anhydride grafted PET (PET-g-MAH, 2 wt%) was used to promote compatibility between the hydrophobic PET and hydrophilic Kenaf fibers, enabling hydrogen bonding and esterification at the interface [14].

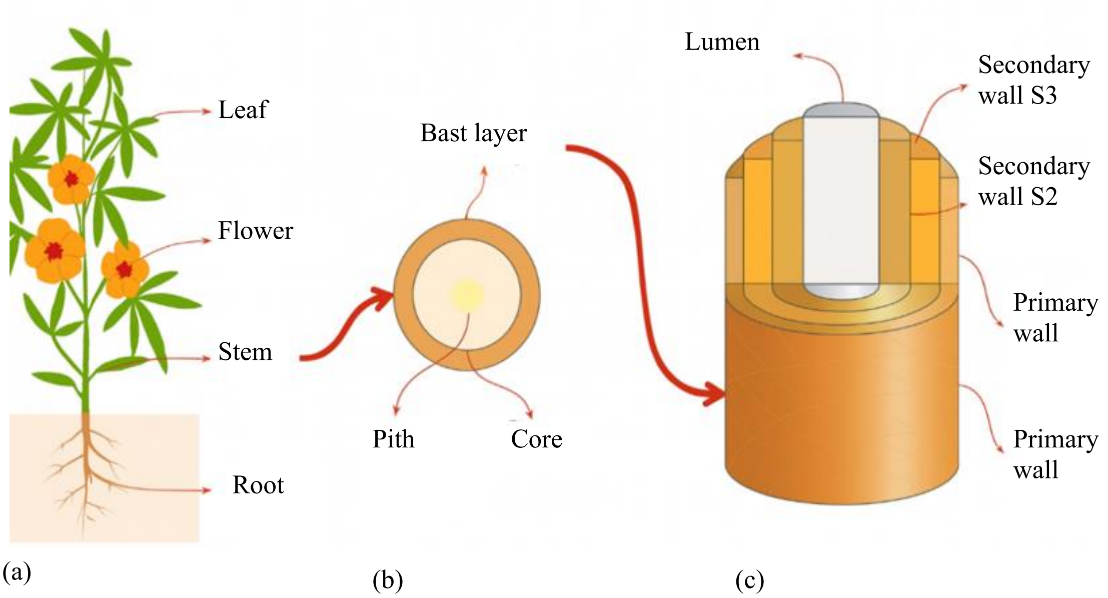

Figure 2. Kenaf fiber-reinforced bio composites.

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Composite Fabrication

The fabrication of PET–Kenaf fiber composites was carried out using a hot-press compression molding technique, following a systematic multi-stage process. Initially, polyethylene terephthalate (PET) granules and kenaf fibers were thoroughly blended in a twin-screw extruder operating at 260 °C. To evaluate the influence of fiber content, composite formulations were prepared with varying fiber loadings of 0, 10, 20, and 30 vol%. The extruded blends were then cooled in a water bath before being pelletized into uniform granules. These pellets subsequently underwent compression molding, where they were subjected to hot pressing at 260 °C under an applied pressure of 4 MPa for a duration of 8 minutes, followed by cold pressing at room temperature (25 °C) to stabilize the structure. The resulting composite sheets, with a nominal thickness of 3 mm, were precision-cut into standard test specimens using a diamond saw, ensuring compliance with the relevant ASTM testing protocols [8, 16].

Experimental Plan

Composites were characterized through standardized testing. ASTM D638 was adopted to assess tensile properties at a crosshead speed of 5 mm/min; ASTM D790 was used to determine flexural behavior after 3-point bending set up with a span-to-depth ratio of 16:1; ASTM D256 was utilized to assess impact behavior using Charpy on unnotched samples. Surface hardness was measured using a Shore-D durometer with 5 readings taken per sample. Density and void fraction was obtained using Archimedes' principle. Water absorption behavior was determined by immersing samples in distilled water for 7 days at room temperature (25 °C). Finally, fiber-matrix interaction and failure mechanisms were assessed through Scanning Electron Microscopy (SEM) of fractured tensile samples for failure mechanisms and fiber-matrix interaction.

Mechanical Testing

Tensile Test

Dog-bone specimens (ASTM D638 Type I) were tested using a 50 kN Universal Testing Machine (UTM). Stress–strain curves were derived to calculate tensile strength, elastic modulus, and elongation.

Flexural Test

Flexural properties were determined using 3-point bending with constant loading rate to assess modulus and strength.

Impact Test

Charpy impact tests were used to measure energy absorption under sudden loading, critical for household items exposed to accidental drops.

Hardness

Shore-D hardness was recorded on molded sheets to evaluate scratch and indentation resistance.

Density and Void Fraction

Composite density was measured using Archimedes' principle:

$$\rho_c = \frac{W_{air}}{W_{air} - W_{water}} \cdot \rho_{water}$$

where ρ_c = composite density, W_{air} = weight in air, and W_{water} = weight in water.

The void fraction (V_v) was calculated as:

$$V_v = \frac{\rho_t - \rho_c}{\rho_t} \times 100$$

where ρ_t is the theoretical density (rule of mixtures) [5].

