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Eco-friendly composites from waste materials

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ABSTRACT

Rising agricultural and plastic wastes pose a severe environmental problem, as the plastic and agricultural wastes need to be valorized in sustainable ways. Recycled sources of low-density polyethylene (LDPE) were used in this experiment as a matrix, whereas rice husk powder, groundnut shell powder, and recycled high-density polyethylene (HDPE) flakes were used as fillers. Agricultural fillers were treated using alkali (NaOH) to offer improvement in adhesion as well as dispersion in the polymer matrix and the interfacial adhesion. The process of making composites was carried out through blending using mechanics, after which they were subjected to compression molding. Detailed characterization was performed in order to determine the mechanical, thermal, and morphological behavior of the developed composites. By using the test/mechanical test by ASTM specifications, it was noted that the alkali-treated fillers resulted in substantially better tensile strength, flexural strength, impact resistance, and Shore D hardness as compared to the untreated group. Stability to thermal and crystallinity tests was determined by carrying out by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC), respectively, where results showed that the composites treated had increased decomposition temperatures and crystallization behavior. These results were also supported by scanning electron microscopy (SEM) that showed homogeneous dispersion of fillers as well as increased bonding between the filler and the sample as a result of alkali treatment. WAB, measured according to ASTM D570, indicated a lower uptake on treated composites, and this indicated the existence of a more compatible filler-to-matrix system. Also, an upfront life cycle assessment (LCA) showed probable decreases in carbon footprint and resource utilization because of the incorporation of waste-based fillers. This paper finds that the hybrid filler systems, made of agricultural and plastic waste, when treated, can be utilized as a simple modality to achieve a high-performance, sustainable polymer composite performance that can be used for structural and packaging purposes.

Keywords: recycled LDPE, agricultural waste fillers, alkali treatment, polymer composites, mechanical properties, thermal stability.

INTRODUCTION

Industrialization and urbanization have affected the world by generating solid waste that has placed a dire, serious challenge on the environment and health of the population. Lignocellulosic by-products that the waste stream includes are post-consumer plastic waste and agricultural residues, including rice husk, coconut shells, groundnut shells, and other forms of agricultural by-products, which make up a significant part of the global solid waste streams. Most of these wastes end up being incinerated or dumped in the land, contributing to greenhouse emissions, soil pollution, and wastage of the useful resources in most development regions. Traditional means of disposing of waste are gaining critics with regard to being unsustainable, since not only do they negatively affect what is happening to the environment, but they also squander the potential value of the waste as a secondary source (Cabrera, 2021). Values of circular economy and sustainable material management in circular economy and sustainable material management focus on the reproduction of added-value goods and services out of waste and hence, decrease the extent of reliance on virgin raw materials as well as the carbon footprint. The composites made of waste fit in this sustainability model by turning the low-cost waste that was abundantly available to serve a wide range of purposes. The new policy frameworks and global sustainability targets, such as the United Nations Sustainable Development Goals (SDGs), promote the implementation of the waste utilization strategies in the production of materials, which pushes both governments and researchers even more towards making such composites based on the waste resources ecofriendly (Mitra, 2014).

A proper choice of a polymer matrix was also a critical way by which the performance and sustainability of waste-derived composites can be determined. Low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polyethylene terephthalate (PET), and other conventional petroleum polymers have made up the greatest numbers of matrices because of availability, processability, and mechanical stability. Nevertheless, their non-biodegradable content and the fact that they are based on fossil resources lead to environmental concerns, and the research of recycled as well as bio-based materials was underway (Aiduang et al., 2022). The more cost-effective matrices used in recycling thermoplastics are the packaging wastes and post-consumer items that have been recycled into thermoplastics. They have the advantage of aiding in reduction of wastes, besides conservation of resources. Experiments have stated that LDPE and PP that have been recycled when reinforced with either natural materials or waste material fillers provide the same robustness as the polymers that are new in terms of their mechanical performance and are more environmentally friendly in terms of metrics. Other forms of bio-based, biodegradable, and renewable polymers, like polylactic acid (PLA), polyhydroxyalkanoates (PHA), and starch plastics, are also explored, but they are more costly and thermally unstable than petroleum-derived plastics, which limits their large-scale use. Usage of waste fillers in the recycled or partially bio-based polymer matrices falls within the comprehensive approaches to sustainable development, minimizing the presence of environmental effects with no loss of functional performance. Recent studies focus on the hybrid matrices that are made using a blend of recycled plastics and bio-based resins in order to obtain an optimal compromise between durability, cost, and environmental friendliness and can hence be used in semi-structural applications (Agarwal et al., 2020).

The industrial by-products or agricultural residues have become a much-sought-after reinforcing filler of polymer composites because of their high availability, cheap price, and the fact that they are renewable resources. Some of the materials that contain a significant proportion of lignocellulosic components include rice husk, wheat straw, coconut shell powder, groundnut shells, jute, and banana fibers, and when these are integrated within matrices containing polymers, they gain moderate mechanical strength and stiffness. Tensile reinforcement was due to the presence of cellulose, hemicellulose, and lignin and the thermal stability of the composites. However, since the hydrophilic character of these agricultural wastes tends to cause a weak interfacial adhesion between them and hydrophobic polymer matrices, it implies low mechanical performance. In order to meet this challenge, different methods of surface modification have been utilized to enhance the filler-matrix compatibility, including alkali treatment, silane coupling and acetylation, and the increase of surface roughness as well as elimination of amorphous materials such as lignin and hemicellulose (Girijappa et al., 2019). Accounts being given by literature indicate that reinforced composites made with treated rice husk or coconut coir reported superior tensile and flexural results than those made with untreated fillers. The particle size reduction and optimum filler loading are other very important parameters affecting the dispersion and the efficiency of stress transfer. Other than contributing to the performance of the composite at a relatively reduced cost, the use of agricultural wastes serves as a sustainable source of solution to agro-residue management (Ali et al., 2021a).

The developed sustainability composites can be reinforced by plastic and industrial wastes, as they are widely available and show desirable mechanical properties. The recycled thermoplastic wastes generated during post-consumption recycling, like recycled HDPE, PET flakes, and polypropylene wastes, have been used to enhance the stiffness, impact, and dimensional stability of thermoplastic matrices in conjunction with enviromental stress-related burdens on plastic. Some alternative cost-effective fillers have also been considered, such as industrial by-products (fly ash, slag, rubber tire powder, and e-waste fibers), which have been found to give enhanced thermal stability and wear resistance to composite uses. The addition of fillers, such as finely ground plastics and industrial wastes normally enhances the density and hardness of composites, which are applicable in constructions and automobile components (Ali et al., 2021b). The difficulties of inadequate dispersion, agglomeration, and ineffective interfacial bonds between hydrophobic polymer matrices and some inorganic filler are a key factor. These shortcomings have been said to be reduced by surface treatment of fillers, addition of compatibilizers, and improved processing conditions, leading to enhanced stress transfer and homogenous distribution of fillers. The reuse of plastic and industrial waste as reinforcement would keep much of the waste out of landfills and contribute to circular economies, as the end-of-life material would be used to create economically useful products (Suresh et al., 2020).

The high research interest attracted by hybrid and natural fiber-reinforced eco-composites was related to their potential of attaining the optimum balance of mechanical performance, cost-effectiveness, and environmental sustainability. Hybridization refers to the mixture of two or more kinds of natural fillers or waste fillers, e.g., using rice husk and jute fibers together or coconut coir and recycled PET flakes to benefit from the advantages of both types of reinforcements. Experiments demonstrated that hybrid composites agree with the better tensile and flexural strength than unit systems because of synergistic trends occurring between particulates and fibers that can maximize stress carryover and crack integrity (Yashas Gowda et al., 2023). Jute, sisal, hemp, and banana can also be used naturally in an attempt to enhance impact strength and toughness but retain lightweight qualities with a combination of agricultural or industrial waste products. Also, hybrid composites have a stronger thermal stability and dimensional integrity than regular composites, so they can be used in semi-structural elements and automobiles. Their behavior greatly relies on the fiber orientation, filler loading rate, and chemical treatments, with exposure to alkali and silane modification being a widely used means of enhancing their interfacial adhesion. Production of hybrid eco-composites complies with the principles of circular economy, as it uses a maximum of waste and minimizes the use of virgin synthetic fibers, thereby providing an alternative to various environmentally friendly engineering applications (Palaniappan et al., 2023).

The manufacturing method was a critical factor in the quality of waste-based composites in regard to the structural integrity, mechanical performance, and the commonly used fire-retardance. The most common ones are related to the conventional process of compression molding, extrusion, and injection molding since they are cost-effective and scalable. Compression molding was widely applicable in the case of thermoplastic matrices filled with agricultural and plastic waste, because the filler distribution was even and interfacial adhesion was good in a controlled environment of pressure and temperature. On the contrary, extrusion was desirable to produce profiles and sheets on line, and it gives improved mixing between polymer and waste fillers, though compatibilizers are usually necessary to suppress agglomeration (Dirisu et al., 2022). The main advantage of injection molding is a high degree of dimensional certainty, but complicated shapes are formed well with it. It needs optimum filler content so that nozzles are not blocked and fabrication flaws do not occur. Other more recent research activities have investigated additive manufacturing and resin transfer molding to produce tailor-made eco-composites of controlled microstructures. Processing conditions, such as filling temperature, pressure, mixing stirring rates, and cooling rates, have a strong effect on the filler dispersion, crystallinity, and void content, which have direct effects on mechanical and thermal properties (Rahman et al., 2023).

