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Original Article

Mechanical Behaviour of composite with Tamarind and Groundnut shell

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Abstract: *The research of sustainable materials has gradually become one of the major research directions in the field of modern engineering, and the replacement for synthetic reinforcement has generated increasing attention as the calls of utilizing eco-friendly,cheap and biodegradable materials continue to be heightened. Bio-waste reinforced composites offer a distinct advantage in that they not only result in composites with superior mechanical behaviour, but also offer a solution to the environmental problem of the storage and disposal of biomass. In this paper, Tamarind shell and Groundnut shell powders were employed as reinforcing agents in polymer composites with the objective of studying their mechanical properties and scope of food packaging applications. The shells collected in plenty as agro-waste, cleaned, dried, powdered into finer particles by grinding, sieved to uniform particles size and loaded into a polymer resin matrix. Composites samples were prepared by compression molding method with different filler loadings to investigate the effect of Tamarind shell and Groundnut shell in tensile strength, flexural strength, impact resistance, hardness.*

The stiffness and impact strength of these composites were also higher than those of pure resin matrix as was also established from experimental investigations. The lignocellulosic architecture of tamarind shell particles resulted in the improved flexural strength and facilitated the load transfer within the polymer matrix. It exhibited higher toughness and better dimension stability using the light and cellulosic groundnut shell powder. The combined reinforcement of both Tamarind and Groundnut shell exhibited the synergistic effect by balancing of strength, toughness and less cost. The optimum filler loading was between 20 and 30 wt. %) for mechanical properties, over which the agglomeration deteriorated the interfacial bonding and properties.

The present study demonstrates the potential of Tamarind and Groundnut shell waste as eco-friendly reinforcement for producing cost-effective composites for automotive interior, furniture, construction panels, and packaging purposes. Results of mechanical testing are in line with the literature of natural filler composites, but this research work goes a step forward by comparing two agricultural waste lesser known for their reinforcement potential in order to achieve better synergy. This study also values the environment by valorizing agro-waste, landfill pressures reduction, and provides circular economy model. Moreover, the study highlights how mechanical testing can provide direction for future scale-up of composite formulations for industrial manufacturing.

The results of this work have an importance not only for the research field in materials engineering, but also from the environmental point of view. The non-renewable glass and carbon fibers could be minimized in industries by adding Tamarind and Groundnut shell to composite materials. This drive supports environmentally sound material creation, fosters the conservation of resources, and opens up the creation of sustainable technologies in line with global climate targets. As such Tamarind and Groundnut shell filled composites are an attractive green material, wherein mechanical performance is coupled with eco-friendly footing.

Keywords: *Composite; Tamarind Shell Powder; Groundnut Shell Powder; Agricultural Waste Utilization; Mechanical Properties; Polymer Matrix Composites; Eco-Friendly Materials; Circular Economy; Tensile Strength; Bending Strength.*

I. INTRODUCTION

A. Background

Composites have been an increasingly important area of interest in the materials science and engineering discipline primarily for their capability to meld favorable properties of two or more phases into a single material system. Synthetic fibers, e.g. glass, carbon and aramid fibers etc., have been traditionally used as strengthening material for reinforcing polymer composites, so as to improve its mechanical properties. However, the use of the finite source, the high energy cost for production, the supply chain and the non-biodegradability generate environmental and economic issues. Such examples have driven the quest for alternative, natural and sustainable solutions that are also more affordable and green.

Agricultural residues, as well as biomass, have been recently identified as potential reinforcing fillers in composites. A number of natural fillers including rice husk, coconut shell, banana fiber, jute, hemp, and bamboo have been considered for enhancing strength and reducing the environmental footprint. In such scenario, Tamarind shell and Groundnut shell, as an abundant agro waste materials, are under utilized as composite filler. They are available, lignocellulosic and their mechanical properties qualify them as a potential reinforcement in polymer composites.

B. Tamarind Hull and Its Importance

Tamarind is grown extensively in Africa, India and other parts of Asia. Huge amounts of shells are generated as waste material during processing of tamarind. Lignin and cellulose are the constituents responsible for the mechanical strength and stiffness properties when tamarind shell is utilized in composites. The relatively hard, fibrous shell structure of walnut shell also imparts to the shell material high load strength which makes it a good candidate for reinforcing polymers. Although a potentially useful resource, tamarind shell waste commonly ends in landfills without its economic use, causing environmental problems.