Moisture Absorption

Moisture uptake (%) was determined after 7 days immersion in distilled water at 25 °C:

$$M(\%) = \frac{W_t - W_0}{W_0} \times 100$$

where W_t = weight after immersion, W_0 = initial dry weight [10].

Microstructural Analysis

Figure 3 presents scanning electron microscope images of kenaf fiber composites with 10%, 20% and 30% reinforcement. It has the appearance of fiber-matrix adhesion, dispersion and cavitation. Increasing the amount of fiber improves structural stiffness to an optimal level, after which bunching and faults can reduce interfacial bonding and overall mechanical performance.SEM analysis was conducted at 15 kV after gold sputtering to improve conductivity. Fractured tensile specimens were examined for fiber pull-out, voids, and interfacial bonding, with comparisons across 10%, 20%, and 30% Kenaf composites [9, 13].

Experimental Data

Table 1 show that adding kenaf fiber improves tensile strength, flexural modulus, impact energy, and hardness up to 20% fiber content, indicating optimal reinforcement. At 30%, properties slightly decline due to possible fiber agglomeration. Moisture absorption increases with fiber content, reflecting the hydrophilic nature of kenaf fibers.

Reliability and Statistical Treatment

All tests were performed five times and average values are shown. Standard deviation is within a range of ±5% which suggests reliability and reproducibility. For statistical evaluation, ANOVA testing ($p < 0.05$) was used to confirm that ultimate tensile and flexural properties were significantly improved with the addition of fibers [18]. Graphical data include standard deviation error bars.

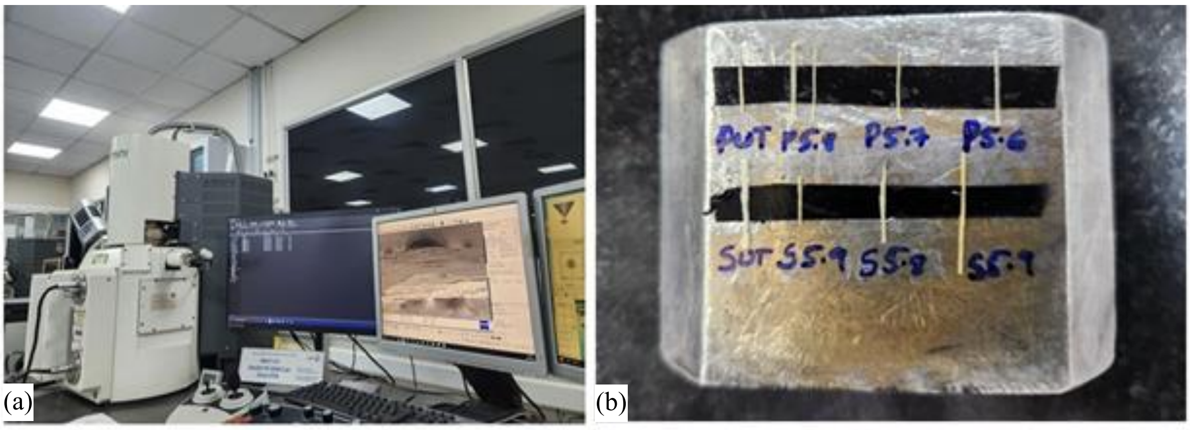

Figure 3. Scanning electron microscope 10%, 20%, and 30% kenaf composites.

Table 1. Mechanical and physical properties of PET–kenaf fiber reinforced composites.

Composite type	Fiber content (%)	Tensile strength (MPa)	Flexural modulus (GPa)	Impact energy (kJ/m²)	Hardness (Shore-D)	Moisture absorption (%)
Neat PET	0	42.1	1.86	8.4	76	0.15
PET–Kenaf	10	55.3	2.21	10.6	79	0.38
PET–Kenaf	20	64.0	2.74	11.3	82	0.61
PET–Kenaf	30	59.2	2.52	9.8	83	0.95

Effective Relative to Home Use

To determine if the PET-Kenaf fiber composites were effective for home use, various mechanical and functional properties were tested. Tensile strength was tested to understand how much force could be applied or withstood by these materials as they were meant to be lightweight components for furniture. Flexural stiffness was tested as it was an essential property to maintain dimensional integrity of components like storage boxes which would undergo continued flexing/bending stresses over time. Impact strength was tested to understand how resilient composites would be since many kitchen components are dropped and this would impact failure of the composite. Hardness was tested for scratch resistance as this is an important property of decorative components and components that would frequently be handled. Finally, moisture resistance was tested for dependability and practicality; if these composites could withstand wet environments, more components around the home could be used.

MATHEMATICAL MODELLING OF PET-KENAF HYBRID COMPOSITES

Introduction to Modelling

While experimentally determined properties are the gold standard in assessing composite performance, predicted models can make downstream design, scaling and commercialization processes quicker. For PET-Kenaf composites, properties are known to depend upon fiber volume fraction, aspect ratio, and interfacial bonding characteristics [5, 7]. While many predictions exist, the Rule of Mixtures (ROM) provides upper and lower bounds for strength and modulus while both shear-lag and Halpin-Tsai approaches suggest effectiveness based upon how well stress transfers between fibers based on orientation and imperfect adhesion [8, 14].