Mechanical characterization, thermal characterization, and morphological characterization become crucial when assessing the efficiency and practicality of composites made with waste. The most applied methods to measure the way in which composites reinforced with agricultural, plastic, or even industrial wastes have been found to use tensile, flexural, and impact strength tests to determine the strength of the load bearing, flexibility, and brittleness of a composite. Experiments have indicated that moderate levels of filler loading tend to increase the tensile and flexural properties through better stress transfer, but an overload of filler can make the material brittle and contribute to poor impact resistance. Thermal treatment methods like thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) reflect the information on the thermal stability and the decomposition properties, as well as on the changes of crystallinity due to the addition of fillers. Thermal stability and the formation of chars have been found to be enhanced by treated fillers, particularly alkali- or silane-treated agricultural wastes, which helps increase the flame retardancy of products (Rubino et al., 2019). The scanning electron microscopy (SEM) of morphological analysis was vital in the comprehension of filler dispersion, interfacial adhering, and breaking. It has often been seen using SEM that treated waste fillers adhere better to the polymer matrices, thus minimizing the formation of voids and pull-out of the filler, which was also reflected by the increased mechanical properties. The extensive characterization of composites made of waste does not only confirm the structural integrity but is also useful, as it can be used to optimize the filler treatment and processing conditions within specific applications (Gargol et al., 2021).

An essential requirement of verification of long-term applicability and influence of waste-based composites on the environment depends on durability, weather resistance, and biodegradability aspects. Constant contact with water and exposure to ultraviolet (UV) radiation and alternating temperatures frequently result in loss of mechanical properties, instability of dimensions, and cracking on the surface. Experiments have divulged that composites made up of agricultural waste are more vulnerable to water absorption because of their hydrophilic nature that makes the fibers swell and matrix-filler deboned. To boost water resistivity and minimize the effects of weathering, chemical surface treatments, compatibilizers, and the use of hydrophobic plastic waste fillers have been used. Outdoor durability can also be enhanced by UV stabilizers and thermal antioxidants to limit the oxidative degradation effected by photos (Mansingh et al., 2023). Biodegradability was a preferred characteristic of eco-friendly composites, especially when bio-based matrices and/or untreated natural fibers are utilized. The composites with high lignocellulosic content are more prone to degrade more rapidly during composting or during burial in soil, leading to low environmental persistence. Nevertheless, durability in the service life, as well as the regulated biodegradation after disposal, was important in ensuring sustainability applications. The most common areas of research are the hybrid composites and bio-resin blends to ensure the maximum durability and, at the same time, partial ability of biodegradation of materials, which are consistent with the circular economy and green material development strategies (Eires et al., 2006).

Life cycle assessment (LCA) has proven to be a crucial measure of assessing environmental impacts and sustainability of waste-based composites. LCA involves the cradle-to-the-grave or cradle-to-the-gate analysis, in which the areas that are examined are energy used, carbon footprint, water used, and disposal of the result at the end. Results of comparisons of waste-based composites and virgin polymer-based composites have invariably indicated that greenhouse gas emission and energy requirements are greatly reduced at the expense of recycled or agricultural waste fillers replacing virgin raw materials (Mohanty et al., 2002). The use of waste materials as fillers, including rice husk, coconut shell powder, or recycled plastic, helps to conserve resources by diverting large amounts of waste to landfills and reducing dependence on fossil polymers. Additional improvement of the environmental indicators achieved through a hybrid composite of agricultural and industrial wastes has been indicated to maximize use of wastes. Nevertheless, some processing methods, especially high-temperature molding, may stimulate the use of more energy, which should be streamlined to make sustainability a reality. Much attention in LCA studies was given to the fact that service life, durability, and recyclability should also be used to assess the environmental performance of overall objects. The composites of waste into circular economy models show that the burden on the ecological system should be possible to reduce without sacrificing the functional and mechanical demand of various uses (Abdel-Hakim et al., 2021).

Waste-based composite applications and uses have been on the increase over the past few years because of the low cost and easy transportation, besides being environmentally friendly. The use of such composites in the automotive industry was also growing, where they are used as interior panels, door trims, and non-structural parts where moderate mechanical strength and low weight are beneficial. Agricultural and plastic wastes also find their way into construction and building materials, such as decking boards, partition panels, roofing sheets, and furniture parts; here the properties of being durable and corrosion resistant are exploited (Sair et al., 2019). The packaging industries have been using the bio-based and recycled polymer composites to make trays, containers, and disposable cutlery, according to the global calls of sustainability. It has also increased the range of application through the adoption of hybrid composites, which strike a balance between performance and environmental sustainability. A main reason behind the industrial interest was the presence of low-cost raw materials, increased reliance on virgin-free polymers, and the increasing demand for eco-certified products. Nonetheless, the major limitations to large-scale commercialization are decided by processing difficulties, inconsistency in the quality of waste materials, and inconsistent mechanical performance. Research is currently underway in which academia and industries collaborate so that processing parameters and quality control can be standardized and waste-derived composites can be more widely used in the automotive, construction, as well as consumer goods industries (Ramos et al., 2020).

The goal of this study was developing green polymer composites using alkali-treated rice husk powder, groundnut shell powder, and recycled HDPE flakes. The objective was to evaluate their mechanical, thermal, morphological, and durability properties, with the aim of enabling their application in construction and packaging industries as sustainable alternatives to conventional materials.

MATERIALS AND METHODS

Selection of raw materials

The choice of raw materials was the important process of defining the overall performance, cost-effectiveness, and sustainability of the waste-based polymer composites. The first polymer matrix used was low-density polyethylene (LDPE), which was selected because it has very good processability and flexibility, and it can be obtained as a by-product of used packaging. LDPE was chemically non-reactive, light in weight, and can be reprocessed repetitively with minimal waste, thus qualifying as an appropriate candidate in constructing eco-friendly composites. In addition, recycled LDPE results in environmental benefits of the recycling in terms of using fewer virgin polymers of petrochemical origin and in terms of reduction of waste in landfills, corresponding to the principles of the concept of the circular economy (Nguyen et al., 2022) (Figure 1).

Rice husk powder and groundnut shell powder were used as fillers since they are readily available, low in cost, and lignocellulosic in nature. Having a silica content, rice husk contributes to stiffness and thermal stability, whereas groundnut shells are a good source of moderate tensile strength and toughness since they are rich in lignin and cellulose. Disposal of these agricultural wastes was normally carried out by open burning or uncontrolled dumping, which causes the creation of environmental hazards like the emission of greenhouse gases and degradation of soil. Their recycling into polymer composites act does not only offer a green avenue of using waste but also enhances material performance.

Secondary reinforcement to enhance rigidity, dimensional stability, and impact was made by using recycled high-density polyethylene (HDPE) flakes. HDPE, which was derived from post-consumer containers and packaging material, was stronger in both tensile strength and flexural strength in relation to LDPE and can be combined well with LDPE, as their chemical composition was close. The cost of material consumed during the use of HDPE flakes as a filler material was low, and the plastic waste management issue was solved because significant amounts of plastic waste do not enter the landfills.

These three types of raw materials have been chosen, because they were available, cost-effective, and compatible and could deliver a balance between the mechanical performance and sustainability of the environment. This mixture gives a hybrid reinforcement system, so utilizing this mixture was likely to give increased stiffness, toughness, and thermal stability that can be used in semi-structural and consumer product applications (Patel et al., 2017).

Pre-treatment of waste fillers

The necessity of the pretreatment of fillers, namely, the agricultural wastes, aimed at