C. Groundnut Shell And Its Characteristics

Peanut (Arachis hypogaea) is a major oilseed crop in the world. The shells produced in peanut processing make up 25–30% of the pod weight and are wasted as agricultural by-products with low economic value. Groundnut shell contains high cellulose, hemicellulose, and lignin content and has low density and can therefore be used as a composite filler for polymers. It enhances toughness and decreases brittleness and dimensional stability. Furthermore, groundnut shell can be used as low-cost reinforcement candidate for large scale industrial applications.

D. Sustainable Perspective

The use of tamarind and groundnut shells as composite reinforcements has a double edge benefit-being of value addition to the agro-waste and reduction in environmental degradation due to biomass disposal. From a sustainability standpoint, the use of bio-composites reduce reliance on synthetic reinforcements and are in line with international movements toward circular economy concepts. Industrial cost-effective production utilizing agricultural byproducts for high-performance materials and reducing the waste and making resources more sustainable and optimized is possbile.

E. Research Objectives

The main objective of this study is to evaluate for the mechanical properties of tamarind shell powder and the groundnut shell powder as the reinforced polymer composites. The specific objectives include:

- To fabricate composite samples with tamarind and groundnut shell fillers in different ratios.
- To evaluate its tensile, flexural, impact and hardness of the composites.
- To analyze the mechanical performance of the composites made from single and hybrid fillers.
- To verify the environmental and industrial importance of these agro-wastes utilization in sustainable material development.

F. Scope of Study

The main classical concept analyzed in this study were composites with tamarind and groundnut shells as fillers. The work does not include highly modified (chemically) fillers and prefers to consider them in their untreated, powder form (powder fillers). The scope is constrained to polymer matrix composites manufactured by means of compression molding, which is widely used to prepare homogeneous and high performance materials. The data obtained are aiming to be used as a base for a further possibility of utilization of filler functionalization and screening and large-scale application.

G. Significance of Mechanical Property Test

The application capabilities of a composite are governed by its mechanical properties. Tensile strength offers information on the material's ability to resist pulling forces and flexural strength on the capacity to resist tension. Strength is the toughness and the absorption of energy, while hardness is the resistance to deformation on the surface. By analyzing these parameters, researchers can evaluate the potential of tamarind and groundnut shell composites for use as automotive interiors, furniture, building panels and packaging material etc.

H. Comparison with Other Natural Fillers

Some of these natural fillers include rice husk, coconut shell and sawdust, among others as they are commonly investigated. These fillers increase mechanical properties and lower construction price. Tamarind and groundnut shells possess same or higher strength characteristics than coconut shell in some application like flexural and impact. This shell is hard and more fibrous compared to some other agro-wastes which help in promoting a good interfacial bond with the polymer matrix.

Table 1: Comparison of Properties of Agro-Waste Fillers Commonly Used in Composites

Agro-waste Filler	Main Components	Density (g/cm^3)	Co ntribution to Mechanical Properties	Availability
Rice husk	Silica, cellulose	1.35	Hi gh tensile and compressive strength	High
Coconut shell	Lignin, hemicellulose	1.40	High hardness, impact resistance	Moderate
Sawdust	Cellulose, lignin	0.90	Lightweight, moderate strength	High
Tamarind shell	Lignin, cellulose	1.25	Flexural strength, stiffness	Moderate
Groundnut shell	Cellulose, hemicellulose	1.20	Toughness, dimensional stability	High

I. Research Significance

This research serves three interconnected aims, namely, (a) materials development, (b) ecological neutrality and (c) cost-effectiveness. Materials-wise, investigation of tamarind and groundnut shell as reinforcement acquire understanding for bio-composite science. Ecologically, this study provides the possibility of transforming agricultural waste into value-added products, thus relieving the pressure on the environment. The economic production of large amounts of these shells is also making it increasingly possible to use them as inexpensive reinforcements of composites in industries of less developed regions.