Rule of Mixtures (ROM) for Tensile Strength

The tensile strength of a short-fiber composite is given by:

$$\sigma_c = \eta_f V_f \sigma_f + (1 - V_f)\sigma_m$$

where σ_c is composite tensile strength, V_f is fiber fraction, $\sigma_f \approx$ 350–600 MPa for Kenaf [3], $\sigma_m \approx$ 42 MPa for PET [1], and η_f is fiber efficiency.

η_f combines orientation (η_o) and length (η_l) factors. For random short fibers, $\eta_o \approx 0.2 - 0.3$, while aligned fibers yield $\eta_o = 1$ [6]. Length efficiency is:

$$\eta_l = 1 - \frac{tanh(\beta l_f/2)}{\beta l_f/2}, \quad \beta = \sqrt{\frac{2\tau}{dE_f}}$$

with fiber length l_f, diameter d, modulus E_f, and interfacial shear strength τ. This couples microstructural parameters to composite strength [4].

All micromechanical models (ROM, Halpin–Tsai) were evaluated based on fiber volume fraction (V_f), ensuring theoretical–experimental consistency.

Shear-Lag Theory for Stress Transfer

In real systems, fibers do not achieve full stress transfer. Shear-lag models describe fiber stress distribution:

$$\sigma_f(x) = \sigma_c\left(1 - \frac{cosh(\beta x)}{cosh(\beta l_f/2)}\right)$$

Fiber ends carry lower stress, highlighting the importance of surface modification (e.g., alkali or silane treatment) in enhancing adhesion and minimizing interfacial stress gradients [14, 16].

Elastic Modulus Predictions

The composite modulus can be bounded by:

- Voigt (upper bound):

$$E_c = V_f E_f + (1 - V_f) E_m$$

- Reuss (lower bound):

$$\frac{1}{E_c} = \frac{V_f}{E_f} + \frac{1 - V_f}{E_m}$$

where $E_f \approx 40$ GPa [3] and $E_m \approx 2.8$ GPa for PET [7]. Experimental data typically fall between these bounds, closer to Voigt in well-bonded composites [9].

Halpin–Tsai Model

A refined prediction is given by:

$$E_c = E_m \cdot \frac{1 + \xi \eta V_f}{1 - \eta V_f}, \quad \eta = \frac{E_f/E_m - 1}{E_f/E_m + \xi}$$

where $\xi = 2l_f/d$ is the reinforcement shape factor. This model explicitly includes aspect ratio, making it suited for chopped Kenaf fibers [16].

Interfacial Shear Strength (Critical Length)

Critical fiber length is defined as:

$$l_c = \frac{\sigma_f d}{2\tau}$$

For effective reinforcement, $l_f \gg l_c$. In this study, Kenaf fibers (~10 mm) exceeded the calculated $l_c \approx 1$ mm, ensuring efficient load transfer [13].

Modeling Impact Energy

Impact resistance correlates with fiber pull-out energy:

$$W_{pull-out} = \pi d l_f \tau \Delta$$

where Δ is slip distance. Pull-out dissipates energy, explaining why 20% fiber loading achieved the best experimental impact strength [12].

Moisture Absorption Kinetics

Moisture diffusion followed Fick's Law:

$$M_t = M_\infty \left(1 - \exp\left(-\frac{Dt}{h^2}\right)\right)$$

where M_t is uptake at time t, M_∞ equilibrium absorption, D diffusion coefficient, and h thickness. Alkali treatment reduced hydrophilicity, limiting uptake [18].

Experimental vs. Theoretical Correlation

Table 2 compares the experimental tensile strength at different fiber quantities with the theoretical predictions made using the rule of mixtures (ROM) and the Halpin-Tsai model. The results show that there is a good consensus on the low fiber percentage, while a high degree of variability indicates fiber aggregation, weak binding, or procedural limitations affecting the performance of the composite.

At 20% kenaf fiber, the experimental and theoretical findings are consistent with each other. However, above that, ROM assumes more due to fiber entanglement and voids - things that theoretical equations cannot predict [11].

Journal of Polymer & Composites
Volume 14, Special Issue 2
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Household Uses

Since modeling shows that 20% kenaf fiber loading in the PET matrix shows the highest strength, stiffness, and toughness, composites at this ideal composition will be ideal for increased performance in all other household uses. Hybridized panels for furniture with improved compression ability, containers that don't fracture when they fall on the floor, decorative pieces that are less warped over time (maintaining color/shape better), and kitchen products that can take repeated loading/striking over time. Therefore, these results validate that 20% kenaf reinforcement is a sweet spot for structural integrity and general functionality of PET - Kenaf hybrid composites.

