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MECHANICAL CHARACTERISATION OF RECYCLED HIGH-DENSITY POLYETHYLENE HDPE (rHDPE) REINFORCED WITH BANANA STEM FIBRE USING MIX-DESIGN OF EXPERIMENTAL (MDOE) ANALYSIS

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ABSTRACT

This study investigated the development of a thermoplastic composite from waste recycled high-density polyethylene (used water bottle) using overleaf banana pseudo-stem as fibre. Recycled high-density polyethylene (rHDPE) was used as a polymer matrix, and the fibre was prepared via mechanical methods. The banana stem fibres were introduced at 10, 20, 30, 40, and 50% volume fractions. The matrix and the fibre were compounded using a two-roll mill machine at the temperature of 170°C then compressed using a compression moulding machine at 150°C for 5 minutes and at 2.5Pa. The thermoplastic composites produced were characterised and optimised to examine the effects of fibre ratio on mechanical properties, including tensile strength, hardness and impact strength. The properties of the composite material increase as the fibre content increases but decrease when the fibre loading decreases in combination with recycled low-density polyethylene (rHDPE). Thus, the critical loading ratio of fibre to rHDPE was obtained at optimal design parameters of 22.8% (Fiber) and 77.2% (RHDPE), respectively, at a p-value of 5%. The predicted properties of the composite at these optimum conditions were 16.39 MPa, 96.18 shores and 1.14 J/mm for tensile, hardness and impact properties, respectively, with a 10% margin error for model acceptance. The research demonstrated that converting banana stem fibre and RHDPE into composite material is a sustainable and environmental waste disposal and management approach.

KEYWORDS
Thermoplastic, composite, pseudo-stem, optimisation, fibre-matrix

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INTRODUCTION

Green composites composed of biopolymers derived from renewable resources and cellulose fibres have been gathering much attention from the standpoint of protecting the environment from waste polymeric material disposal problems and saving petroleum resources (Reddy, 2013). Composites have many advantages: low cost, lightweight, nontoxic, and biodegradable. There are two basic phases of composite materials: one is known as matrix, and the other is called reinforcing material. Reinforcing material is a discontinuous phase embedded over a continuous phase (matrix material). Hence, the reinforcing phase improves the properties of the composites while stress relief in between and protection of the reinforcing phase from environmental damages is ensured by the matrix (Chauhan, 2011).

Banana fibre is a lignocellulose fibre obtained from the pseudo-stem of the banana plant (*Musa genus*) upright, central support structure of the banana plant belonging to the *Musaceae* family. Despite their name, Banana stemsstems are not true stems but are pseudo-stems comprised of overleaf sheaths. Once the fruits of the banana plants are cut, the plant's stems are usually thrown as waste, which accumulates in the areas of the plantation. This fibre is known to be the best, with relatively good mechanical properties (Yagyu, 2014; Seena, 2006).

The bulk density, water absorption and tensile strength of the BF/HDPE composites increased with fibre content (Neher *et al.,* 2022). Another study by Tuan *et al*., 2022 Babatunde *et al.* (2016), and Emekwisia *et al.* (2019) was carried out to investigate the effect of mercerisation of banana fibre in polylactic acid (PLA) composite. The results revealed visual evidence that surface impurities were removed from the fibre by NaOH treatment, and increases in mechanical properties of banana fibre-reinforced polylactic acid (PLA) composites were obtained. It is shown that using treated banana stalk fibre as reinforcement in LDPE and polyester improves the physico-mechanical properties of thermoplastic and thermosetting composites, respectively.

Essam *et al.* (2021) investigated the effect of physical, mechanical, and thermal properties and soil biodegradation of HDPE blended with PBS/HDPE-g-MA composites. The results revealed their physical interaction between the components and mechanical properties analysed, establishing that the different ratios of PBS and HDPE-g-MA to the HDPE matrix resembled those of the neat HDPE. Accumulation of synthetic plastic products such as carry bags, pouches or multilayered packaging, which have been discarded after use in the environment to the point that they create problems for wildlife and their habitats simply causing significant aesthetic blight and clogging drainage systems, hence, due to the plastics have attracted increasing attention as a largescale pollutant (Charles, 2022).