J. Chapter Summary

Chapter One Introduction This chapter introduced the background, the problem statement, the significance, the objectives and the scope of the study of tamarind and groundnut shell reinforced composite. It has set the background for sustainability, introduced the possibility of these agro-waste materials and emphasized the requirement of mechanical property studies. Chapters that follow will survey the available literature, discuss the methodology employed, report experimental results, interpret results and discuss uses for these composites in industrial and environmental settings.

II.LITERATURE REVIEW

A. Introduction

Researchers are now focusing on the use of natural fibers and agro-waste as reinforcement in polymer composites because of increasing demand for the cost effectiveness of production process, environmental sustainability, and the decreasing sources for petroleum derived materials. Agro-based filler literature reported the enhanced mechanical, thermal, and tribological properties of the composites over the neat polymers. The present work is centered on Tamarind shell and Groundnut shell as reinforcements, but it is important to revisit the studies on natural fillers, mechanical consequences and present research gaps to understand the originality of this work.

B. Composites with Natural Fibers and Agricultural Waste

In the recent decade, considerable attention has been paid toward the use of natural fillers including rice husk, wheat husk, coconut shell, jute, hemp and sawdust as low cost reinforcing agents. According to Mohanty et al. (2000) stiffness increase is achieved as natural fibers not only increase stiffness but also decrease the fiber volume, and thereby the weight of the composite, leading to lightweight material development. John and Thomas (2008) also observed that lignocellulosic fillers have increased interfacial bonding with polymer matrices because of the rough surface morphology, which facilitates stress transfer. Agricultural residues are widely available and can be scaled up for mass production of composites without compromising the food source.

C. Mechanical Properties of Compounds with Natural Fillers

Mechanical performance is one of the most important properties of NFCs. Joseph et al. (1999) also found that the addition of coconut shell powder to polyester composites increased impact resistance and hardness with a minor decrease in tensile strength at higher filler content. Similarly, Singh et al. (2013) proved that the silica in husk has greatly enhanced the flexural strength of the rice husk reinforced composites. This implies that the mechanical properties are substantially affected by the filler nature and morphology

D. Tamarind Shell Used as Composite Reinforcement

The study of tamarind shell as a reinforcement is limited, however undergoes continuous and intensive development. A study by Kumar et al. The flexural properties of the epoxy composites containing tamarind seed and shell powder were found to be better than those of the neat epoxy composites, as reported by (2016). The presence of lignocellulosic matrix in tamarind shells strengthens and dimensional stabilizes the boards and high lignin content enhances moisture resistance. Further, Reddy et al. (2020) tamarind shell powder enhances the thermal stability of polyester-based composites, rendering them as good candidates in the area of moderate heat resistant applications. However, the mechanical properties measurements are insufficient and more in-depth studies are required.

E. Groundnut Shell In Composites.

Groundnut shell was investigated in greater detail than the tamarind shell. According to Aigbodion et al. (2010) reinforcement of aluminum composites with groundnut shell ash increased the hardness and the wear resistance factor significantly. Groundnut shell powder has also been reported to promote tensile and impact strength in polymers composites (at 15–25 wt.%) and impact testing (15–20 wt.%) with the polypropylene (Adekunle et al., 2014; Satapathy and Tripathy, 2014). %. Its low density and high cellulose content make it an interesting candidate for lightweight construction. Moreover, groundnut-shell-based composites have been shown to have good resistance to water absorption following chemical treatment of the surface as reported by Idicula et al. (2016).

F. Hybridization of Reinforcement

Natural Fillers Only hybrids Drawbacks While the use of three-dimensional material as mentioned in the first section of the article certainly contributes significant enhancement of the properties, the UF/ MDF composites mass density is found to be reduced by densification via hot compaction.

Graphical Abstract Open image in new window Hybrid composites of two or more natural fillers have been emerging as promising materials due to their synergistic effects. Sreekala et al. (2002) as optimal property enhancer with regards to tensile strength and toughness that hybrid materials themselves, natural-synthetic fillers strokes to take care. Similarly, Mishra et al. (2018) studied the enhancement of flexural and compressive strengths of epoxy composites by using BST pulverized from coconut shell and rice husk. This approach indicates that a better performance of tamarind and groundnut shells may be achieved when used in combination other than separately. This balance between stiffness and toughness is crucial from the perspective of the practical application of hybrid composites.

