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Screening and Ranking of Critical Process Parameters Influencing the Mechanical Properties of Plantain-Bamboo Reinforced High-Density Polyethylene Composites

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Abstract: Composites made of natural fibers reinforced polymer are constantly under consideration as the sustainable alternatives to synthetic reinforcements, but the fact that these materials are incredibly vulnerable to the processing conditions makes the problem of achieving a consistent mechanical performance one of the primary issues. Changes in fiber content, blending ratios and molding parameters tend to cause uncertainty in the strength and elasticity, making optimization challenging. This paper solves this problem by filtering and prioritizing the significant process parameters that affect the mechanical property of the plantain-bamboo reinforced high-density polyethylene (HDPE) composite. The experiment involved chemically modified plantain and bamboo fibers, which were processed by using NaOH, acetic acid, bleaching agents, and compatibilizers, and HDPE as a matrix. Fibers were washed, milled to (75 µm), and mixed with HDPE in given volume ratios. The five most important process variables were considered, including the volume fraction of fibers, the ratio of bamboo fibers to other fiber types, the temperature at which it is molded, the clamping pressure, and the cure time. The compression molding was done under controlled conditions to generate composite samples. The response to each variable was analyzed in terms of influence on the yield stress, yield strain, and elasticity with the best results of fiber content and curing time. Five important variables were filtered; fiber volume fraction (VF), bamboo fiber ratio (BFR), molding temperature (T), clamping force (F), and curing time (t). The yield stress and strain decreased and became low at low fiber content, decreasing between (88 MPa) and (2.4) at (10 percent) VF and (26 MPa) and (0.5) at (50 percent). Pure plantain fiber was stronger, but the small bamboo fractions (03) enhanced elasticity. Increasing temperatures and forces at clamped end beyond (2400 N) minimized stress and strain. The best holding time was around (1823) minutes. In sum, reinforcement was best enhanced by low VF and sufficient curing period. The research provides a definite order of process importance and provides the basis on which the process could be optimized further and composite design could be enhanced.

Keyword: natural fiber composites, plantain fiber, bamboo fiber, process parameters, HDPE composites

INTRODUCTION

Assessment and prioritization of key process variables that affect the mechanical properties of plantain-bamboo reinforced high-density polyethylene (HDPE) composites has emerged as a primary theme in the study of natural fibre composite materials. The issue is that natural fibres, despite being renewable and lightweight, offer variability in properties as they are sensitive to moisture, surface chemistry, thermal degradation and fibre-matrix incompatibility, thus effective management is very essential (Chen et al, 2021; Egwu & Ekwe, 2024; Ezugoh et al, 2023;).

The mechanical properties of plantain and bamboo fibres mixed with HDPE are highly affected by a number of interacting process variables and it is therefore required to study how mechanical properties depend systematically on which variables have strongest effect (Ku et al., 2011; Kabir et al., 2012). Weak control of these variables results in poor dispersion, weak interfacial adhesion, fibre pull-out and eventually reduced tensile, flexural and impact behaviour. Hence, the design of stable, high-performance bio-composites needs screening and ranking.

According to the literature, the parameters that recur most when discussing natural fibre-polymer composites are fibre loading, fibre geometry, fibre surface treatment, compatibiliser concentration, moisture content prior to processing and compounding or moulding conditions. One of the most significant variables is the fibre loading, which directly affects the stiffness, strength and density. Numerous studies suggest that at excessive fibre addition, agglomeration, voids, and fewer transfer of stress occur, whereas optimum fibre loading improves modulus and tensile strength (Ihueze et al., 2016). The fibre morphology such as length of fibre, aspect ratio, and particle size influences the load transfer efficiency. Smaller sizes/fragmented fibres can decrease tensile strength, longer fibres enhance reinforcement but can be damaged during high-shear processing (Al-Maharma and Al-Huniti, 2019).

Surface treatment and compatibilisers like maleic anhydride grafted polyethylene (MAPE) highly increase fibre-matrix adhesion by increasing wettability and decreasing interfacial gaps. The chemical treatment is always noted in reviews among the most significant variables after fibre loading as it assists in the minimization of water absorption and maximizing the bond between the interfaces, thus enhancing strength and durability (Kabir et al., 2012). Coupling agents, in the case of bamboo-HDPE composites, improve tensile and flexural strength significantly by promoting the compatibility of the hydrophilic fibre and the hydrophobic matrix (Xian et al., 2018). In the case of plantain fibre composites, this problem has been solved through effective use of compatibilisers and controlled particle sizes that have significantly improved stiffness and surface bonding (Ihueze et al., 2016).