The indiscriminate burning and dumping of plastic (such as rHDPE) solid waste produces climate-related emission that causes climate change, and the residue may be channelled into a water source, polluting the water and aquatic environment. Therefore, this research investigates the mechanical properties of banana fibre/rHDPE composites using Mix-Design Experimental analysis for optimum parameters.

MATERIALS AND METHODS

High-density polyethylene (HDPE) and banana stem (*pseudo-stem*) were sourced from the Gyallesu area, Zaria local government in Kaduna State. rHDPE was washed with detergent to remove debris and sun-dried, followed by further reduction into smaller portions before being shredded into pieces by a shredding machine (DHS, 20). As reported by Tuan and Thi (2022), the fibre was extracted using a mechanical method, washed thoroughly with water, sun-dried for 30 hours (from 8 am to 6 pm three times) and cut into 5 mm size through scissors.

Composite Preparation

Thermoplastic composites manufactured

Thermoplastic composites were produced in a two-stage process. For the first stage, shredded rHDPE was fed into the rolls of two - a roll mill machine (802T-WSIP) through the nip. A band and bank were allowed to form on the front roll before introducing banana stem fibre, which was previously cross-mixed for 2 minutes. Before this, the rolls' nip setting attained the desired thickness of 3mm. The temperature of the rolls for the two-roll mill machine was set to absolute 170°C, the temperature was allowed to be altered for 45 minutes, and the machine was operated at 240 rpm.

For the second stage, thermoplastic composite test specimens were produced using a hot press compression moulding machine (3851-0) at 150°C for 5 minutes and 2.5Pa in a standard mould size of 120mm x 120mm x 3mm was utilised. It was pre-heated before melting for five minutes under heat and cooled for three minutes. All samples were made according to American Society for Testing and Materials (ASTM) standard specifications and cut to specific dimensions for characterisation. Specimens were stored in controlled conditions at 50% relative humidity and 25°C before testing according to ASTM standards.

Design of Experiment by Mix-Design

Today, the Mix-Design of RSM is widely used to optimise process variables in mixing proportion. This technique is based on a multivariate model consisting of an experimental design to provide sufficient and reliable response values, provide a mathematical model that best fits the data obtained from the experimental design, and determine the optimum value of the independent variables (Al-Salihi *et al.*, 2022).

Thermoplastic composites composition of banana fibre to RHDPE ratio were formulated by Design of Experiment (DOX) as shown in Table 1 with each independent variable of low and high coded factors. Design Expert 13.0.1 software was used for the ANOVA, regression and graphical analysis of the data statistically at probability ($p<0.05$). Mechanical properties were taken as the response of the design experiment for the thermoplastic composite process. The experimental data obtained by the above procedure was analysed by the mixture design of response surface methodology in design expert using equation (1)

$$Y_{response} = \beta_i X_i + \beta_J X_J + \beta_{iJ} X_i X_J \sum_{i,j}^{n} \quad [(A - B) + (A - B)^2] \qquad (1)$$

Y is a response, i and j are linear coefficients, X_i and X_j are coded independent variables variables variables of A and B, respectively, β is the regression coefficient, and n is the number of factors studied. The equation was also validated by carrying out a confirmatory experiment through equation (2)

$$Confidence\ Interval = y \pm 3 \times \frac{S.D}{\sqrt{n}} \qquad (2)$$

Table 1: Mixture components for thermoplastic composites composition

Component	Name	Units	Type	Coded Low	Coded High
A	A: RHDPE	%	Mixture	+0 ↔ 50	+1 ↔ 90
B	B: Fiber	%	Mixture	+0 ↔ 10	+1 ↔ 50
			Total=	100.00	L_Pseudo Coding

Composite Characterisation

The various groups of prepared thermoplastic composites were characterised by each sample's mechanical properties and behaviours at different test conditions. Impact, tensile and hardness behaviour of prepared composites were evaluated through the utilisation of Resil impact tester (CEAST resil family 6957-500-NILEST Zaria), Durometer hardness tester (Muver Duromeler-2019 NILEST Zaria) and Tensometer (Houndfied tensometer W6465- NILEST Zaria) respectively. The test data were analysed by Mix-Design of design expert software.