G. Chemical Composition of Agro-Waste Fillers

The mechanical properties of agro-based composites are directly affected by the chemical structure of fillers. Lignin is responsible for rigidity and thermal stability, whereas cellulose and hemicellulose contribute strength and flexibility. Table 2.1/chapter 2 summarizes the normal chemical composition of tamarind and groundnut shell in comparison with other agro-wastes.

Filler Type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash Content (%)	Reference
Rice husk	35–40	25–30	20–25	15–20	Singh et al. (2013)
Coconut shell	30–35	20–25	40–45	1–3	Joseph et al. (1999)
Tamarind shell	28–32	20–22	35–40	5–8	Kumar et al. (2016)
Groundnut shell	32–36	25–28	28–32	2–5	Satapathy (2014)

Referring to the table tamarind shells high lignin and binder value provides stiffness and moisture resistance and groundnut shells provide high cellulose value leading towards toughness and flexibility. Therefore, it is anticipated that composite of the two [21, 22] would have superior mechanical properties.

H. Problems Encountered During the Use of Agricultural/Waste Fillers

There are however also disadvantages to the use of natural fillers. The weak interfacial interaction between the hydrophilic fillers and the hydrophobic polymer matrix will weaken the mechanical properties of the composites. The heat treatment, alkali treatment, silane coupling, or acetylation have become typical surface processing treatments to improve its compatibility with matrix (John & Thomas, 2008). On the other hand, filler agglomeration occurs at the high loading with the stress is concentrated and the property is degraded. Moisture absorption is also a problem, adversely affecting the dimensional stability in wet conditions.

I. Research Gaps

- Although many studies have been conducted with agro-waste fillers, few issues exist that have not been covered:
- Irrevocable tests were performed on shell of kernel of tamarind as reinforcement material for polymer composites, particularly in untreated powder form.
- There are hardly any comparative studies that compare tamarind shell and groundnut shell as hybrid fillers.
- In the case of active damping capacity, there is no simultaneous universal mechanical characterization (tensile, flexural, impact, hardness).
- Lack of political agape/panophagy.RELATED Industrial-sized analyses of cost-effective returns deny nature.
- These lacunae underscore the novelty of the current work which explores the mechanical performance of tamarind shell and groundnut shell composites systematically in individual and hybrid modes.

J. Summary

This review has summarised the literatures pertaining the natural fillers and their utilization in composites and highlighted on the tamarind shell and groundnut shell. Although groundnut shell has been well studied, tamarind shell is less studied despite of its appealing properties. The review revealed that the hybrid reinforcement may be used for enhancing the strength and toughness, and holds a promising direction for future studies. The research gaps identified are therefore employed as the basis of the methodology used in this work to provide a comprehensive characterisation of the mechanical properties of tamarind and groundnut shell composites and their possible applications.

III. MATERIALS AND METHODOLOGY

A. Introduction

Since the fabrication of composites involves the proper selection and preparation of materials, a suitable fabrication and testing procedure, efficient and economical production is much dependent on success. The chapter focuses on raw materials of fabrication, process used for the preparation of tamarind and groundnut shell powders, production of composites with polymer matrix and mechanical testing techniques that were used to study the developed composites.

B. Raw Materials

a) Tamarind Shells

Tamarind pods were obtained from local tamarind processing units as the waste material. The shells were also rinsed several time to clean them from dirt, residue of pulp, and other impurities. They were sun dried for few days and later oven-dried at 80°C for 6 h to ensure moisture removal. The dried shells were milled in a ball mill to a powder. The powder was passed through a 100 μm mesh sieve to obtain uniform particle size, promoting uniform composite reinforcement.

b) Groundnut Shells

Groundnut shells were collected from oil extraction units as they are normally disposed as waste. The shells were washed to eliminate any remaining seed and fines. Like tamarind shells, they were carefully dried in an oven at 80°C for six hours to reduce absorption of moisture. The dried faeces were grounded by high-speed grinder and then sieved by 100um meshes. The density of groundnut shell powder was lower than that of tamarind shell powder, suggesting that it has potential for use in lightweight composites.

c) Polymer Matrix

The matrix material was chosen in the form of polyester resin because of its broad use, adequate mechanical strength, low cost and easy processing. A methyl ethyl ketone peroxide (MEKP) curing agent was used, along with cobalt naphthenate which serves as an accelerator. Epoxy was replaced by polyester in favor of a cheaper price, which fits a large-scale use in growing sector of new technology.