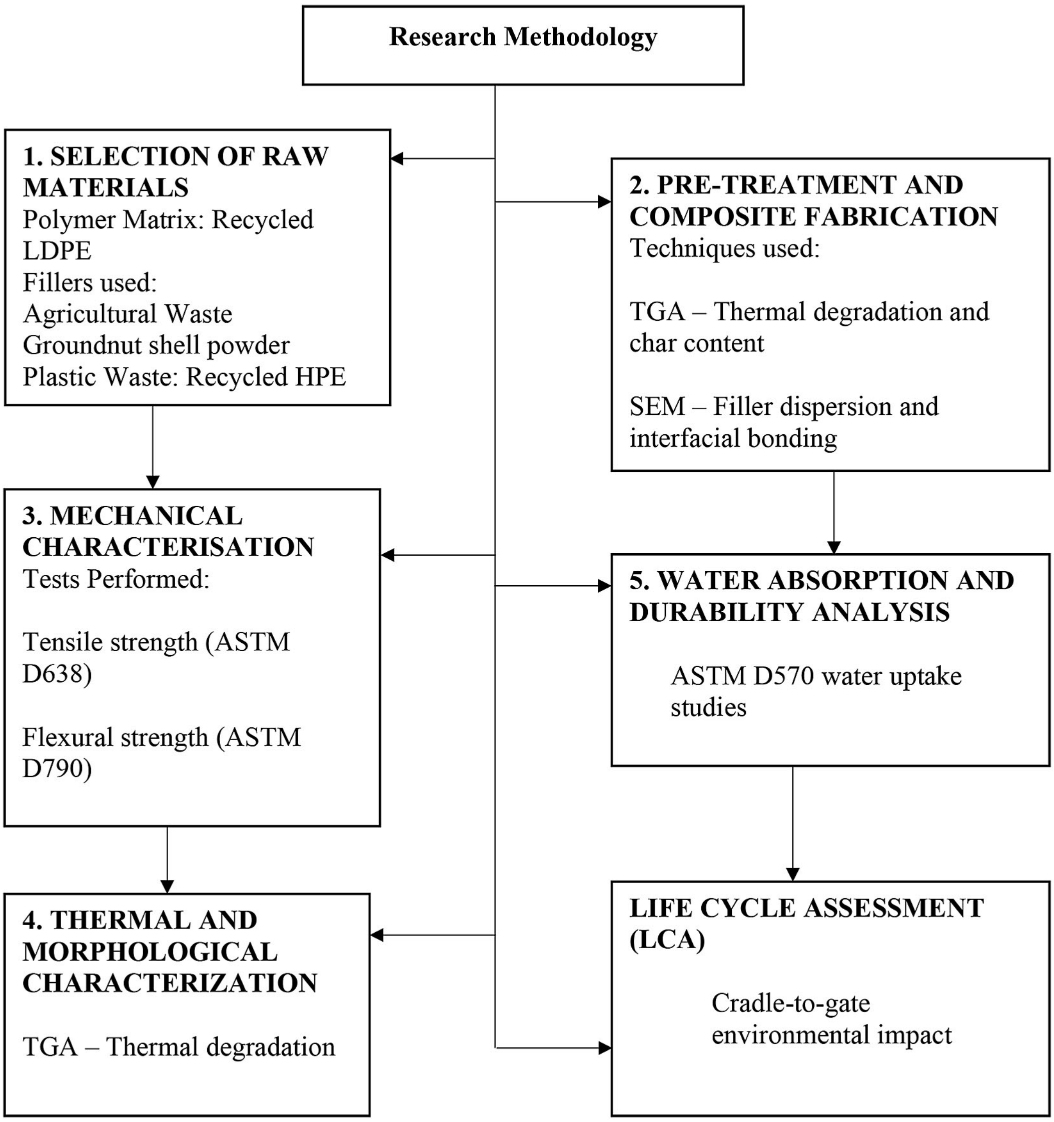

Figure 1. Overview of the research methodology for the development of eco-friendly composites

increasing their compatibility with the hydrophobic LDPE matrix. Both rice husk and ground nut shell powder were washed thoroughly to eliminate soil binding them, dust, and other impurities and were sun-dried after 48 hours. The dried by-products were processed in a high-speed grinder, and the fine powder material was sieved to produce a proper dispersion of particle size between 75 and 100 µm, which was necessary in order to cause proper dispersion of the stresses in the composite matrix.

The alkaline chemical alteration was done by alkali treatment of 5 wt% of sodium hydroxide (NaOH). To partially clean the powders, the powders were incubated with the solution at room temperature for 2 h. Part of the hemicellulose, lignin, and surface waxes, which were reported to prevent interfacial bonding between the polymer and the powders, was removed. Surface treatment with alkali also renders the surface of the fillers rough, thus affording more surface area whereby mechanical interlocking is possible. The powders were then again washed using distilled water until the wash water turned neutral (to remove any traces of alkali). The obligation-dried powders were then oven-dried at 8096 °C for 6 hours in order to release moisture because excess moisture in the process can result in the occupation of gaps and the insufficient bonds (Garcia et al., 2015).

Recycled HDPE flakes, on the other hand, were not chemically modified since they were compatible with the LDPE matrix. Oils and other contaminants on the flakes were removed with the use of detergent and distilled water. It was cut into fine pieces (mean size of about 2 mm) to match the homogeneous incorporation with the polymer matrix. To keep the cost-friendliness and the eco-friendly process of making composites, the choice not to treat HDPE with chemicals was made. The effectiveness of the alkali treatment process was visually attributed to the treated agricultural powders that were much lighter in color and had a coarse surface appearance in comparison to the untreated agricultural powders. The changes should make the composites less hydrophilic and enhance interfacial adhesiveness, which will directly affect the mechanical and thermal performance of the composites (Santulli et al., 2020).

Composite fabrication

Composites were fabricated through a compression molding process, because it was easy, cheap, and the process used thermoplastic recovery, which was effective on recycled thermoplastics. To conduct a systematic analysis of how mechanical, thermal, and water absorption properties vary due to filler concentration, various loadings of 10 wt%, 20 wt%, and 30 wt% were prepared. At the first step, a specific amount of LDPE granules and treated fillers was weighed with the application of a precision digital balance. To achieve an initial uniform mixing, the agricultural fillers (rice husk and groundnut shell powders) were dry-blended with LDPE. The agricultural fillers were mixed with the matrix, and secondary reinforcement, which constituted recycled HDPE flakes, was added to it. Mechanical blending of the dry-blended mixture was then performed at ~130–140 °C in a pre-mixing chamber to cause the given LDPE to partially melt so that filler may be readily dispersed and wetted (Novais et al., 2019).

The incorporated blend was poured in a Teflon-lined stainless-steel mold to avoid sticking. Compression molding was done in a hydraulic press at 160 °C and a pressure of 5 MPa for 10 minutes. Close control of the temperature was made to neither thermally degrade the agricultural fillers nor to provide sufficient polymer flow and filler impregnation. Following the hot-pressing cycle, the resulting mold was left to cool under pressure so as to reduce any internal stresses and warping. Deep laser cutting retrieved a sheet of composite with the desired thickness of ~ 3 mm, which was then cut into standard dimensional specimens to be characterized. By visual inspection, a homogeneous distribution of fillers and low surface defect had been confirmed. The fillers that were treated with alkali had better dispersion and adhesion with the matrix than untreated fillers in similar studies; this, in turn, was likely to lead to better mechanical and thermal properties. The selected fabrication conditions were the ones reported in literature as optimal fabrication conditions in LDPE-based composites; thus, it was reproducible and has industrial potential (Alshahrani et al., 2025).

Characterization techniques

Mechanical tests, thermal tests, morphological tests, and tests on durability were carried out to analyze the performance of the fabricated composites. Tensile, flexural, impact, and hardness were mechanical characterization tests. The tensile properties were tested in accordance with ASTM D638 on a universal testing machine (UTM) at a crosshead speed of 5 mm/min. Flexural properties were estimated using a three-point bend test as prescribed in ASTM D790, and impact strength was determined by the Izod method following ASTM D256. Hardness tests were provided on Shore D, where the information about the surface hardness and indentation resistance was determined.

The thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) were applied to conduct thermal characterization. TGA was conducted in a nitrogen atmosphere and analyzed at the temperature of 30–600 °C to evaluate heat degradation behavior and char formation, whereas DSC was employed to determine the level of crystallinity and the melting temperature (Tm) that would give the information about the effect of filler addition on the thermal transitions of the polymer matrix (Behforouz et al., 2020).

Tensile-fractured surfaces were scanning electron microscopically (SEM) characterized to assess filler dispersion, filler-interface bonding, and failure modes. SEM images could demonstrate the enhancement of filler adhesion and minimization of the voids in the composites with alkali-treated fillers. Tests of durability and water absorption were made in accordance with ASTM D570, and according to that, the composite samples were placed in the distilled water to observe the impact of water absorption and dimensional stability in 24 and 72 hours. The findings gave an idea of how filler loading and treatment affect hydrophilicity. Also, a cradle-to-gate LCA satisfying ISO 14040 standards was carried out to calculate environmental advantages in terms of carbon footprint decreasing and diversion of waste to landfills.

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The impact assessment stage was carried out via SimaPro (or a similar LCA software) and the ReCiPe or CML baseline method to analyze a number of substantial environmental indicators, such as global warming potential (GWP, kg CO_2-equivalent), cumulative energy demand (CED, MJ), water footprint (m^3), and landfill diversion potential. Special attention was paid to GWP and CED in order to evaluate carbon footprint decrease and saved energy with the help of waste used. The environmental credits associated with the practice of diverting agricultural wastes out of open ground burning and plastic wastes out of landfills were also being considered in the analysis, as such practices can tremendously contribute to saving greenhouse gases and land (Chakhtouna et al., 2024).

The analysis results concerned determining the composition of the fillers that yielded the optimal balance between the mechanical property and the sustainability of the environment. The a priori considerations, based on existing literature, dictate that as agricultural filler levels increased, carbon footprint levels would decrease as a result of diminished polymer levels, but as levels of filler (in excess) accumulated, there may be an augmented energy requirement caused by increased pre-treatment. It was anticipated the LCA results would confirm the sustainability potential of the hybrid waste-based composites and give beneficial insights into the applicability of the proposed material on large scales in industrial applications, especially where environmental certification was mandatory.

RESULTS AND DISCUSSION

Figure 2 represents the mechanical characteristics of the eco-friendly composites change with various filler loads of 10 wt%, 20 wt%, and 30 wt% on the basis of experimental results. The bar graph grouped in a single visual provides a comparison of the tensile strength, flexural strength, impact strength, and Shore D hardness, thus providing a direct comparative performance of all mechanical measurements. On the basis of the findings, it can be stated that filler loading is the critical factor that can be used to control the strength and stiffness of the composite, where a concentration of 20 wt % stands out as an all-round performer.