RESULTS AND DISCUSSION

Statistical Analysis of the Model

Table 2: Analysis of variance for thermoplastics composite

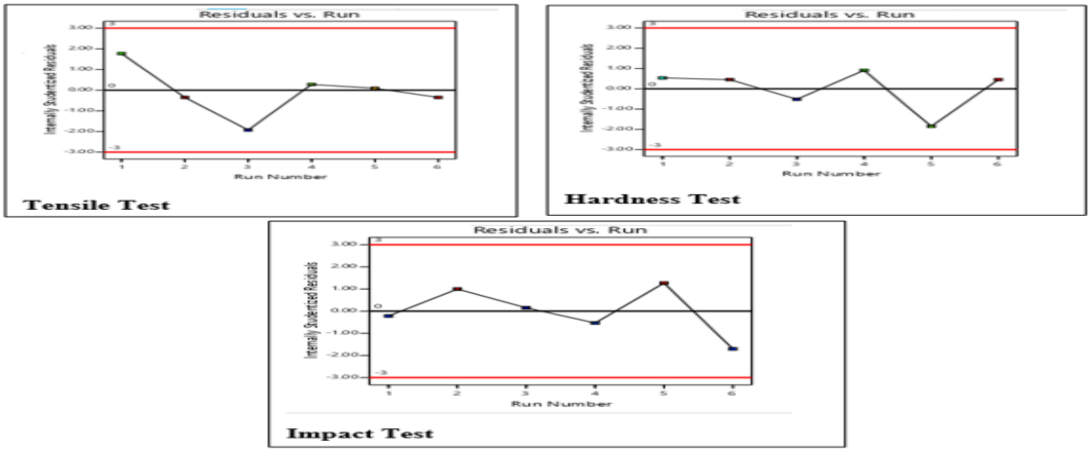
Source	Sum of Square					
	d_f	Tensile Test	d_f	Hardness Test	d_f	Impact Test
Model	1	46.75*	1	8.69*	1	1.25*
(p-value)		(0.0027)		(0.0003)		(0.011)
Residual	4	4.26	4	0.2392	4	0.2522
Adq.Precision		12.5661		22.8753		8.4497
Std. Dev.		1.03		0.2446		0.211
Cor. Total	5	51.01	5	8.93	5	1.50

, **, significant at $p<0.01$ and $0.01\leq p<0.05$

Table 2, obtained from the mix design of RSM, showed inference for linear mixtures using Type I sums of squares. The model F-value of 46.75, 145.36 and 19.83 for tensile strength, hardness and impact, respectively, implies that the model is significant at $p< 0.05$. Adeq Precision measures the signal-to-noise ratio and shows that a ratio greater than 4 is desirable with a correlation coefficient of less than 0.2 between differences of predicted (R^2) and adjusted (R^2) in reasonable agreement.

Table 3: Regression coefficients of coded variables

Coefficient	Tensile Test	Hardness Test	Impact Test
β_i	18.79	97.21	1.53
β_j	11.31	93.98	0.31



Tensile Test **Hardness Test** **Impact Test**

Figure 1: Reliability of the Experimental Test

The model's regression coefficients (β) show the relationship between changes in process conditions and changes in properties of thermoplastic composites (Table 3). The regression coefficient Table 3 results implied that model equation (2) was reduced to equation (3) because no interaction factors were significant to the model. The reliability of the experiment diagnoses with internally studentised analysis (Figure 1) indicated that none of the experimental runs were affected as obtained values fell within the control limit.

$$Y_{response} = \beta_1 A + \beta_2 B \qquad (3)$$

Effect of Process parameters (RHDPE/Fiber Ratio) on Tensile Strength, Hardenability and Impact strength of Thermoplastic Composite