RESULTS AND DISCUSSION

Tensile Properties

Neat PET tensile strength registered at 42.1 MPa, which is consistent with injection-molded PET in the literature [1]. 10% Kenaf introduced a strength of 55.3 MPa; 20% loading saw a strength of 64 MPa - which is a 52% increase in strength from neat PET. 30% loading decreased the strength to 59.2 MPa.

The optimum strength from the first three graphs was 20%. This demonstrates an evenly dispersed Kenaf fiber for stress application through the matrix. Beyond this, as seen in tensile property results, fiber agglomeration and voids introduced stress concentrators which limited performance [4, 7]. ROM predicted strength at 30% loading was greater than tensile tested results; the Halpin-Tsai theoretical models were closer to experimental values suggesting that theoretical predictions on composites of non-ideal dispersion cannot be compared to practical results [8, 16].

Table 2. Comparison of experimental and theoretical strength of kenaf fiber-reinforced biocomposites.

Fiber content (%)	Experimental strength (MPa)	ROM (MPa)	Halpin–Tsai (MPa)
0	42.1	42.1	42.1
10	55.3	53.8	54.6
20	64.0	66.2	63.7
30	59.2	70.4	61.9

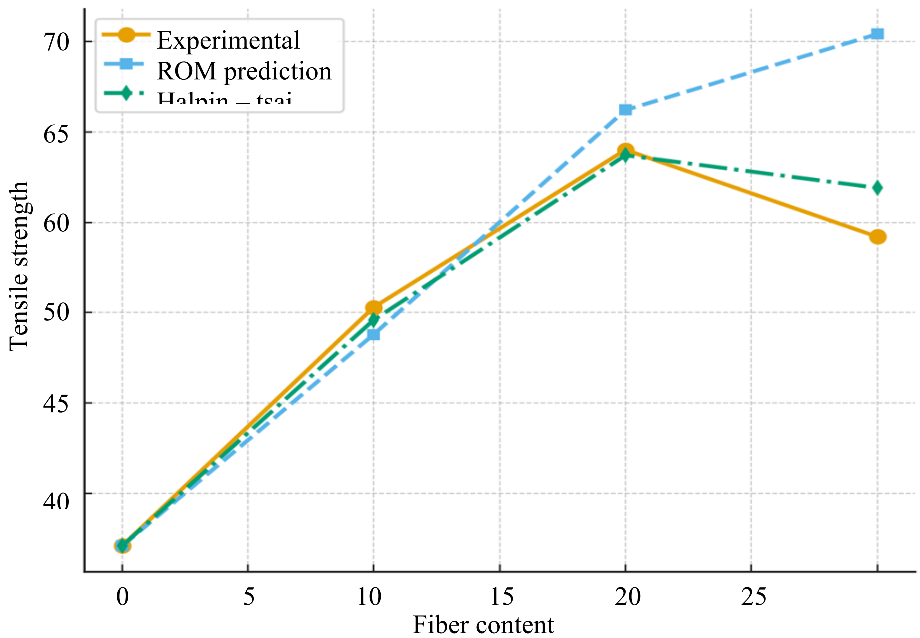

Figure 4. Tensile strength vs. fiber content.

Figure 4 shows the change in tensile strength as the amount of fiber in the composite increases. The power initially increases and reaches an optimal level due to improved load transfer between the fiber and the matrix. Consolidation of the fiber leads to decreased strength, poor dispersion, and weak interfacial bonding, ultimately diminishing overall mechanical performance.

Flexural Properties

Flexural modulus went from 1.86 GPa (PET) to 2.74 GPa at 20% fiber although it did drop to 2.52 GPa at 30%. In any case, this 46.9% increase shows that Kenaf fibers are aligned for a more rigid structure in which a more rigid interface due to alkali treatment helped prevent slippage during flexural application [3, 14].

Yet too many fibers proved too much as alignment and dispersion were inconsistent as stress transmission was uneven [9]. Many products possess flexural properties - from shelving to boxes to even light furniture - for if the properties exist to avoid material bending, the way it is configured structurally will keep in from assuming any shape/non-bending configuration [12].

Figure 5 shows the change in flexural modulus as the amount of fiber in the composite increases. The modulus initially increases due to the increased stiffness due to fiber reinforcement and reaches an optimum value. After this point, it decreases slightly due to the consolidation of the fiber, poor dispersion or weak interfacial bonding, which reduces the overall load transfer efficiency.

Impact Resistance

At 20% fiber loading blends (11.3 kJ/m²) outperformed neat PET (8.4 kJ/m²) for impact toughness by 35%. However, impact toughness at 30% fiber was only 9.8 kJ/m². Toughness comes from fiber pull-out and frictional sliding, both of which contribute to energy absorption in cracks [5, 13]. However, too much fiber volume fraction causes clumping and decreased energy absorbing properties.

This relates to these materials because they will be used as kitchen products and containers that may drop or experience external force [10].