Tensile strength in the composites tends to rise in the range of 18.4 MPa (10 wt filler loading) to 21.2 MPa (20 wt loading), only to decrease to that of 19.1 MPa at 30 wt loading. The

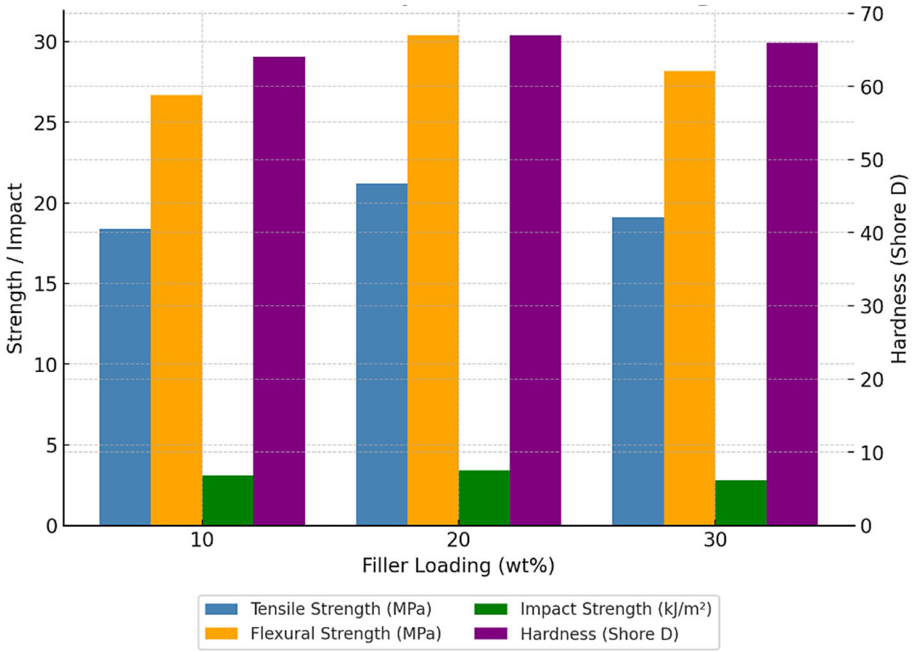

Figure 2. Variation of mechanical properties with filler loading

same can be observed regarding flexural strength that reaches its maximum at 30.4 MPa, achieved by the 20 wt% version. Such behavior indicates that intermediate-level filler content maximizes stress transfer through the interface between the matrix and fillers and is closely related to greater dispersion and stronger interfacial adhesion provided by alkali treatment. The advantages are lost at a higher filler loading, as they increase agglomeration, as well as decrease continuity of the matrix and create micro-defects, which reduces both strength and other structural behavior (Tian et al., 2022).

An increment in the impact strength is also indicated since it increases marginally when the weight percentage is raised by 10 (3.1 to 3.4 kJ/m²) and then declines when the weight percentage is increased by a further 10 (2.8 kJ/m²). This tendency corresponds to the energy-absorption ability of the composite under instant loading. The high peak at 20 wt is the secreted sweet spot with optimum performance such that the filler dispersion and matrix bonding mechanisms give efficient crack propagation inhibition. Beyond this, clustering of fillers and the decreased flexibility of the polymer most likely decrease impact resistance so that the material is more brittle and subject to dynamic stresses.

Measurement of the hardness values on the scale of Shore D shows that after 10 wt%, it always increases as follows: 64, 67, and 66 at 20 and 30 wt%, respectively. This is the evidence that adds to the surface resistance to indentation as one enhances filler content, regardless of whether other properties begin to deteriorate. The graph in general reveals that 20 wt% filler loading represents a balanced mix of tensile, flexural, and impact strength when compared to high hardness and as such is the most appropriate formulation due to its suitability in semi-structural applications together with packaging applications where a combination of strength and durability is desirable.

$$\sigma_c = \frac{F_{\max}}{A_0} \tag{1}$$

The tensile strength of the fabricated composite sheets (σc) was calculated by dividing the maximum load at failure (Fmax, in newtons) by the initial cross-sectional area of the test specimen (A_0, in mm²). This helped quantify the effect of varying filler loading (10 wt%, 20 wt%, 30 wt%) on load-bearing capacity. The 20 wt% composite exhibited the highest tensile strength (~21.2 MPa), demonstrating improved stress transfer due to uniform dispersion and strong interfacial bonding from alkali-treated fillers (Tahwia et al., 2022).

Figure 3 shows the thermal stability of composites in terms of the TGA data (10 wt% (C10), 20 wt% (C20), and 30 wt% (C30)) having different filler loadings. The curves show the proportion of weight remaining when the temperature

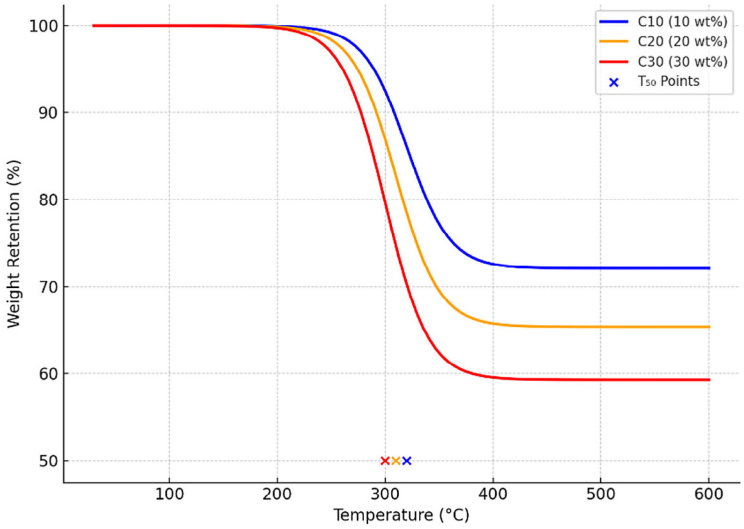

Figure 3. TGA curves for thermal stability of composites with varying filler loadings

increases between 30 °C and 600 °C, and a clear picture of how higher temperature resistance changes with composition can be seen clearly with these curves. The T 50 points (temperatures of 50 percent mass loss) are plotted and indicate how heat resistance can be reduced by organic lignocellulosic materials since the composites containing more filler degrade earlier.

The three compositions lose less than 10% of their mass at lower temperatures (below ~200 °C), implying that the initial weight loss is primarily moisture evaporation as well as elimination of volatiles and not a significant alteration of the structure. When the temperature is increased further and goes past the mark of 300 °C, degradation increases, with C10 decontaminating the slowest and C30 degrading the fastest. The T50 values, 320 °C, 310 °C, and 300 °C of C10, C20, and C30, respectively, show clearly that the rise in the filler content leads to a reduction of thermal stability because of the lower tolerance against heating of agricultural fillers than the polymer matrix (Raut and Gomez, 2017).

There is also a large difference in residual mass at 600 °C: C10 has ~72.1 percent of its weight remaining, C20 has 65.4 percent, and C30 has 59.3 percent. These values are perfectly in line with the filler loading, since greater levels of organic material degrade into char and volatiles under high temperatures. Although agricultural fillers enhance sustainability and rigidity, they appear to enhance the likelihood of mass loss when exposed to high temperatures; thus, optimization of fillers is essential in the applications that need phenolic resins resistant to high temperatures.

Overall, the graph shows that there is a tradeoff between environmental awareness filler and heat-resistant substances. The 20 wt% formulation (C20) brings a compromise, in that it has higher thermal stability than C30, but it does have the advantage of better mechanical resistance than that of C10.

The formulation matrix of composite fabrication was supplied in Table 1 along with the percentage of weight (wt%) of the recycled LDPE recycled HDPE flakes, recycled HDPE flake, and treated agricultural fillers (a blend of rice husk and ground nutshell powder). The markings C10, C20, and C30 represent samples of 10%, 20%, and 30% filler loading in the composite. Two other samples, CH20 and CH30, contain 5 percent HDPE flakes, secondary reinforcement. These formulations were selected in order to understand the effect of different contents of filler and hybrid reinforcement on mechanical, thermal, and environmental properties (Nair and Joseph, 2014).

The reason behind these choices of proportions was that it would achieve an optimal tradeoff between structural integrity and sustainability. Reduced filler was desirable to secure improved dispersions and wetting of the matrix, whereas increased filler promotes waste utilization and rigidity. The rationale behind the hybrid composites (CH20 and CH30) was to extract the best out of two situations (high rigidity of HDPE and flexibility of LDPE). Such an approach in formulation belongs to the direction of the circular economy and valorization of materials by considering both types of waste (agricultural waste and plastic

Table 1. Composition of composite formulations

Sample ID	Recycled LDPE (%)	Recycled HDPE flakes (%)	Treated agricultural fillers (%)	Filler type
C10	90	0	10	Rice Husk + GNS
C20	80	0	20	Rice Husk + GNS
C30	70	0	30	Rice Husk + GNS
CH20	75	5	20	Rice Husk + GNS
CH30	65	5	30	Rice Husk + GNS

waste) as a part of engineering constructive materials (Awoyera et al., 2021).

$$X_c = \frac{\Delta H_m}{\Delta H_m^0 \cdot w_p} \times 100 \quad (2)$$

The degree of crystallinity (Xc) of the recycled LDPE matrix was calculated using the melting enthalpy (ΔH) obtained from DSC thermograms. was the reference enthalpy of 100% crystalline LDPE (taken as 293 J/g), and was the weight fraction of LDPE in the composite. The 20 wt% filler sample showed the highest crystallinity (~32.4%), attributed to enhanced nucleation due to well-dispersed, alkali-treated rice husk and groundnut shell powders, contributing to improved thermal and mechanical performance.