Processing parameters are also important. Melt temperature, screw speed, injection pressure, holding pressure and cooling rate affect fibre dispersion, fibre breakage, crystallinity development and void formation. Experiments with Taguchi techniques and response surface techniques often show that temperature and pressure conditions are some of the best predictors of mechanical strength, especially processing natural fibres prone to degradation. As a case in point, increased melt temperatures can enhance HDPE flow and fibre wetting but can also damage plantain or bamboo fibres when temperatures become greater than their thermal stability. Processing shear affects fibre length retention, that subsequently affects modulus and tensile properties. The interactions necessitate systematic experimental optimisation (MohanDas et al., 2019).

To overcome this complexity, screening and ranking techniques have been extensively utilised. Taguchi designs are traditionally utilized in preliminary screening as they minimise experimental runs without resorting to the most significant parameters based on signal-to-noise ratios and ANOVA. Fibre loading tends to be the highest ranked factor, then fibre treatment or particle size, and then processing temperature or pressure. After identifying the key parameters, the response surface methodology or grey-fuzzy multi-response optimisation is employed to optimise interactions between factors to achieve a better stiffness, strength and impact resistance. Taguchi-based designs in the study of plantain fibre-HDPE have clearly demonstrated that injection pressure, melt temperature, fibre concentration, and particle size are all independent variables that influence mechanical responses, and hybrid plantan-bamboo systems would probably exhibit a similar pattern as they share common natural fibre properties (Ihueze et al., 2016).

A literature synthesis indicates that the optimal optimisation system of plantain-bamboo reinforced HDPE composites must start with screening of fibre loading, fibre size, compatibiliser type and processing temperatures or pressures of key elements. These considerations are always among the top ones in research of natural fibre composites. Optimisation should later be used to optimise interactions between the highest ranked variables, with moisture management and sufficient fibre drying. The pattern is similar across studies, in that fibre loading, fibre morphology and fibre–matrix interface quality control the mechanical behaviour, whereas processing parameters are secondary but nonetheless significant factors. The study on screening and ranking critical process parameters that affect the mechanical properties of plantain-bamboo reinforced high-density polyethylene (HDPE) composites is deeply rooted in the context of the unresolved variability in the performance of natural fibre-polymer composite.

Even though research has demonstrated that factors like fibre loading and fibre size, surface treatment and processing temperature have a strong influence on strength and stiffness (e.g., Ku et al., 2011), the current literature seems to focus on the independent variables individually, which makes it unclear which variables have the largest combined effect. Other publications on plantain fibre composites have identified the problem of poor interfacial bonding and poor particle dispersion (as seen in investigations like Ihueze et al., 2016), but they have not evaluated them against other factors to establish their relative importance to each other. On the same note, bamboo–HDPE experiments document the enhancement of strength in the presence of compatibilisers, yet the interaction between fibre type and processing conditions is underutilised (as observed in other studies such as Xian et al., 2018).

The research paper thus addresses a methodological and empirical void by performing a systematic screening and ranking of the most impactful parameters through systematized experimental designs. Through this method, the key factors governing the mechanical properties can be identified with better clarity, and more reliable results can be achieved on optimisation of hybrid plantain-bamboo HDPE composites to be used in engineering

METHOD

The research was based on the integration of treated biofibers and polymer materials to design and test natural fiber reinforced composites. The materials used in extraction and chemical activation of fibers were water, sodium hydroxide (NaOH), acetic acid neutralization, acetic anhydride stabilization, and maleic anhydride grafted polyethylene, which was the compatibilizer. More bleaching agents in the form of hydrogen peroxide, hypochlorite, and caustic soda were used to enhance the purity of the fibers and surface features. To make composites, the most important materials were high-density polyethylene (HDPE) of density 0.96 g/cm 3, and activated plantain and bamboo fibers.

The design was an experimental design. Plantain and bamboo fibers were collected, washed, dried and milled to a particle size of (75 µm) a figure that has been used on the basis of evidence acquired previously demonstrating the optimum operation. The fibers were mixed with HDPE which acted as the matrix material and weighed carefully to attain the required volume fractions. The experiment was guided by five key process parameters: fiber volume fraction (VF), bamboo fiber ratio (BFR), molding temperature (T), clamping force (F) and curing time (t). The choice of these variables was influenced by their known influence on composite behavior. The ratio bamboo fiber was adjusted (01.0) to compare pure plantain fiber composites, pure bamboo fiber composites and blends. Earlier thermal analysis was used to determine the molding temperature levels to prevent polymer degradation.