C. Composite Fabrication

Uncompensated Shaping by Mixing of Filler and Resin During the mixing the fillers with resin in which the the resin/filler proportion, which has been described under 2.1. The tamarind and groundnut shell powders were redried and then mixed to remove the moisture induced during formulation. The powders were blended with the polyester resin at different weight ratios: 10 wt. %, 20 wt. %, and 30 wt. %. In case of hybrid composites, tamarind powder and groundnut powder were combined in equal proportion (e.g., 10% each, in a 20 wt. % composite). Fillers were evenly dispersed in the resin by mechanical stirring.

a) Molding Process

The composites were produced by hot compression molding. A stainless-steel mold was used with dimensions of 150 mm × 150 mm × 10 mm. The mold was treated with a thin layer of polyvinyl alcohol (PVA) as a release agent. The resulting resin-filler composition then was introduced into the mold and leveled to prevent the formation of "pockets" within the surface. Compression was performed by hydraulic press at 20 MPa and the composites were cured for 24 h at room temperature and then post-cured at 60 °C for 3 h to enhance cross-linking.

b) Composite Variants

With changing the filler composition, a set of composite samples were prepared. The material proportions adopted for this study are presented in Table 3.1.

D. Mechanical Testing Methods

ASTM D638 standard was applied in tensile measurements by UTM. Dog-bone shaped (165 mm × 19 mm × 3 mm) samples were produced. The test was carried out at a cross-head speed of 5 mm/min and the tensile strength, tensile modulus, and elongation at break were recorded. Flexural strength was measured according to ASTM D790 (three-point bending test). Rectangular samples of size 125 mm × 13 mm × 3 mm were used. The gauge span was fixed at 50 mm at a rate speed of 2 mm/min. Flexural modulus and maximum bending stress were determined. Charpy Impact resistance test ASTM D256 was conducted. The energy absorbed during fracture was examined using unnotched specimens with size 65 mm 12.7 mm 3 mm. This test revealed the impact of the composites' toughness. hore D hardness of all samples were tested according to ASTM D2240. Five readings were recorded for each specimen and reported as mean. It was essential to study the resistance of the surface indentation and sliding wear.

E. Data Analysis Approach

The mechanical properties of composites filled at several weight fractions were compared with the pure matrix to evaluate the experimental results. The influence of increasing the filler content was investigated in order to determine the optimal loading. Synergistic effects were studied between hybrid composites and individual filler composites. The findings were further compared with those of earlier investigations on other agro-waste fillers for similarities and differences.

F. Limitations of the Methodology

This methodology had certain limitations. The authors used untreated tamarind and groundnut shell powders; we suspect that chemical treatments could enhance interfacial bonding with the polymer. The researches were limited merely on the mechanical performances, and the thermal and tribological behaviors were not studied. Additionally, upscale of the production was not successful and the obtained values are not more than laboratory-scale sample results.

G. Chapter Summary

This chapter also explained the materials used and the process in which tamarind and groundnut shell-filled composite were fabricated. The detailed methods for the systematic preparation of fillers, the fabrication of composites by compression molding, and the mechanical testing were described elsewhere [26]. Various compositions were also prepared to study the effect of filler loading on mechanical properties. In the next chapter, experimental results obtained from mechanical test will be presented, uncovering the effect of tamarind and groundnut shell powders towards composite performance.

IV MECHANICAL PROPERTIES AND TESTING

A. Introduction

Mechanical properties evaluation is extremely helpful in the assessment for potential engineering and industrial application scope of TMA and GNS composites. Strength, toughness, and surface hardness are desirable properties in a material when used for load-bearing and impact applications. The tensile, flexural, impact and hardness of composites were investigated in this chapter for the composites prepared with different fillers compositions as shown in the methodology section. These values are contrasted with those for neat resin and used to optimize the composition of the filler.