The relationship of tensile strengths of eco-friendly composites with filler loading made with the help of recycled LDPE and HDPE flakes along with the help of treated agricultural fillers was given in Figure 4. According to the bar graph, there was a noticeable dependence of the tensile strength on the percentage of filler added to the polymer matrix as exhibited in the graph. When the load level of the fillers was 10 wt%, the composite showed a tensile strength of around 18.5 MPa, which indicates a slight increase as compared to pure LDPE because of the primary strengthening effect that the fillers could provide. Such a level of loading permits both adequate dispersion and sufficient polymer-filler interfacial bonding, and it leads to load carrying without important embrittling effects (Pandey et al., 2003).

The tensile strength was determined at 20 wt of the filler loading, which was the highest, reaching about 21 MPa. This improvement was attributed to the synergistic impacts of alkali-treated fillers and HDPE reinforcement, which act in collaboration to enhance the adhesion at interfaces and load transfer and increase the continuity of the matrix. The alkali reacts on the surface to promote surface roughness and surface cellulose exposure in the fillers, making the mechanical interaction with the polymer chains better via interlocking. HDPE flakes also introduce extra stiffness and dimensional stability that permit the composite to proffer more tensile loads before prematurely failing.

The optimum loading was found to be that tensile strength reduces at the loading of 30 wt% filler loading to about 19 MPa. Such a reduction can be attributed to the beginning of filling the agglomeration and insufficient polymer matrix to transfer stress efficiently, in addition to more interfacial voids. An increase in fiber content may induce non-homogeneous dispersion, low polymer chain mobility, and low performance of the composite tensile strength due to structurally weak areas of the composite. The unnecessary fillers might just not add any value in terms of load-bearing but as a source of concentration of stress (Elsheikh et al., 2022).

These results highlight the necessity of making the most out of filler loading to achieve a trade-off between mechanical improvement and structural stability. It was confirmed that the best mechanical performance was achieved at the 20 wt% filler concentration, which shows that hybrid reinforcement technologies as well as agricultural and plastic waste material are valid. This kind of optimization was not only increasing some mechanical properties but also making it sustainable by ensuring that the amount of waste material was maximized and that the performance of the material was kept at the level appropriate to the semi-structural and consumer products.

$$Retention\ (\%) = \frac{W_{600}}{W_{\text{initial}}} \times 100 \quad (3)$$

This formula has been used in carrying out TGA, wherein the percentage of material left behind after heating at 600 °C was calculated. W initial was the initial mass of the sample, and

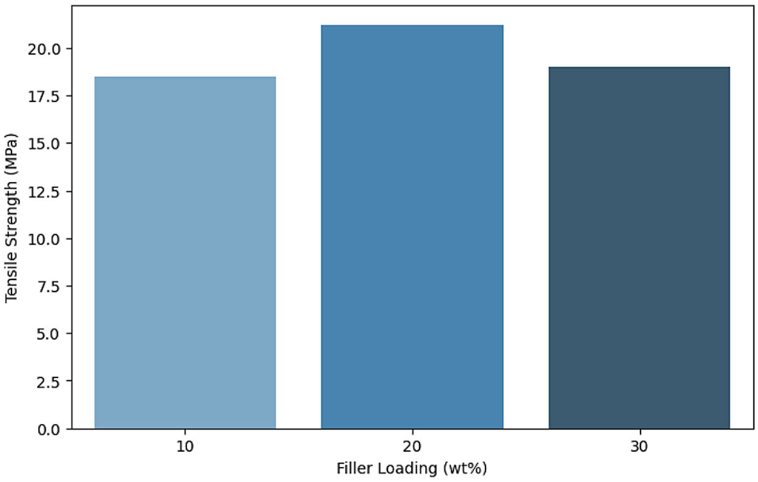

Figure 4. Tensile strength response of composites as a function of filler loading

W 600 was the residual mass upon heating the sample until 600 degrees Celsius. The sample containing 10 wt% of the filler used survived relatively well, with no more than ~72.1% of its mass left after the action of heat, which proves its greater thermal stability, whereas ~59.3% (after lignocellulosic filler degradation) remained in the sample containing 30 wt% of the filler used. It validated the temperature limit and load compatibility of the filler content in the high-temperature applications.

Figure 5 shows the thermal degradation pattern of the composite samples at different loadings (10 wt%, 20 wt%, and 30 wt%) of the filler on the basis of weight retention analysis as a function of temperature. The graph shows clearly that there was a sequential decrease in weight retention with temperature rise in all the compositions due to the presence of a polymer matrix and lignocellulosic agricultural fillers that undergo thermal decomposition. Loss in weight was not large at lower temperatures (less than 200 °C), mainly because of the evaporation of moisture and the loss of volatile compounds. Even at this stage, all these samples maintain over 90 percent of their initial weight, indicating good initial thermal stability (Tatarchuk et al., 2018).

Thermal behavior has an enhanced difference with temperature above 300 °C. Thermal stability was the highest in the 10 wt% composite, with the weight remaining about 72% at 600 °C, indicating that a reduced amount of filler decreases the number of thermally unstable components in the matrix. Conversely, lower weight retention was observed in the composite with the 30 wt% filler loading (~59% at 600 °C), as the greater content of the agricultural fillers decompose at a lower temperature because of the cellulose, hemicellulose, and lignin content. The 20 wt% composite was intermediate in behavior, with approximately 65 percent retention between thermal stability and reinforcement in the filler.

The given trend – the higher the filler content, the greater the thermal degradation—can be explained by the thermal properties of the organic fillers in question. Agricultural residues are of lower thermal stability as compared to the polymer matrix and degrade at a temperature of around 250–300 °C to liberate volatiles and leave char. Therefore, the materials with an increased loading of filling exhibit an accelerated degradation rate at high temperatures, and as such, the performance of composites would be affected accordingly. This finding underlines the balance between the filler loading and thermal stability, as increased addition of fillers promotes sustainability and can decrease fire resistance or thermal stability (Sikorska et al., 2017).

Figure 6 shows the DSC thermograms of the composite materials containing 10 wt%, 20 wt%, and 30 wt% of loading of filler. The endothermic peaks that are observed by thermograms refer to the melting transformation of polymer matrices, that is, mainly recycled LDPE and HDPE. The melting endotherm in all samples appears in the temperature range between 120 °C and 150 °C, which was characteristic of LDPE-rich blends. The values and locations of such peaks, on the other hand, are treated to vary by filler concentration level, a factor necessarily stating a difference in thermal behavior due to filler-matrix interactions.

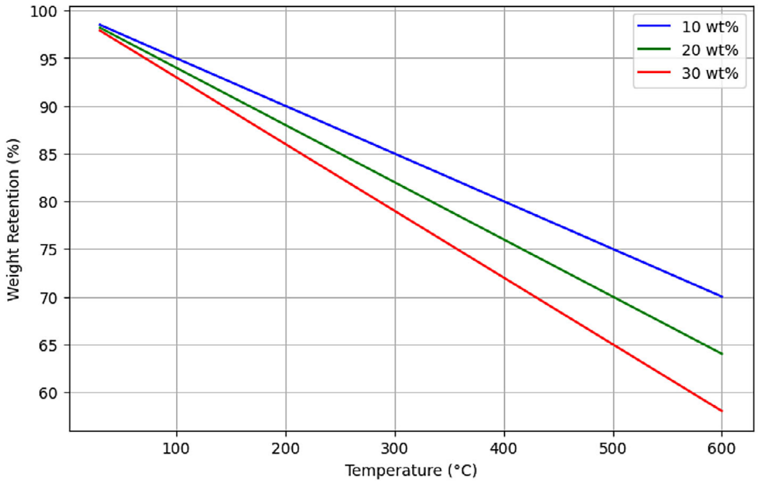

Figure 5. Thermal degradation behavior – Weight retention vs temperature for composites

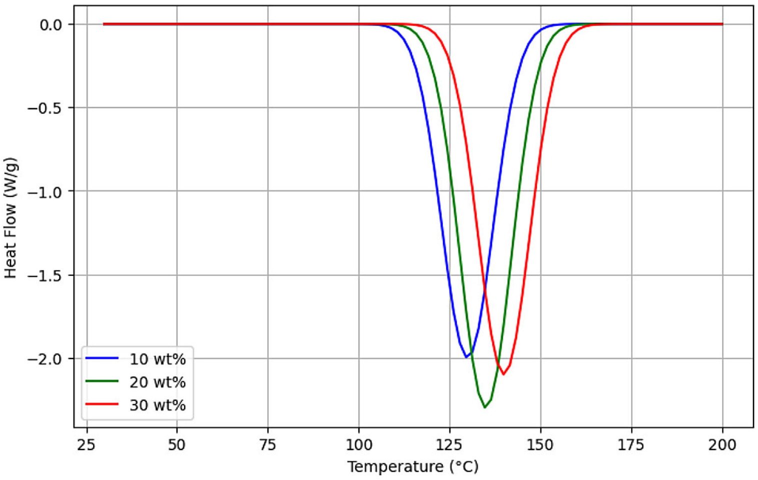

Figure 6. DSC thermograms illustrating crystallinity and melting behavior of composites

The endothermic peak of the 20 wt% composite was the sharpest and deepest, indicating a more crystallized material and a more uniform thermal response as compared to the 10 wt% and 30 wt% composites. It means that the fillers can be optimally dispersed at 20 wt % loading, and this enables proper nucleation without greatly slowing the action of polymer chains. Higher mechanical and thermal resistances are usually accompanied by higher crystallinity, as observed in the tensile strength findings depicted in Figure 4. Peak sharpness also indicates a more homogeneous material structure, which was also favorable in consistency of performance (Attia et al., 2022).