They were compression molded to create composite samples. The mixture of fiber and HDPE was preheated and put into a mold subjected to controlled clamping pressure and cure time. The experiments were combinations of the factors chosen in a unique way. Samples were cured and then cooled before being trimmed and ready to undergo a mechanical test. Mechanical characterization was concerned with yield strain, yield stress and elasticity. The stress strain data were obtained using a universal testing machine at least three specimens per condition were tested to enhance reliability. The key mechanical properties could be determined by the resulting curves. Data analysis was focused on the relative effects of each variable to pattern out the distinct trends of lower stress and strain in high content of the fiber, higher elasticity in moderate content of bamboo mix, and best performance with the help of correct curing time.

RESULT AND DISCUSSION

In the process analysis, five major factors including volume fraction of the fiber (VF), bamboo fiber ratio (BFR), molding temperature (T), clamping force (F) and curing time (t) were identified as the process variables. Fiber particles of size $75\mu m$ earlier reported as optimal particle size in a closely related study was considered to reduce the number of independent variables. These factors were studied selectively to monitor their individual effects on the system response. Figure 1(a) and Figure 1(b) show the effects of the volume fraction of the fiber on the yield stress and the yield strain of the composite material. The observed trends suggest that both yield stress/strain decreased exponentially from a significantly high value of 88MPa and 2.4% respectively observed at low fiber concentration of 10% to a low value of yield stress below 26MPa and strain below 0.5% obtained at high fiber concentration of 50%. In other words, the modulus of elasticity of the composite material and other elastic properties were largely preserved within the observed range of the parameter adjustment.

Attempt to compare the performances of the plantain fiber and that of the bamboo fiber shows that the use of pure plantain fiber gives a composite material of greater yield strength compared to the various blends with bamboo fiber at the observed ratios as shown in Figure 4.2(a). However, further analysis shows that using fiber blends having small fraction of bamboo fiber in range of 0 – 0.3 ratio results in materials of improved strain/elasticity with minimal tradeoff on the yield stress as shown in Figure 2(b).

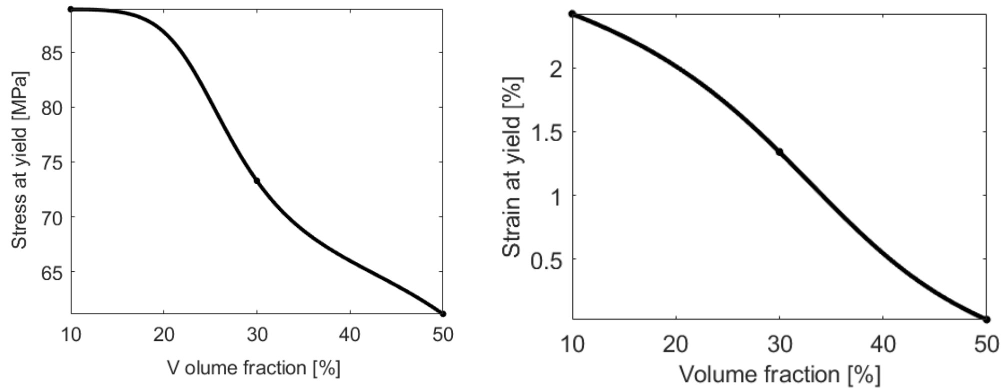

Figure 1: Effects of volume fraction of fiber on (a) yield stress and (b) yield strain

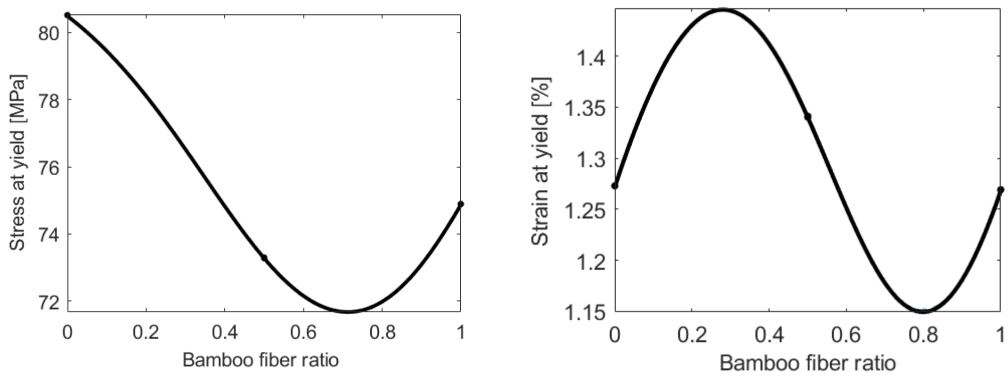

Figure 2: Effects of bamboo fiber blend ratio on (a) yield stress and (b) yield strain

Figure 3 which describes the effects of molding temperature shows that there was also approximately exponential decrease in the yield stress/strain of the composite material towards higher temperature. However, compared to the result obtained for the base material, significant increase in yield stress was obtained in the given temperature range.