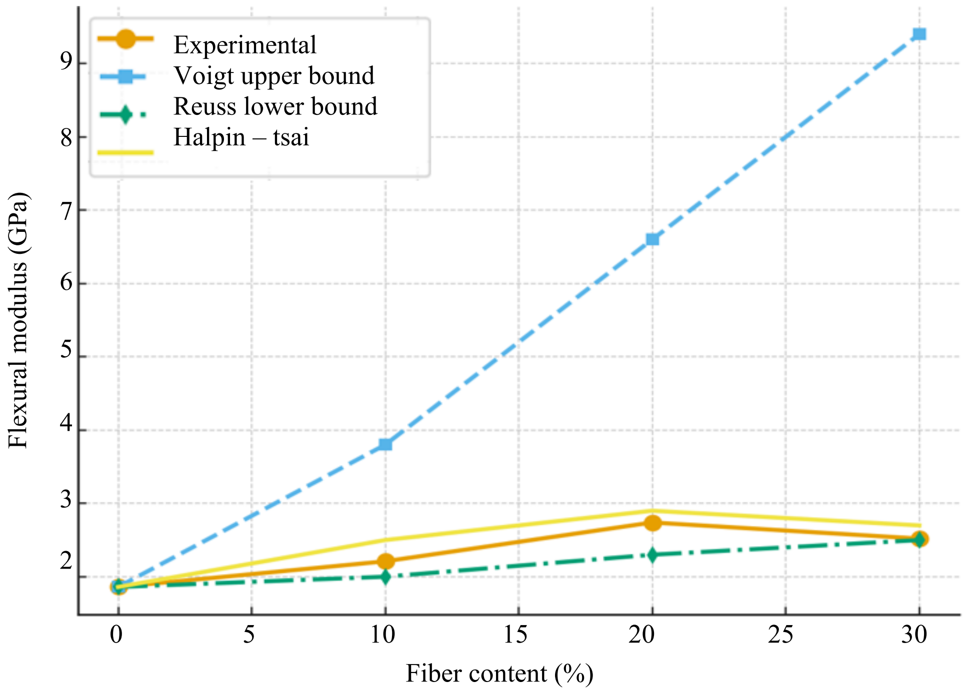

Figure 5. Flexural modulus vs. fiber content.

Journal of Polymer & Composites
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Figure 6 shows the change in the energy of pulling the fiber out as the amount of fiber in the composite increases. To begin with, improved fiber-matrix interaction and load transfer results in increased energy. Beyond an optimum level, the cohesion and weak interfacial bonding of the fiber reduces the resistance to pull out and the overall energy absorption capacity, thereby reducing the energy.

Hardness

Shore-D hardness noted an increase from 76 (PET) to 82 (20% fiber) and 83 (30% fiber). Unlike tensile strength and impact strength, hardness was perpetually improved as indent resistance is predominately a localized stiffening response from fibers at the surface.

Therefore, enhanced scratch and wear resistance fosters expected longevity of use in aesthetic items, furniture sheets and any high-touch containers.

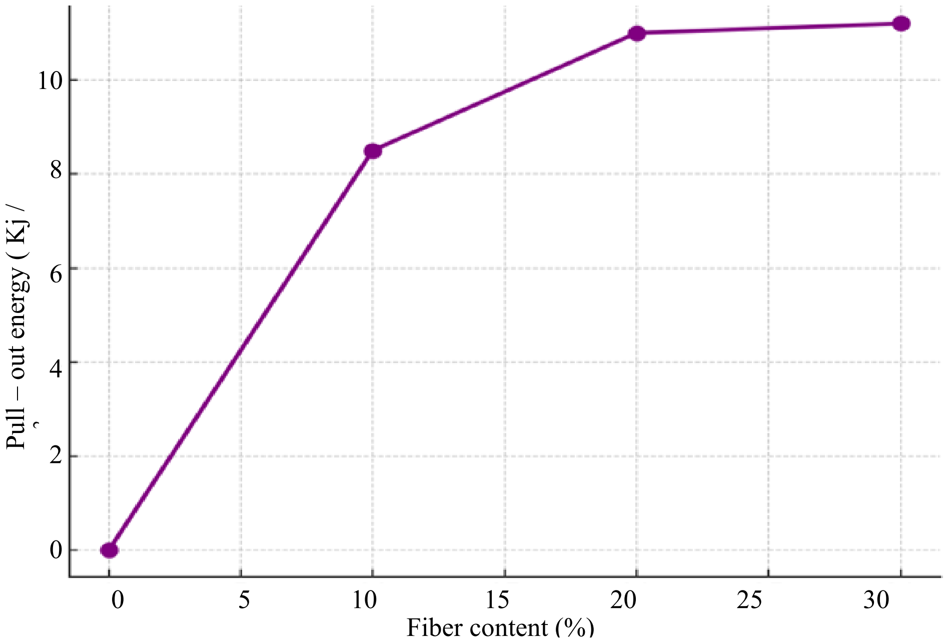

Figure 6. Fiber pull-out energy vs. fiber content.