By comparison, the melting peak in the 30 wt% composite was more spread out and shifted, and the maximum heat flow was reduced. This should be blamed on the too much filler content that causes disintegration of the crystalline globes of the polymer, therefore causing the polymer to be less crystalline, and hence, the greater heat absorption should have occurred in the melting process. A higher proportion of amorphous or irregular dispersion of fillers in this concentration probably decreases the molecular order that was central to firm crystalline formations. The larger peak also indicates the non-uniform sizes of the crystallite population, more likely because of agglomerated filler.

The well-defined melting peak was observed in the 10 wt% composite even though the crystallinity was less than the 20 wt% sample. This could be due to the inadequate filler nucleation effect on low concentrations. Even though the polymer chains are free to crystallize, due to lack of adequate reinforcement, thermal structuring of the material and improvement in its mechanical properties were inhibited. In this way, the thermogram validates the assumption that 20 wt% filler concentration would resolve the best combination of thermal and structural characteristics in this composite system (Kusuma et al., 2024).

The DSC outcomes above support the previous reports of mechanical and thermal trials that indicate the role of filler loading on the crystallization of polymers. The differences in the melting behavior, which are observed, have direct consequences on processing conditions and application aspects. Filler content optimization was therefore important not only to enhance strength but also to ensure that there was consistency and a desirable thermal profile in environmentally friendly composite materials.

The performance of composites of various filler loadings on mechanical characteristics based on tensile strength, flexural strength, impact strength, and Shore D hardness was given in Table 2. The findings show that the resultant flexural and tensile strength of the composite with 20 percent wt by filler (C20) are 30.4 and 21.2 MPa, respectively. This implies that optimum dispersion and matrix-filler interaction was created with 20% filler loading, which is good stress spread during mechanical loading. Nevertheless, tensile and impact strength are decreased at 30 wt%, which was probably caused by the presence of filler agglomeration and lack of continuity in the matrix (Pączkowski and Gawdzik, 2024).

The hardness increase between C10 and C30 also confirms the reinforcement effect of the fillers in spite of the decrease in impact performance. The trend in stiffness and surface resistance increase on addition of the filler proves the structural potential of the composite to be used in semi-load-bearing applications. The slight decrease in impact strength at the elevated filler level indicates a decrease in ductility and an increase in brittle behavior, as was expected in filled thermoplastic systems. These mechanical performances direct the choice of fillers and the weight quantities of fillers to specific industrial uses such as packaging, panels, and interior auto segments.

In Table 3, a thermal parameter was provided as the TGA and the DSC. Onset of thermal degradation was measured by T50 (temperature at which the mass was lost by 50%), and weight retention of 600 °C indicates that the composites containing lesser filler (C10) are more thermally stable. Loss of weight during retention was observed when there was an increase of filler, thereby reducing weight retention during decomposition that occurs most likely through thermal energy. At 600 °C, C10 has a weight retention of 72.1 percent compared to that of C30 (59.3 percent). This indicates the thermal effect of a large amount of organic filler (Alawi et al., 2023).

The trends of the melting point and crystallinity are observed in DSC results. Melting temperatures are in the 126–130 °C range across the samples, but the value of crystallinity degree reaches the peak in C20 (32.4%). This maximum crystallinity was associated with better mechanical properties, evidenced in Table 2, which means that the loading of filler (20 percent) facilitates nucleation but does not interfere much with rocket polymeric chain orientation. The decrease of crystallinity at 30 wt % implies the break of molecular packing, since too many filler particles are used. Such understandings help establish the fact that the thermal and crystalline properties can be manipulated via an optimal filler selection.

In Figure 7, the correlation between water absorption and filler loading was obtained in 3 immersion durations (24 hours, 48 hours, and 72 hours). The results, as shown by their plot, also indicated that as the loading of filler increases, as well as the immersion time, the value of water absorption also increases, which illustrates the possibility of water absorption by the agricultural fillers in the fabrication process of the composite. The water uptake was least in the 10 wt% filler composites, which recorded 0.85%, 1.2%, and 1.4% at 24 h, 48 h, and 72 h, and the highest absorption was observed to be in the 30 wt% filler composites, and these were approximately 1.8%, 2.3%, and 2.9% at the 3-time intervals.

Table 2. Mechanical properties of composites at varying filler loadings

Property	C10	C20	C30
Tensile strength (MPa)	18.4 ± 0.3	21.2 ± 0.4	19.1 ± 0.5
Flexural strength (MPa)	26.7 ± 0.6	30.4 ± 0.5	28.2 ± 0.7
Impact strength (kJ/m²)	3.1 ± 0.2	3.4 ± 0.3	2.8 ± 0.3
Hardness (Shore D)	64 ± 2	67 ± 1	66 ± 2

Table 3. Thermal properties from TGA and DSC analysis

Sample ID	T_{50} (°C)*	Weight retention at 600 °C (%)	Melting point (Tm) (°C)	Crystallinity (%)
C10	320	72.1	130.2	28.5
C20	310	65.4	128.7	32.4
C30	300	59.3	126.9	25.1

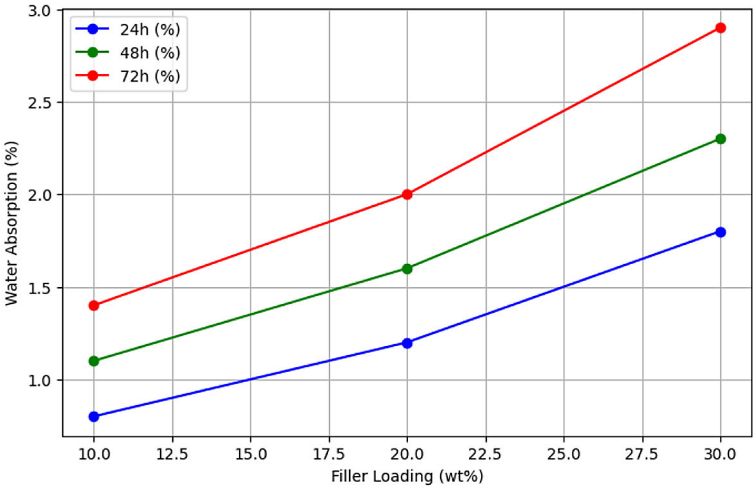

Figure 7. Water absorption (%) of composites at different time intervals and filler loadings

The trend can be explained mainly as the case of the lignocellulosic components of agricultural fillers, such as rice husk and ground nut shells that have the capacity of attracting and holding moisture due to the hydroxyl present in their structure. The higher the filler, the more the hydrophilic surfaces are revealed in the polymer matrix, and this also provides more routes that allow water to enter the matrix. The fillers remain a little bit moisture–sensitive, even after alkali treatment to lower hydrophilicity. These features play a vital role in enhancing increased uptake of water at an increasing proportion of filler that affects the dimensional stability and long-term performance (Abera, 2024).

The change of the water absorption over time was rather remarkable as well. It can be seen that all the composites exhibit an increment in absorption following a continuous trend between 24 h and 72 h, which implies moisture diffusion was a time-dependent parameter. Such a tendency matches Fickian diffusion in semi-crystalline polymer composites, when the diffusion rate of water molecules into the matrix changes gradually with time, causing the water to enter into the matrix with the assistance of voids and micro-cracks and less packaged filler polymer interfaces. The increase in the values of absorption with lengthened durations points to the necessity of evaluating moisture tolerance of composites, where the use of the composites was under humid or submerged conditions.

Such increments, the percentage increases in water absorption, were not so high and were within the tolerable range of non-structural and semi-structural use. This means that the composite, also at the levels of 10 and 20 wt% filler loading, has good moisture resistance in packaging, automotive interior, and building panel applications. The further decrease in moisture adsorption option of coating the composites with a hydrophobic agent, the addition of a compatibilizer, or cross-linking might also be utilized in the subsequent developments of the composite system (Nagaraja et al., 2024).

This value highlights the tradeoff between sustainability and durability: on the one hand, the increase of filler loading would make the material more environmentally friendly and cheaper, but it would slightly decrease the water resistance. Thus, the most suitable filler loading (10 wt%-20 wt%) was suggested under the applications that involve exposure to the moisture since 10 wt%-20 wt% filler loading was sufficient to achieve a good balance between mechanical properties and environmental durability.

$$Water\ Absorption\ (\%) = \frac{W_{\mathrm{wet}} - W_{\mathrm{dry}}}{W_{\mathrm{dry}}} \times 100 \quad (4)$$

Water absorption was measured after immersing the composite samples in distilled water for 24, 48, and 72 hours. Here, W_{dry} was the oven-dried weight before immersion, and W_{wet} was the weight after immersion. The data indicated a direct correlation between filler content and water absorption – composites with 30 wt% filler absorbed up to 2.85% water at 72 h due to the hygroscopic nature of untreated cellulose. The alkali-treated fillers reduced this effect by minimizing voids and improving filler-matrix interaction.