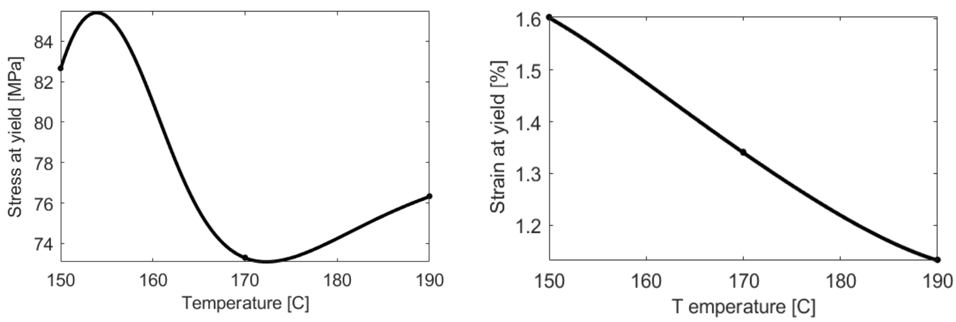

Figure 3: Effects of molding temperature on (a) yield stress and (b) yield strain

The results presented in Figure 3(b) suggest that the strain at yield, as well as the elastic properties of the composite material depreciated at higher molding temperature, while that of Figure 4(a) indicate that in the lower range of clamping force < 2400N, the material stress at yield decreases and the yield strain increases resulting in geometric fall in the elastic modulus of the composite material. Higher clamping forces > 2400N lead to degradation of both stress and strain at yield.

In the same vein, the effects of holding time on the material properties were investigated. The results presented in Figure 5 suggest that the optimal holding time for improved stress/stain at yield may lie in the range of 18 – 23 minutes.

Comparing the results obtained for the individual effects of the process variables, one can understand that the volume fraction of fiber and holding time are the most influential process variables. Basically, the volume fraction of fiber should be kept low while the holding time is made sufficiently high to achieve improved material reinforcement. Since, the base material (HDPE) is relatively costly compared to the reinforcement material (plantain/bamboo fiber), it could be inferred at this point that relying on low fiber concentration and high holding time for enhanced material reinforcement may not favor overall cost reduction. Thus, later discussions on the interaction effects of the process variables under multivariate analysis would explore alternative routes to a more competitive product.