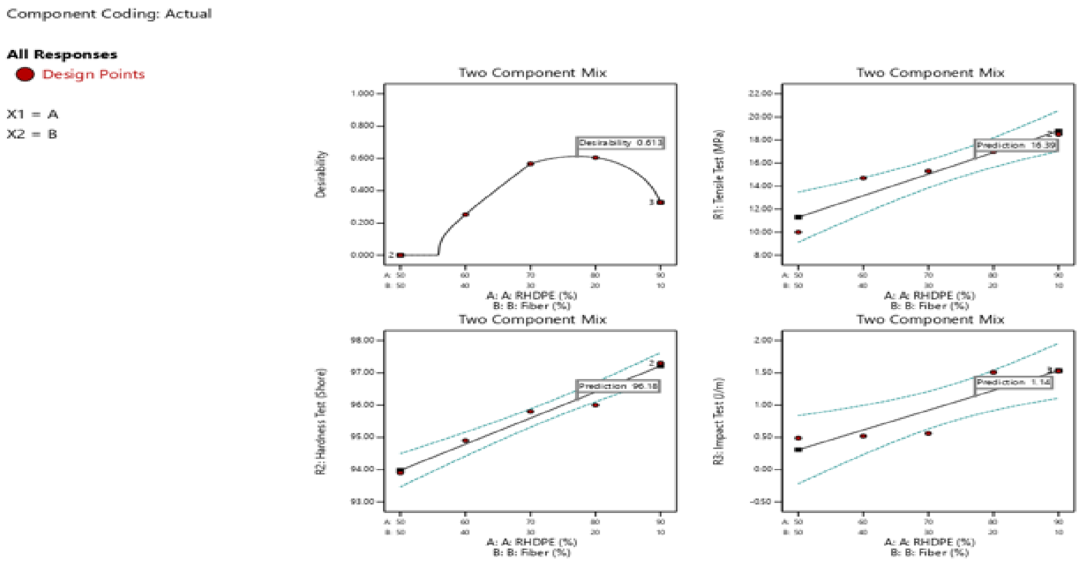


Figure 2: Effect of RHDPE/Fiber on Mechanical Properties of Thermoplastic Composites

Figure 2 shows the effect of filler loading on the mechanical properties of banana stem fibre/RHDPE composites. The tensile strength decreased with an increasing fibre content of the composites from 18.554MPa to 9.907MPa with 10% to 50% filler loading, respectively. The decrease might be attributed to poor interfacial adhesion between the filler and matrix (Raj *et al.*, 1996). However, several factors determine this property, including the nature of the fibre and polymer components, processing method, and fibre treatment (Obasi, 2015). The hardness value decreased with the increasing fibre content of the composites from 97.3(shore) to 94.0(shore) with 10% to 50% filler loading, respectively, because the dispersion of the filler into the matrix with the minimal void and stronger surface bonding between the filler and the matrix. The filler increment reduced the brittleness of the RHDPE, thereby increasing the stiffness of the composite. Hardenability is the measurement of the resistance of a material to surface indentation.

In addition, it is a function of the stress required to produce some specific type of surface deformation (Swamy *et al.*, 2011). The decrease in impact strength of thermoplastic composites from 1.719J/mm to 0.516J/mm with an increase in filler loading from 10% to 50 % was attributed to saturation of the RHDPE by the fillers. This prevents proper bonding of the fillers from forming strong composites, as observed. It might also result from the non-inclusion of coupling agents in the composite (Musa *et al.*, 2019). The impact strength is the ability of the composite material to withstand shock loading (Swamy *et al.*, 2011). It has been reported that high fibre content increases the probability of fibre agglomeration, which results in regions of stress concentration that require less energy for crack propagation (Karmarkar *et al.*, 2007). As the filler loading increases, a disturbance in the 3-D network of the polymer matrix results in a decrease in the mobility of matrix molecules (Shenoy & Melo, 2007).