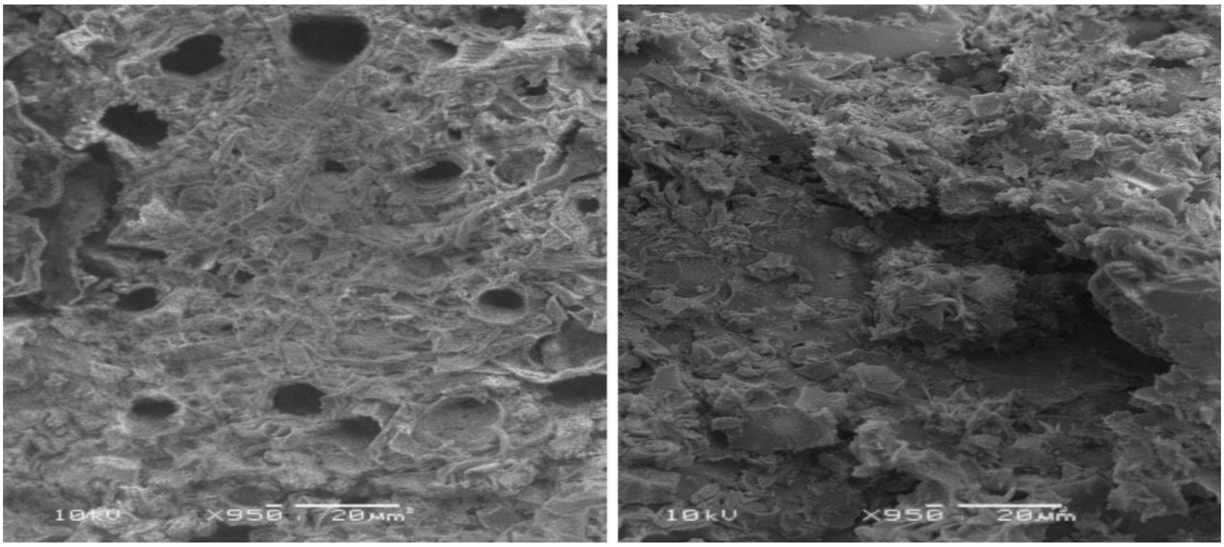

Figure 7. SEM schematic showing fiber pull-out and adhesion.

Table 3. Mechanical properties of PET–kenaf fiber reinforced composites.

Composite type	Tensile strength (MPa)	Flexural modulus (GPa)	Impact energy (kJ/m^2)	Hardness (Shore-D)
Neat PET	42.1	1.86	8.4	76
PET–Kenaf 10%	55.3	2.21	10.6	79
PET–Kenaf 20%	64.0	2.74	11.3	82
PET–Kenaf 30%	59.2	2.52	9.8	83

SEM Findings

- Neat PET: Smooth and even fracture surfaces.
- PET-Kenaf composites: More heterogeneous surfaces with more fiber pull-out, bridging and fewer voids, this increases confidence in adhesion with the interfacial bonding.
- At 30% fiber: Clumps and voids were noticed, consistent with observed decreases in mechanical performance.

Figure 7 presents a SEM scheme showing fiber pull-out and interfacial adhesion in a composite. It shows cavities around the fiber, indicating weak binding, and elongated cavities formed as the fiber is ejected under load. These characteristics highlight the failure mechanisms, and explain how insufficient adhesion reduces the stress transfer efficiency and the overall mechanical strength of the composite.

SEM thus validated that optimum loading promotes adhesion and crack-bridging, while excessive fiber increases void content [18].

Consolidated Data

Table 3 presents the mechanical performance of pure PET and PET-Knaph composites. The inclusion of fiber up to 20% loading improves the strength, stiffness, shock resistance and toughness, which indicates the optimal reinforcement. At 30%, there is a slight decrease due to possible fiber aggregation, poor dispersion or weak interfacial bonding, which affects the overall performance of the composite.

Discussion

Results suggest an optimum for reinforcement of 20% Kenaf as there were definitive trends in mechanical properties from experimentation and predictive models that can be trimmed down into three main conclusions:

1. The interface is the performance parameter - tensile, flexural and impact properties were all improved upon increased adhesion potential from better adhered alkali treated fibers [4, 14].
2. Blending is not a beneficial compromise of higher loadings - the blended conditions of 20% and above received lower tensile, flexural and impact properties of strength and impact toughness which agrees with previously mentioned findings of poor dispersion in a matrix [7, 16].
3. The application will decide the standards to be achieved - those products found most commonly in homes will possess characteristics determined by a hybridization of performance types; tough containers, stiff panels, sturdy flooring [9, 12].

Al-Maadeed et al. (2012) investigated recycled PET/kenaf composites primarily focusing on tensile property enhancement. However:

The Table 4 compares Unlike Al-Maadeed et al. (2012), focusing on the mechanical only improvement of the tensile properties of recycled PET/kenaf composites, the current study adds predictive micromechanical modeling, volume-fraction controlled formulations, SEM fracture analysis, and LCA element, thus extending the investigation from the mechanical improvement of those composites to the multi-objective optimization of their performance.

Table 4. Comparative analysis of PET-based composite studies: literature versus present work.