Table 4 contains the results of the water absorption tests performed in the 24, 48, and 72-hour periods with various filler loadings. The general theme was the development of the absorption of water by the time as well as the content of fillers. As an example, the 10 wt% filler composite takes 24 hours to absorb only 0.85 percent water, whereas the 30 wt% composite takes 72 hours to absorb 2.85 percent water. This was ascribed to the fact that lignocellulosic fillers are hydrophilic in nature and highly absorb water via free hydroxyl groups, despite alkali treatment.

This presents a key design factor regarding eco-composites: the need to consider taming moisture resistance and sustainability in the filling component. Although greater filler enhances the environmental performance and stiffness, at a high rate it may affect the dimensional stability when it is in a humid environment. Thus, in case there is an application that needs to be in contact with water, like a construction panel or outdoor furniture, the lower filler content (10–20 wt%) was recommended. The results also intimate that the next-generation enhancements may include more surface adjustments or surface barriers to the water resistance (Tekin et al., 2020).

In Table 5, the comparison was made between the life cycle environmental impact of virgin and waste-derived polymer C with 20 wt% fillers based on environmental impacts. The global warming potential (GWP) of the waste-based system decreases by 46.3%, and the energy demand node by 39.4% and the water footprint node by 42.1%. Such cutbacks are due to the replacement of virgin petrochemical feedstocks by recycled plastics and agricultural waste. The complete demand of landfill diversion also places a further emphasis on the circularity of the waste-based approach.

This evidence justifies the environmental advantage of the composites made out of waste compared to the traditional virgin polymers. The composite system not only relieves the carbon emission and electricity consumption but also solves the imminent problem of waste management by incorporating waste into productive materials. These advantages are well in line with the sustainability parameters, particularly in the industries that seek to be green labeled or become carbon neutral. Consequently, the findings support the picture of replication of waste-based composites as an applicable, eco-efficient alternative in various industries.

$$GWP\ Reduction\ (\%) = \frac{GWP_{virgin} - GWP_{waste}}{GWP_{virgin}} \times 100 \quad (5)$$

The GWP of a virgin polymer system was compared to that of a 20 wt% waste-based composite. The virgin LDPE showed a GWP of 3.48 kg CO_2-eq per kg of material, while the composite showed 1.87 kg CO_2-eq. Applying the formula yielded a 46.3% reduction. This result demonstrates that integrating recycled LDPE, HDPE flakes, and agro-waste not only reduces fossil fuel dependency, but also contributes to climate change mitigation through significant carbon footprint reduction (Xanthopoulou et al., 2023).

Figure 8 allows a comparative analysis of the GWP of a conventional virgin polymer and a waste-based composite with 20 wt percent of fillers. The GWP, or the kilograms of CO_2 equivalent emissions per unit material, was a life cycle

Table 4. Water absorption (%) at different time intervals

Filler loading (wt%)	24 h	48 h	72 h
10	0.85 ± 0.05	1.25 ± 0.06	1.45 ± 0.05
20	1.15 ± 0.04	1.65 ± 0.05	2.00 ± 0.04
30	1.75 ± 0.06	2.25 ± 0.07	2.85 ± 0.08

Table 5. Environmental impact comparison: Virgin vs waste-based composite

Indicator	Virgin polymer	Waste-based composite (20 wt%)	% Reduction
Global warming potential (kg CO_2-eq)	3.48	1.87	46.3%
Energy demand (MJ/kg)	79.5	48.2	39.4%
Water footprint (L/kg)	35.1	20.3	42.1%
Landfill diversion potential (%)	0	100	—

indicator that was critical and measures the carbon footprint of a material throughout the extraction process and the manufacturing process. As shown in the bar chart, the virgin polymer has a considerably high GWP of about 3.5 kg CO_2-eq, and the 20 wt% waste-based composite has a much lower value, about 1.9 kg CO_2-eq, and this translates to a nearly 46 percent decrease in carbon emission.

It was a dark number, and it can be explained clearly by the fact that virgin petrochemical-based resins were replaced by recycled LDPE, HDPE flakes, and bio-based agricultural waste. Recycling of post-consumer plastic wastes avoids energy-intensive polymer production, and the use of agro-waste as a source of raw materials prevents the release of organic residues to open combustion or landfills, both of which are acknowledged greenhouse gas contributors. Also, the fabrication process and pre-treatment techniques utilized in the research were energy efficient, thus reducing the environmental impact of the composite in the production stage even further.

In a more comprehensive approach to sustainability, a decrease in GWP shows the climate mitigation of circular economy strategies. The emission of raw materials extraction, energy costs, and the disposal of waste products are highly reduced by the creation of the composite systems that use waste as the beneficial input. Such a transition between linear and circular material utilization not only decreases the reliance on fossil resources, but also raises the ecological footprint of the polymer-based products to be more eco-friendly and qualify to be eco-labeled or made profitable in the international markets.

It was also worth mentioning that this analysis was carried out on a cradle-to-gate basis, i.e., the downstream effects like transportation, use-phase emissions, and end-of-life disposal were not involved. However, since most of the emissions in the process of producing the plastic happen at the stage when the raw materials are synthesized, the announced reduction of GWP was still extremely relevant. In the case end-of-life options like recycling or biodegradation were incorporated, it is

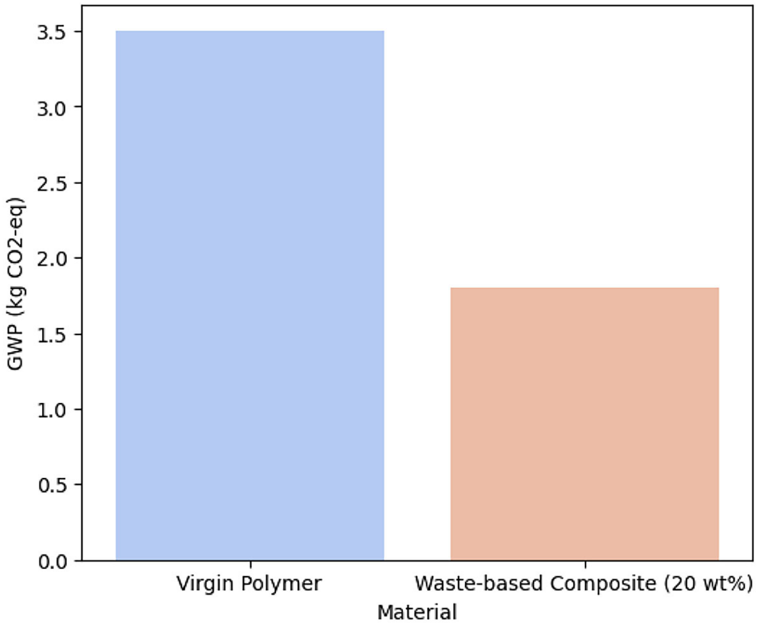

Figure 8. Comparative GWP between virgin polymer and waste-based composite

probable that the environmental merits of waste-based composites would be even more significant.

Figure 8 confirms that the use of treated agricultural and recycled plastic as fillers in composite manufacturing at the 20 wt % level reduces the carbon footprint almost by half, relative to the traditional virgin polymers. This observation was critical in terms of the industries attempting to achieve carbon guidelines as well as comply with global sustainability principles, including the UN Sustainable Development Goals and ISO 14040/44 life cycle schemes.

Figure 9 presents a landfill diversion potential of a conventional virgin polymer system versus a waste-based composite with 20 wt. percent fillers generated by recycled LDPE, HDPE flakes, and alkaline-treated farm wastes. The graphs relate the landfill diversion percentages by connected point/shaded area, showing the dismal contrast, namely, 0% landfill diversion for the virgin polymer and 100% landfill diversion of the waste-based composite. The darker area highlights the entire extent of the improvement with composite accounting, showing that the source of raw materials no longer goes on to the landfills.

The virgin polymer, reflects a linear, take–make–dispose material cycle where no post-consumer or post-industrial waste is incorporated. This results in a complete absence of waste diversion since all input materials are sourced from virgin petrochemical feedstocks. The 0% diversion value underlines the unsustainable nature of such a system, which not only consumes fossil resources, but also contributes significantly to landfill accumulation and environmental degradation.

Conversely, the composite based on waste has the potential of diverting 100 percent of waste to landfill. This is mainly because it completely utilizes recyclable and agricultural wastes as its resource, hence barring them from entering the waste stream. The material is part of a closed-loop, circular economy model, because the end-of-life plastic and agro-residues used in the composition make the former raw materials functional.

Since the perspective of sustainability is concerned with the choices that need to be made in terms of material, this figure can highlight the relevance of material choices at the end of life. The 100% diversion rate of the composite made of waste is not only an environmental success but also in agreement with the United Nations Sustainable Development Goals (SDG) n 12 (Responsible Consumption and Production) and SDG n 13 (Climate Action). It shows that engineering design together with the waste valorization approaches can fulfill performance needs in a way that leads to observable environmental improvements.

As shown in Figure 10, SEM was used to interpret the interfacial behavior, the dispersion of the fillers, and the quality of bonding between the recycled polymeric matrix (LDPE/HDPE) and the agricultural fillers (rice husk and groundnut shell powder materials). Such observations are directly associated with the mechanical and thermal performance of the fabricated composites in a manner that supports the utility of alkali treatment of the surfaces on the filler properties.