B. Tensile Properties

The tensile strength is the maximum amount of tensile stress that the material can withstand before failure occurs. The results showed that composites filled with tamarind shell powder (T20) have a higher tensile strength than those containing groundnut shell powder (G20). Tamarind, rich in lignin, allowed enhanced stress transfer from the resin to the filler in composites properties. However, with higher filler loadings (30 wt. %), the tensile strength of tamarind and groundnut composites also decreased because of agglomeration of fillers and poor interfacial bonding. As revealing the synergism between them, hybrid composites (TG20 and TG30) showed better performances than the single fillers at the same loadings. TG20 showed the best improvement in tensile strength (by about 25% with respect to neat resin).

C. Flexural Properties

Bending test determines the flexural strength of composites. Composite with tamarind shell had higher flexural strength than those with groundnut. This may be because the tamarind shells are stiff and fibrous, and they increased the load-carrying capacity under bending. For example, T20 exhibited 30% flexural strength increase over the neat resin. Groundnut shell composites (G20) showed moderate improvements, but were more beneficial in increasing the flexibility. Hybrid composite once more showed a compromise between stiffness and flexibility, properties, with TG20 yielding a better flexural modulus than all other conditions.

D. Impact Resistance

Impact resistance is its ability to absorb energy before fracturing. The excellent energy absorption of groundnut shell composites could be attributed to cellular structure and the higher cellulose content in shells that otherwise absorbed energy in the impact. the neat resin and maximum improvement of impact strength about 40% for G20 was observed. Higher resistance against impact was observed for the tamarind shell composites, albeit a less impact resistance was reported as a consequence of the stiff core for the samples which prevented energy dissipation. Nevertheless, hybrid composites (TG20 and TG30) could counterbalance this trend and presented acceptable stiffness and enhanced toughness. At the highest total impact performance was achieved by TG20 showing 35% better impact resistance compared to neat resin.

E. Hardness Properties

Tamarind shell composites had higher Shore D hardness than groundnut shell composites, as revealed by hardness test. T30 had a 20% increase in hardness, in particular, in comparison with neat resin. This is attributed to the high lignin content in the tamarind shells, which enhances the rigidity and surface resistance. For GN composites, although they were not harder, better resistance to brittle fracture was observed. Hybrid composites showed adequate hardness with relatively good toughness, which is promising for applications that demand a balance between wear resistance and energy absorption.

F. Comparative Data

Table 3: Mechanical Properties of tamarind and groundnut shell composites

Sample ID	Tensile Strength (MPa)	Flexural Strength (MPa)	Impact Strength (kJ/m^2)	Hardness (Shore D)
Co (Neat resin)	35	55	3.0	68
T10	38	62	3.2	71
T20	44	72	3.5	74
T30	40	65	3.1	82
G10	36	58	3.8	69
G20	42	64	4.2	70
G30	39	60	4.0	72
TG20	44	70	4.1	75
TG30	43	68	4.0	77

It is clear that filler loading has a crucial effect on mechanical properties based on the data. The flexural and hardness characteristics were enhanced by the tamarind shell, but the impact resistance was increased by the groundnut shell. Hybrid structures showed acceptable mechanical properties, the TG20 always being the best group.

G. Discussion

The findings show that agro-waste fillers such as those from tamarind and groundnut shells may substantially enhance the mechanical properties of polymer composites. Tamarind shells provide stiffness, bending strength, and hardness, and can be used for structural stiffening applications. The Tougher and Impact strength can water made to be improve by the inclusion of Groundnut's shells in the mixture, particularly in packaging and automotive interiors. A decrease in mechanical properties at the 30 wt. % w/w filler loading suggests that appearance beyond a certain point fails to result in efficient dispersion, probably due to agglomeration. This may imply that there is an optimal filler loading range of 20–25 wt. % for achieving balanced performance. The hybrid composites showed remarkable reinforcement and good synergy on both strength and toughness, making them applicable in a wider engineering range.

H. Chapter Summary

The mechanical testing of tamarind and groundnut shell hybrid composites is discussed in the next chapter. Composites made with tamarind shell showed better flexural strength and hardness than the groundnut shell composites indicated improved impact resistance. Hybrid composites (TG20 especially) had the best overall balance of mechanical properties in all the tests. These results support the potential of both tamarind and ground nut shel powders as sustainable reinforcements in polymer composites and further analysis would be carried out in the discussion chapter.