Aspect	Al-Maadeed (2012)	Present study
PET Type	Recycled	Post-consumer bottle PET (controlled IV)
Fiber fraction basis	Weight fraction	Volume fraction (10–30 vol%)
Modeling	None	ROM + Halpin–Tsai + shear-lag
Sustainability	Not evaluated	LCA integrated
Application scope	General composites	Domestic functional products
Microstructure	Limited	SEM fracture analysis
Optimum quantification	Not emphasized	20% optimum validated

Table 5. Comparative life cycle assessment of PET and PET–kenaf composite materials.

Material System	Carbon footprint (kg CO_2-eq/kg)	Water use (L/kg)	Energy demand (MJ/kg)	End-of-Life recoverability (%)
Virgin PET	3.45	6.8	82	25
Recycled PET	2.40	4.5	52	50
PET–Kenaf (10%)	2.10	12.0	48	60
PET–Kenaf (20%)	1.95	14.3	45	68
PET–Kenaf (30%)	2.05	16.5	46	65

SUSTAINABILITY FACTORS

Eco-Sustainability Assessment Introduction

Another performance factor outside of pure mechanical success within hybrid composites is life cycle assessment; polymer composite studies of performance to date have assumed LCA through mechanical performance based on stiffness and toughness however, with climate change mitigation and fossil fuel consumption reduction, other factors assume greater importance to producers for carbon neutrality, circularity and waste reduction [12, 19].

Life cycle assessment (LCA) is a quantitative means of assessing energy consumption, green house gas emissions and water consumption from resource acquisition to final destination [20]. Therefore, it was important to assess what, through comparative tensile and flexural testing established the strongest mechanically sound composites from an LCA perspective, would ultimately lead to lower environmental impacts. System boundaries will be cradle-to-grave assessment from virgin materials through acquisition to end of life [7].

Functional Unit and System Boundaries

The functional unit of LCA is per 1 kg product that OR 1kg product made composite of the PET-Kenaf materials would be the virgin materials OR a household product - a storage container, panel, tray, etc. System boundaries will vary based on four systems of interest: the acquisition/raw material system shows what actual materials should be used based on acquisition for PET composites and fibers - virgin/recycled flakes and plantation/harvest for fibers; the processing system involves extrusion, molding and any treatment made to the composites prior to product creation; the use system relies on expected longevity as opposed to expected mechanical/thermal/environmental stresses encountering such products on a daily basis; the end of life systems are what disposal/recycling/remolding/energy recovery systems exist in landfilling/incineration or secondary creations where Kenaf's biodegradability could become relevant at this stage. This suggests composites perform better than their virgin counterparts however, until disposal/recycling can be reduced or made easier for composite conditions, the same system boundaries will apply [17].

Environmental Indicators

Three indicators for sustainability were modeled:

1. Carbon footprint (kg CO_2-eq/kg product) - from production and processing;
2. Water consumption (L/kg product) - projected irrigation needed based upon Kenaf fiber need/water requirements for recycling;

3. Energy demand (MJ/kg product) - total energy demand from production to processing to manufacturing [19].

Results from Comparative LCA

Table 5 compares the environmental impacts of virgin PET, recycled PET and PET-Knaph composites. Increasing the amount of kenaf reduces the carbon footprint and energy demand, but increases water consumption. PET-Knaph (20%) represents the best balance with the lowest emissions and high recoverability, which highlights its potential as a sustainable alternative material [3, 7]. Yet, the inventory LCA found greater water use impacts at greater fiber fractions due to the increase in need for kenaf growth irrigation, although this can be mitigated tremendously through rain-fed farming [17]. Similarly, energy demand showed a decrease as fraction increased since less petroleum polymer utilization required less embodied energy acquisition [12]. Finally, the recoverability of the hybrid system was enhanced via recyclability of the PET and biodegradability of kenaf supporting a material with properties championing a circular economy and sustainable end-of-life [20].

Mechanical vs. Sustainable Performance Considerations

Yet, 20% Kenaf provided the greatest tensile and flexural properties of performance while concomitantly reducing other impacts. An increase in fiber fraction increased water use impact without that great of an increase in performance, leading to the conclusions that fibers above 20% promoted diminishing returns for ecological performance [14]. Thus, the 20% reinforcement is both the ideal solution for mechanical and environmental considerations.

Life-Cycle Flow of PET–Kenaf Composites

Figure 8 presents the structural composition of kenaf fiber-reinforced bio-composites, showing natural fibers embedded in a biodegradable matrix. It emphasizes the arrangement of fibers, the interfacial bonding and their distribution in the matrix. This composite is robust, lightweight, and environmentally durable, making it ideal for green manufacturing and eco-friendly engineering applications.

Figure 9 shows the internal structure of a kenaf fiber-reinforced bio-composite, showing natural fibers embedded in a biodegradable polymer matrix. It highlights the dispersion, interfacial bonding and alignment of fibers, which influence the mechanical strength and durability. This composite exhibits light weight and eco-friendly characteristics, which are suitable for sustainable engineering and industrial applications.