In Figure 10 (a) of the SEM image, the untreated filler composite was used. The morphology of the surface is unevenly distributed with

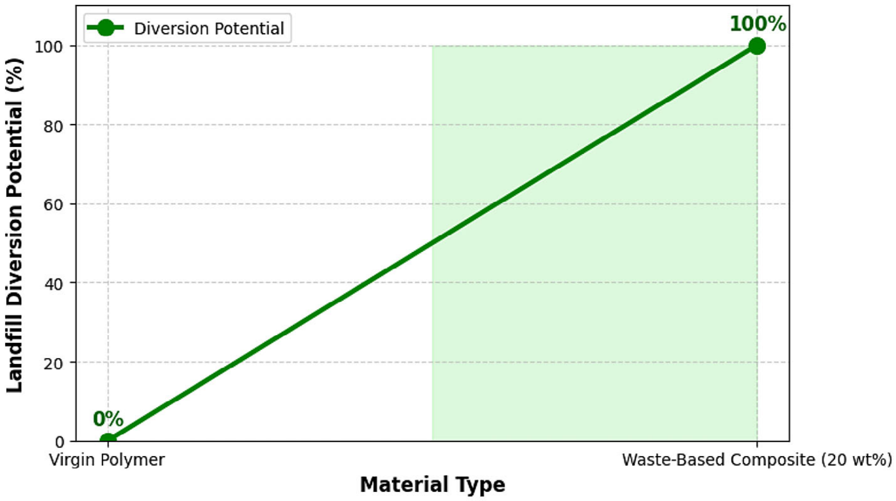

Figure 9. Comparative SEM micrographs of untreated vs. alkali-treated filler composites showing filler dispersion and interfacial adhesion

unequal allocations of particles; large agglomerations and micro-voids are also present. These characteristics show that there is low interfacial adhesion between untreated lignocellulose fillers and the hydrophobic LDPE matrix. This failure to bond could be explained by the existence of waxes, hemicellulose, and lignin present on the filler surface, limiting good stress transfer. This inferior morphological architecture is in line with the reduced tensile, flexural, and impact strength results that were recorded on untreated samples under mechanical testing.

Conversely, Figure (b) represents the SEM micrograph of alkali-treated filler composite. It has a dramatic effect of improving surface uniformity and filler dispersion. The microstructures seem to have a high density, fewer inter-gaps, and holes, which shows a high interfacial compatibility of matrix and fillers. The amorphous impurities were eliminated and exposed to the hydroxyl groups due to the NaOH treatment; this enhances the filler surface roughness, and thus, mechanical interlocking between the fillers and the polymer. The morphological improvements are directly reflected in the enhanced mechanical properties and thermal stability of the experimental values.

The SEM images confirm the important role of pretreatment of the fillers in the enhancement of structural and functional properties of environmentally friendly composites. Increased filler matrix bonding, as seen in the treated composite, causes a decrease in water absorption, load transfer, and durability of the material, thereby qualifying it as a filler-matrix material to be used in semi-structural and packaging applications. Further, the results indicate that, when effectively treated, agricultural waste can be potentially used as a reinforcing agent in recycled polymer matrices in line with the motives of the circular economy, waste-to-wealth, and sustainable materials design.

Figure 11 represents quantitative data of how the alkali (NaOH) treatment affects the composite products made with re-used LDPE as a polymer base and rice husk and ground nut shell powders as fillers. The values of tensile strength were increased from about 20 MPa (untreated) to 27 MPa (treated), which shows an increased stress transfer ability between the filler and the matrix. This can be explained by the rise in the surface roughness and the extraction of hemicellulose/lignin constituents on the surfaces of the filler, which permits enhanced mechanical interpenetration and compatibility with the hydrophobic LDPE matrix.

On the same note, flexural strength rose to an average of approximately 35.5 MPa in the alkali-treated composites compared to the unmixed composites, the flexural strength of which averaged approximately 28.75 MPa. This enhancement was in line with an increase in stiffness and rigidity of the treated system. The arrangement of the NaOH treatment changed the wheat polarity of the agricultural fills, and it was capable of delivering more stresses under bending loads. It also minimized agglomeration of fillers and creation of voids during compression molding that usually undermines flexural properties of untreated bio composites.

Impact resistance remained very low in natural filler composites, but nevertheless increased measurably by ~0.5 kJ/m², to ~2.3 kJ/m², as a result of treatment. This increment indicates a slight

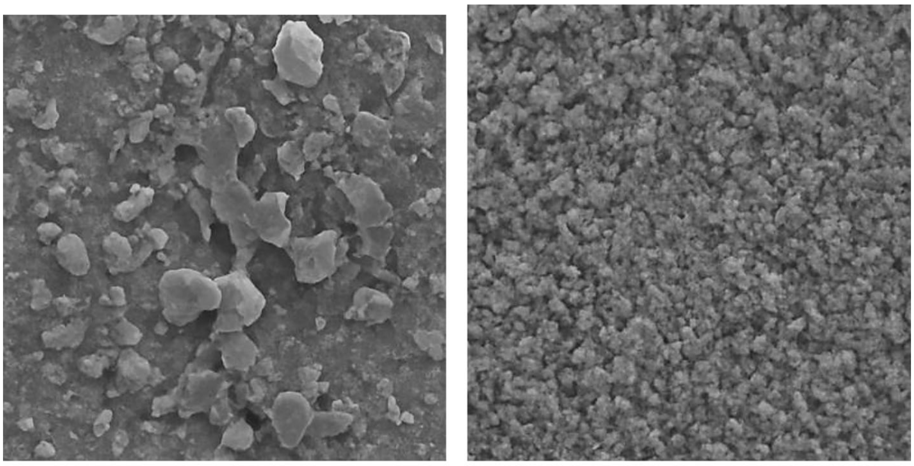
(a) (b).

Figure 10. Comparative SEM image: (a) untreated filler composite, (b) alkali-treated filler composite

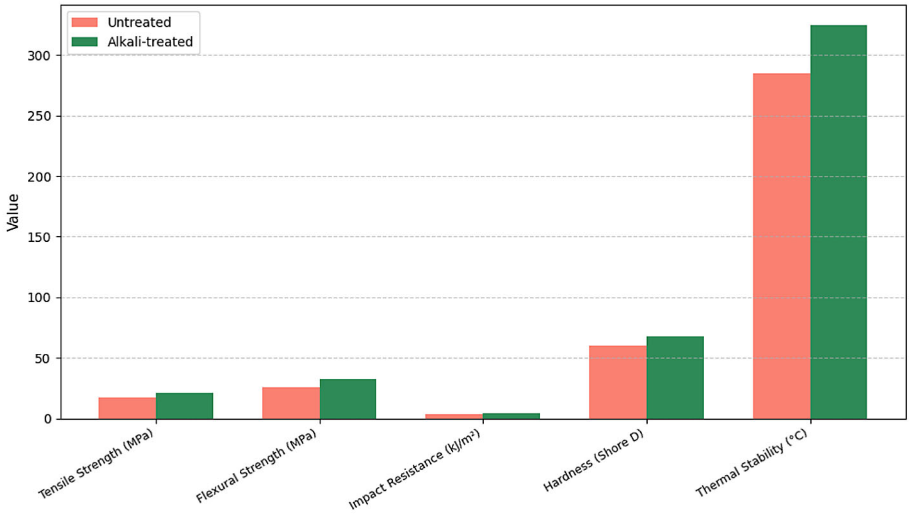

Figure 11. Comparative mechanical and thermal properties: untreated vs alkali-treated filler composites

augmentation in energy dissipation capacity in cracks in expansion and can be associated with a more consistent development of filler dispersion and better ways of load absorption. The Shore D hardness also changed to ~68 (compared to ~60 before), as the resistance to localized plastic deformation was also higher and indicated a tight package of polymer chains induced by filling surface modification.

According to thermal stability data, an increased jump was evident at about 290 °C (untreated) and ~325 °C (treated), as indicated by the thermogravimetric performance. This shows obviously that the addition of NaOH enables fillers in slowing the initiation of thermal degradation, presumably by the increase of filler-matrix bonds and lower thermal stress concentrations. The result of the graph justifies the results of SEM and TGA used in the characterization section of this paper, and hence, the surface treatment of the fillers achieves a great level of change in the thermal decomposition and contributes to a stronger structure in waste-derived polymer composites.

CONCLUSIONS

On the basis of the obtained research results, the following conclusions were drawn:

1. Hybrid composites were successfully developed using recycled LDPE as the matrix and reinforced with alkali-treated agricultural fillers (rice husk, groundnut shell) and recycled HDPE flakes.
2. Alkali pretreatment significantly enhanced the interfacial bonding between fillers and the polymer matrix, resulting in better dispersion and improved mechanical load transfer.
3. Mechanical testing showed that the treated composites had higher tensile strength, flexural strength, impact resistance, and Shore D hardness compared to the composites with untreated fillers.
4. Thermal analysis (TGA and DSC) confirmed enhanced thermal stability and increased crystallinity, contributing to improved structural integrity under thermal stress.
5. SEM imaging demonstrated uniform filler distribution and minimal void formation in the treated composites, supporting the observed improvements in mechanical and thermal properties.
6. Water absorption tests indicated that the treated composites absorbed less moisture, suggesting better durability and resistance to environmental degradation.
7. Utilization of waste-based fillers contributes to sustainable material development by reducing landfill waste and aligning with the circular economy principles.

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