V. DISCUSSION AND ANALYSIS

A. Introduction

From the experimental observations presented in Chapter 5, it is established that tamarind and groundnut shell powders have a strong impact on the mechanical properties of polymer composites. However, the performance of a composite can not be based on individual measures as related to properties and a combined view is necessary to understand the relation between filler properties, matrix interaction, and properties. The chapter elaborates on the findings, interpret how the type of filler and its content influenced these behavior, the comparison of such results with available literature, and implications of using such agro-waste reinforcements in environmentally benign material designs.

B. Influence of Filler Type

Both the tamarind and groundnut shells have different chemical composition and physical structure that account for the differences in mechanical properties. Husks of the tamarind, which had higher lignin content, resulted in higher rigidity and hardness. This led to the enhancement of flexural strength and surface resistance, indicating that tamarind composites could be used for loadbearing and wear applications. Shell of groundnut on the other hand was found to possess higher content of cellulose, low density and therefore higher energy absorption under impact loading. This feature made them most suitable for applications, which require toughness rather than stiffness. The balanced property between flexural, tensile and impact was shown the best in the hybrid composites, and TG20 was better in the combined property of tensile, flexural and impact than the single filler composites. This reinforcement is associated with a good balance provided by stiffness of tamarind shells and the rigidification of groundnut shells improving the stress distribution in the matrix.

C. Effect of Filler Loading

Composites performance was highly sensitive to the load level of the fillers. At 10 wt. %, which were limited, indicating that the filler was not enough to establish a significant reinforcing network. At 20 wt. % of the fiber fraction, all the composites exhibited the best properties, tensile, flexural and impact strength were all up to the maxima. Beyond 30 wt. %, but its mechanical properties reduced on account of filler agglomeration, voids and poor interfacial adhesion. This trend is in agreement with the findings of Joseph et al. (1999) and Satapathy (2014) who found that properties of natural filler composites were observed to be maximum at 20–25 wt. % of the filler. % range. Too much filler is detrimental to the homogeneity, leads to higher concentration of stress, and limits the mobility of the polymer chain, which would hamper the mechanical performance.

D. Comparison with Previous Studies

The results of this study are in line with the literature reports on agro-waste fillers. In the case of coconut shell composites investigated by Joseph et al. (1999) the hardness and flexural strength of the tamarind shell composites were improved. The behaviour of groundnut shell composites was similar to the BH composites reported by Singh et al. (2013), who obtained an enhancement in toughness and impact strength at the low filler loadings. The significance of this work is to use a combination of tamarind and groundnut shells as hybrid fillers. There are few reports on comparing or using the combination of these particular agro-wastes. Significant synergies in the hybrid composite compared with the behaviour of their single-filler counterparts were observed, validating the assertion made by Mishra et al. (2018) in which tensile and impact properties both increase by hybridization.

E. Implications for Industrial Applications

Plot of mechanical properties for the composites of tamarind and groundnut shell indicates the versatility of the materials for various industrial uses. Furnishings, construction panels and automobile dashboards that require stiffness may benefit from hard Tamarind composites. Groundnut composites, which have good impact strength, may be used in packaging materials, helmet linings and protective covers. Hybrid-type composites have the widest potential uses, bring the advantages of fillers and fillers into play together, and are appropriate for multifunctional components for automotive interiors, inexpensive housing materials and consumer goods. Also, tamarind shells and groundnut shells are cheap and readily available which makes the process more economical. Industries located in the producing areas of these crops, namely India, Africa and Southeast Asia, could benefit from the use of this agro-waste and find a way to reduce costs and environmental impact at the same time.

F. Environmental and Economic Perspective

On the environmental perspective, employing agro-waste as composites helps in: (i) waste valorization, (ii) alleviating the pressure on landfills, and (iii) limiting the combustion of shells which triggers carbon release. This is consistent with the circular economic concept of reclaiming waste for productive use. Economically, these fillers reduce the reliance on costly synthetic fibres such as glass or carbon and offer the possibility to produce economical composites that still perform well functionally. The shift to bio-composite reinforcing also benefits global sustainability objectives through the elimination of the need for non-renewable petroleum based reinforcement. Tamarind and groundnut composites present a case of material science converging with environmental betterment and serve as a pacesetter for the intertwining challenges with the effect of sustainable development.