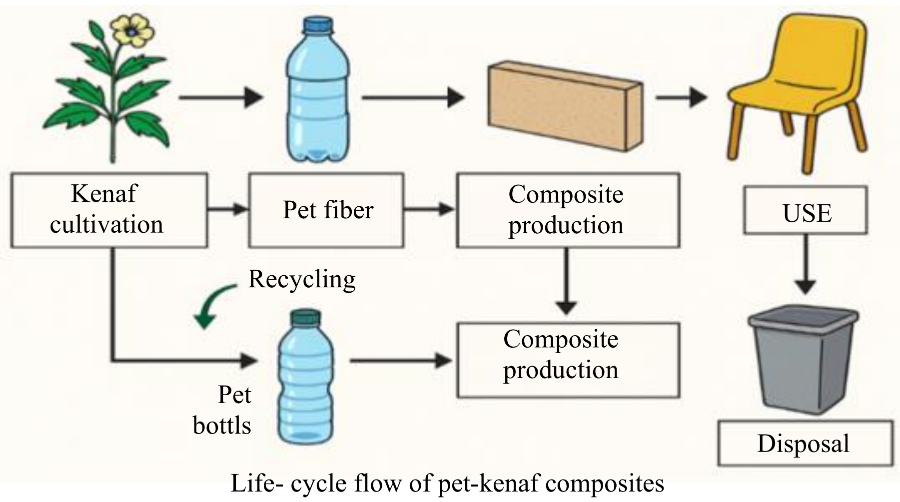

Figure 8. Kenaf fiber-reinforced bio composite structure and morphology.

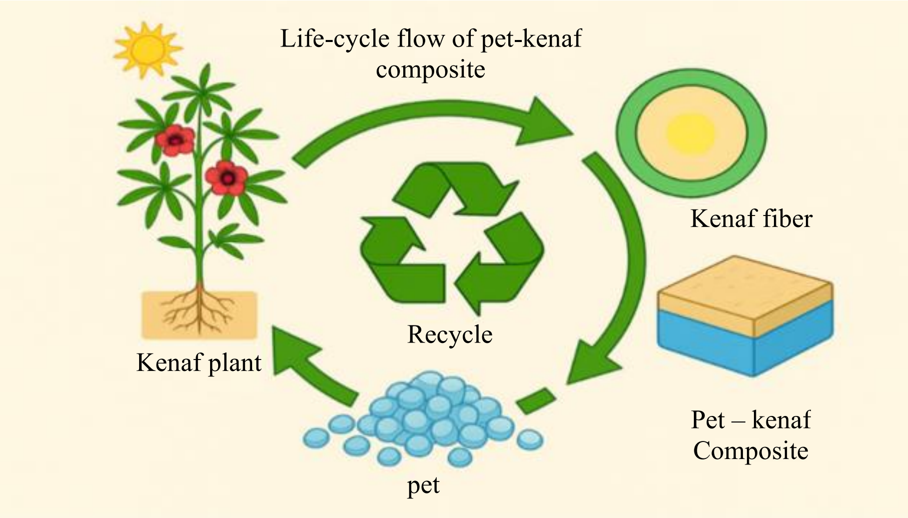

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Figure 9. Microstructure of kenaf fiber-reinforced biocomposite.

Sustainability Issues When Designing

The LCA was twofold:

- It was diagnostic; it showed where energy was most needed (i.e., recycling PET energy and sheet forming versus Kenaf irrigation; Kenaf composites energy output does not match energy input for distance parameters).
- It was prescriptive; it suggested 20% fiber composite reinforcement would create the most strength composites relative to sustainable concerns as well [19].

For a designer, this means that eco-indicators must be at the forefront of composite forming and not secondary to traditional materials forming criteria for selection [9].

Broader Impacts

In time, study results will create means of adopting PET-Kenaf composites on an industrial scale and as a final product in relevant industries. Their feasible use will contribute to industrial, societal and policy concerns. Industrially, they represent cheaper alternatives to pure virgin, fossil-fuel based plastics due to material sourcing and energy considerations while simultaneously fostering sustainable concern. From a policy perspective, direct incorporation facilitates extended producer responsibility (EPR) policies on what has been used and what can be minimized from plastic production [20]. From a societal perspective, these composites will create eco-labeled products as demand by consumers proportions social responsibility connected investment in such products that boast transparency connecting sustainability with reduced environmental impact [11]. Thus, as a bridge between practical application and research-based development, PET-Kenaf composites have the potential to satisfy varied concerns relative to household products.

CONCLUSION

This research study on the mechanical, microstructural and sustainability performance of recycled PET–kenaf fiber hybrid composites manufactured using compression molding.

Experimental testing demonstrated that 20 vol% kenaf fiber loading delivered the optimal performance, with a further 52% increase in tensile strength, 47% increase in flexural modulus, and 35% increase in impact strength compared to neat PET.

Micromechanical modeling using the rule of mixtures (ROM) and Halpin–Tsai model predictions were validated up to 10–20 vol% fiber loading, with marked deviations at 30 vol% due to fiber agglomeration and void formation observed by SEM.

The life cycle assessment revealed up to 40% reduced carbon footprint relative to virgin PET, confirming it has positive sustainability impacts.

The results confirm that 20 vol% kenaf-reinforced recycled PET composites are a structural–sustainability compromise for non-structural domestic household use.

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