Optimisation of Process Parameters

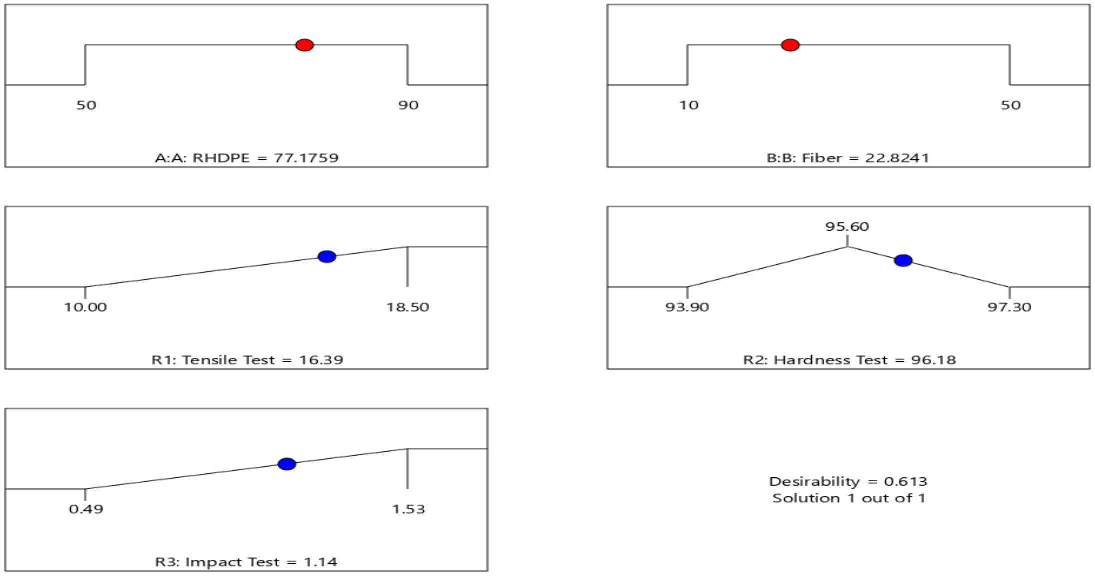


Figure 3: Parametric Optimisation of Mechanical Properties of Thermoplastic Composites

The optimal conditions were obtained by numerical plots (Figure 3), illustrating the effect of the process parameters on the properties of thermoplastic composites such that the value for an optimal design and a steep slope numerical plot indicates that the response is sensitive to the factors. Mechanical properties were obtained by maximisation of tensile and impact strength with targeted hardness value.

Therefore, the plots showed that the ratio of RHDPE/Fibre was mainly influenced by ($p<0.05$) mechanical properties of the thermoplastic composite. Predicted values 77.18% (rHDPE) and 22.82% (Banana stem Fibre) by design software were found to be the optimal parameters for tensile strength, hardenability and impact strength at 16.39Mpa, 96.39 shores and 1.14J/mm respectively with desirability of 61%.

Table 4: Confirmation of predicted results

C-I	**Tensile Test (MPa)**	**Hardness Test (Shore)**	**Impact Test (J/mm)**
Low Value	15.1285	96.094	0.8816
High Value	17.6515	96.6896	1.3984
Predicted Value	16.39	96.39	1.14
% error	7.69%	0.31%	22%

A validation experiment utilised equation (2) to verify agreement between predicted and validated responses. The responses for each property of thermoplastics composites showed that predicted responses for the optimal setting fall within the confidence interval of the confirmation text (Table 4), and less than 10% margin error was obtained for the tensile and hardness properties of the composite. Thus signifying the predictability of the model for both properties.

CONCLUSION

The activity of banana pseudo-stem fibre in the thermoplastic composites using polymer-based RHDPE was successfully developed and investigated. The results of the mechanical properties analysis revealed that a decrease in fibre content caused an increase in the properties of the composites. Optimised conditions at 16.39MPa, 96.18 shore, and 1.14J/mm properties are 77.2% RHDPE and 22.8% banana stem fibre. The model was validated by comparing the actual response with the predicted. Compared values agreed because software prediction falls within confidence intervals (CI) of the actual responses.

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