G. Limitations and Opportunities

However, the limitations were noted despite it's being a very positive outcome. The lack of chemical surface treatments hinder interfacial bonding, and an improvement can be obtained through alkali or silane treatment. Moisture uptake response was not explored in this work which is still crucial for outdoor applications. Moreover, the research was focused only on the mechanical testing, the thermal stability, degradability, and tribological behavior between other studies should be investigated. It is also essential to investigate the possibility of large scale process methods beyond the laboratory scale compression molding. Other processing routes should be investigated for industrial application; e.g. extrusion and injection moulding. Life cycle analysis (LCA) would offer an overar ching perception o f environmental benefits with respect to syntheti c composites.

H. Chapter Summary

This chapter of discussion focused on the results of the mechanical tests and explained how filler type, filler loadings, and hybrid reinforcements affected the RPP composite. Stiffness and hardness were enhanced by tamarind shells, and toughness and impact resistance were improved by groundnut shells. The hybrid composites, especially TG20, obtained the best comprehensive properties, which indicated that there are synergistic effect between the fillers. These findings are in agreement with the reported literature and further knowledge when hybridization of tamarind and groundnut shell blend is concerned. Industrial, environmental and economic implications reveal the prospects of these composites to be sustainable substitutes for synthetic substances. The next chapter will discuss applications and prospects of the tamarind and groundnut shell composites.

VI. CONCLUSION

In the present investigation, an attempt is made to investigate the possibility of tamarind and groundnut shells as reinforcements in polymeric composites in terms of mechanical and overall performance of the material. This work was motivated by the demand for sustainable, low-cost and environmentally friendly replacements of synthetic fillers (e.g., glass and carbon fibers). Through the reuse of agricultural waste by-products that would be otherwise disposed of as waste, this research prompted consideration not just of material performance but also broader environmental and economic performance of agro-waste repurposing. It is concluded that tamarind and groundnut shells have a complementary contribution in mechanical properties as a reinforcing material having differential lignocellulosic content. Evaluation showed that tamarind shell particles were able to increase the flexural strength and hardness as a result of their higher rigidity as well as lignin content. On the other hand, groundnut shell fillers were beneficial for impact resistance and toughness because of their cellulose-rich structure and lighter weight. When both the reinforcements were utilized in hybrid composites, a synergistic effect was realized leading to stiffness-toughness trade-off and delivering a better performing material in comparison to single.filler composites.

The finding of a range of the filler loading usually between 20 and 30 wt. %, in which mechanical properties were remarkably enhanced with no obvious disadvantages. Outside this range, problems such as agglomeration of the filler, poor interfacial bonding and void formation caused a degradation in performance. This finding highlights the significance of well-defined formulation and processing methods in the manufacture of natural-filler composites. These composites have a good application prospects from industrial point of view. At the other end of the spectrum, plastic-matrix composites can be low-cost, lightweight, and have a fair, but not quite steel, strength, and often are used in automotive interior parts, low load-carrying panels, packaging, and furniture. The employment of tamarind and groundnut shells also leads to waste valorization, which consists in removing large amounts of biomass from landfills or incineration (which leads to CO 2 production), to convert them to better uses. This is a direct contribution to global sustainable development goals and is consistent with the rationale of a circular economy.

Apart from the mechanical results, the present work also underlines the eco-society dimension of the materials science. This not only minimizes reliance on non renewable artificial materials, but also develops potential rural industry and small scale industry in the grass root level functioning with locally available agriculture residues. These efforts can also create employment, help farmers and promote rural economies, connecting material innovations to improve social well-being. But there are still some issues to scale up the utilization of tamarind and groundnut shell composites for commercial purpose. However, issues such as water uptake, long-term usage properties and uniformity in filler particle size also need to be dealt with through more research and developments in material processing. In addition, coupling agents, surface treatments or hybridisation with other natural fibres can also improve compatibility and performance of such composites. Finally, it is concluded that the use of the fillers, tamarind and GNS, is a potential class of sustainable fillers for polymer composites. They provide a promising approach to environmentally friendly, low cost and mechanically sound materials that can either substitute or be used in combination with synthetic composites for numerous applications. Follow-up studies should address long-term performance tests, ways of large-scale production and industrial integration to tap the entire potential of these agro-waste composites. Through uniting materials innovation and environmental stewardship, such research opens avenues for more sustainable technologies and a greener future.

VII. REFERENCES

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