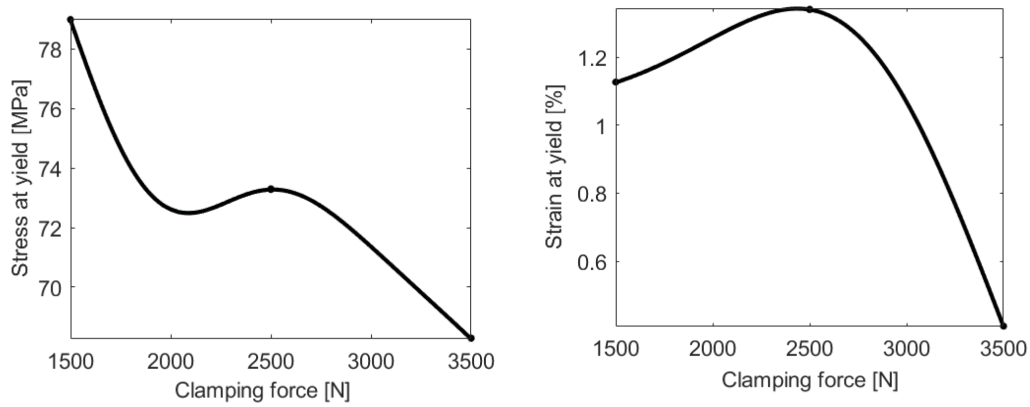

Figure 4: Effects of clamping force on (a) yield stress and (b) yield strain

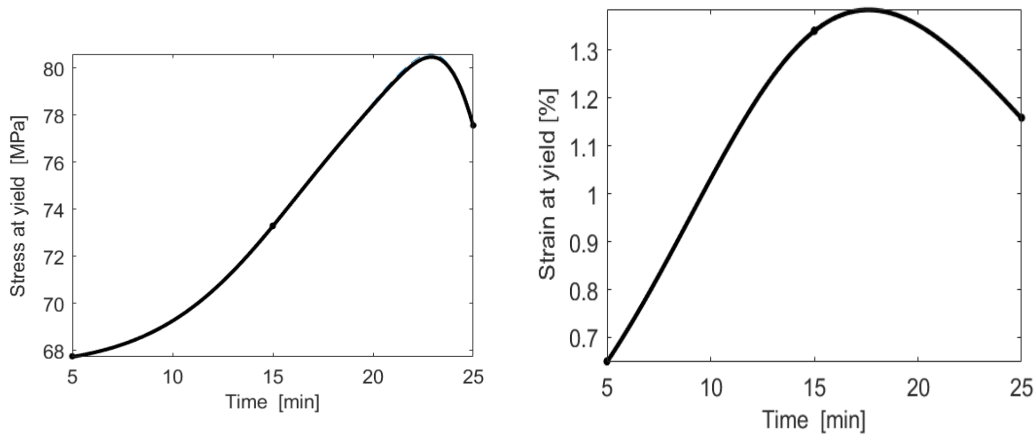

Figure 5: Effects of holding on (a) yield stress and (b) yield strain

The factor-screening results highlight how sensitive plantain–bamboo/HDPE composites are to processing parameters. The dramatic drop in yield stress and strain with increasing fiber volume fraction (from ~88 MPa and ~2.4% at low VF to under ~26 MPa and ~0.5% at 50% VF) reveals a clear trade-off: while adding more fiber intuitively seems reinforcing, in this system excessive fiber possibly disrupts the polymer matrix continuity or increases voids, undermining load transfer. In contrast, some hybrid natural fiber composites show improved stiffness with increasing fiber content (e.g., hybrid natural/synthetic combinations reviewed by Kator Jomboh et al., 2024), but our results mirror concerns raised in other works about natural fibers degrading performance beyond a threshold (Nezafatkhah et al, 2025).

The observation that pure plantain fiber gives higher yield strength, yet small amounts of bamboo (up to a 0–0.3 ratio) improve strain with limited strength loss, is especially interesting. This finding agrees with studies of hybrid fiber systems where blending dissimilar fibers can balance stiffness and ductility: for example, in a bamboo-kenaf-PLA composite, researchers observed that combining fibers improved both strength and resilience (Rahmani et al, 2025).

Regarding molding temperature, the exponential decline of both stress and strain at higher temperatures suggests matrix softening or even thermal degradation. This aligns with concerns in recent reviews: a comprehensive overview by Al-Dala'ien et al, (2025) argued that process conditions like high heat must be carefully controlled, because natural fibers have lower thermal stability and can weaken under aggressive processing.

The effects of clamping force also underscore the delicate balance needed: at low force (< 2400 N), stress falls but strain increases, degrading stiffness, whereas over-compression (> 2400 N) deteriorates both stress and strain. Such non-monotonic behavior indicates that too much compaction likely damages fiber alignment or causes localized stress concentrations. This is consistent with what hybrid fiber researchers note about overcompression creating voids or micro-damage (Wijerathne et al, 2022). The optimal curing or holding time around 18–23 minutes supports the idea that adequate dwell allows better fiber–matrix bonding, leading to stronger, more ductile composites. This finding echoes experimental trends seen elsewhere areca fiber/epoxy composites, longer curing times improved mechanical properties significantly (Miniappan et al, 2023).

CONCLUSION

The objective of this work was to determine the variables that have a critical effect on the mechanical performance of high-density polyethylene composites, reinforced with plantain and bamboo fibers. The results were systematized and show the viability of a systematic screening approach. Among the factors considered, volume fraction of fiber and the time taken to cure proved to be the most powerful factors. The best fiber loading ensured the stiffness and strength of the composite and allowed the necessary interfacial bonding throughout the curing time. Specifically, the addition of a relatively small percentage of bamboo fibers augmented the elongation capability greatly without affecting the strength of the composite. Other processing parameters, e.g. moulding temperature and clamping force, also influenced final material properties, but were only seen to impact at extreme levels. High temperatures or high clamping pressure was predisposed to cause degrading effects. As a result, the choice of reinforcing fibers should be supplemented by the strict management of the processing environment to allow the optimal integration of fibers. The prioritisation of variables resulted in the hierarchically ranked framework that offers a practical guide in the optimisation of the processes.

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