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A comparative study on the tensile properties and environmental suitability of glass fibre/raffia palm/plantain fibres hybridized epoxy bio-composites

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ABSTRACT: Bio-composites have been widely introduced as sustainable alternative engineering materials, due to their environmental friendliness. The aim of this study was to assess the variations in the mechanical and biodegradation behaviours of natural fibres (raffia palm and plantain fibres) reinforced composites, and compared them to artificial fibres composites. Bio-composite samples produced through hybridization of glass fibre, plantain fibre and raffia palm fibre, were tested (mechanical and biodegradability tests) in accordance with ASTM International accepted procedures. The biodegradability results indicated that, the tensile strength and tensile elongation for all composites decreased non-linearly during the 28 days of soil treatment. Also, it was observed that the mechanical properties of the natural fibres reinforced bio-composites declined faster, when compared to the synthetic fibre reinforced composite. The bio-composite produced solely with natural fibres (PFRF) had the highest tensile strength reduction rate (43.86%), while the composite produced with solely synthetic fibre (glass fibre) had the minimum tensile strength declining rate (2.18%), at the end of the soil treatment. Regarding the tensile elongation, the PFRF bio-composite had the highest decrement (89.98%), when compared to the 53.28 and 45.92% recorded in the CFPF and CFRF reinforced bio-composites, respectively. With respect to weight loss, it was observed that the weight loss was gradual during the initial period of the soil treatment. However, the bio-composite with the two natural fibres (PFRF) exhibited more pronounced weight loss (46.4%); while the sample with the synthesized fibre (CF) exhibited more resistance to biodegradation (6.23% weight loss). The study results demonstrated that plantain fibre and raffia fibre are environmentally friendly, and composites produced from them developed appreciable tensile properties; hence, they can be used to produce composite for automobile parts.

Keywords: Environmental pollution, mechanical properties, organic fibres, soil treatment, synthetic fibres.

INTRODUCTION

Materials used for engineering applications should have favourable mechanical, electrical and thermal properties (Myshkin and Kovalev, 2018), to avoid unnecessary failures of the systems/equipment produced from them (Agbi and Uguru, 2021). Bio-composites are one of the engineering materials used in engineering applications, and their popularity is rapidly increasing due to their lightweight, eco-friendliness, availability of the raw materials and good engineering properties (Puglia *et al*., 2004; Fogorasi and Barbu, 2017; Esegbuyota *et al*., 2019). Hence, they helped to reduce the negative impact of carbon emissions on the environment, through the reduction in fuel consumption, resulting from the production of light weight vehicles (Fogorasi and Barbu, 2017; Edafiadhe *et al*., 2019). Most organic reinforcement materials (fibres and fillers) used in bio-composite production have been proven to have adequate mechanical and thermal properties (Mir *et al*., 2012), which are critical factors usually considered during material selection in the automobile industry. This is because they helped to reduce the negative impact of carbon emissions on the environment, through the reduction in fuel consumption (Fogorasi and Barbu, 2017; Edafiadhe *et al*. 2019).

Zah *et al*. (2007) stated that bio-composites involved the utilization of at least one biodegradable material during composite production. These biodegradable materials enhance the conversion of the scrap composite into harmless compounds through microbial activities (Farag, 2017). Furthermore, Kandpal *et al.* (2015) classified bio-composites into two main groups, which are: totally renewable bio-composites and partly renewable bio-composites. According to Kandpal *et al.* (2015), totally renewable bio-composite consists of purely organic materials; while partly renewable bio-composite, consists of either organic matrix or organic reinforcement material(s). The engineering properties and environmental friendliness of the bio-composites are greatly influenced by the engineering properties and volume of the constituent materials (Farag, 2017; Akpokodje *et al.,* 2019; Obukoeroro and Uguru, 2021).

Most natural materials contain a high percentage of cellulose and lignin, which making them good reinforcement materials in composite production (Surata *et al.*, 2014; Edafeadhe *et al*., 2020; Uguru and Obah, 2020), mostly in the engineering field. Oghenerukewve and Uguru (2018) reported that the rupture strength and bending Modulus of the composite increased considerably with the incorporation of oil bean shell particulates into the epoxy resin. According to Bayode *et al.* (2017) snail shell filler enhanced (increased) the tensile properties of polyester matrix composite. Furthermore, Guleria *et al*. (2015) stated that short okra fibre reinforcement increased the tensile and flexural strength of corn-starch matrix composites. A study by Raju and Kumarappa (2012) portrayed that, the tensile and flexural strength of partially renewable bio-composite produced from groundnut shell fillers increased non-linearly, as the fillers' volume increased. Similarly, Sapuan *et al*. (2013) reported that reinforcing polyester resin with glass and sugar palm fibres, produced composites with better tensile and flexural properties, which can be used in the automobile and aerospace industries.

The production of biodegradable composites has arisen in different engineering sectors as an attempt to achieve a more environmentally friendly approach to product manufacturing and design (Vroman and Tighzert, 2009; Koushal *et al.,* 2014). Applications of these bio-composites are widely acceptable in several industrial applications, due to their environmental friendliness, lightweight, cost effectiveness, and their appreciable structural properties (Sudesh and Iwata, 2008; Uguru and Uyeri, 2018). Fortunati *et al*. (2013) studied the disintegration rate of okra fibres reinforced composites for an incubation period of 40 days, in accordance with ISO 20,200 standard. According to Guleria *et al*. (2015), okra bast fibres helped to reduce the degradation rate of cornstarch based composites, attributing it to the increase in the cellulosic content in the bio-composite. Additionally, Reddy *et al*. (2013) stated that cellulose based materials significantly enhanced the biodegradability properties of bio-composites. As seen in previous literatures, hybridization of composites using different natural fillers as substitutes for synthetic fillers/fibres had been done from agro-materials. But literatures review on the substitution of glass fibre with raffia palm and plantain fibres showed very limited results. Hence, this study was aimed at evaluating the tensile properties and environmental suitability of bio-composites produced from different fractions of synthetic fibre (glass fibre) and natural fibres (raffia palm and plantain fibres). The results obtained from this study will enhance the development of bio-composites (green composites) for the various industrial sectors.

MATERIALS AND METHODS

Materials used

The raffia palm fibres were manually inspected to remove damage before they were cut into 30 cm long sizes. The fibre was obtained from the plantain pseudo stem through the retting method, as described by Edafeadhe *et al*. (2020). The fresh plantain fibres were sun-dried for 4 days at ambient environmental conditions (Temperature ~ 29 ± 3^0C; Relative Humidity ~ 80±5%). The matrix materials (epoxy resin and hardener) and the glass fibre were obtained from a chemical shop at Ughelli, Delta State, Nigeria.

Matrix preparation

The two matrix materials - epoxy resin and hardener - were mixed at a ratio of 4:1, and thoroughly mixed and stirred at low speed for approximately 15 minutes.

Preparation of the composite sample

The production process of the composite sample by using a 40% fibre quantity fraction (%), as summarized in Table 1. All the required materials used for this study were weighed out using an electronic weighing balance for accuracy.

During the composite production, the prepared matrix was poured slowly into oiled mould (up to the half of the depth), and then the required quantity of the fibre(s) was laid on the matrix layer inside the mould, which was later covered by another layer of matrix. Then the cast composite was kept under a dead load (15 kg), as described by Umurhurhu and Uguru (2019), at ambient temperature for 12 hours in order to expel all entrapped air from the composite.

Table 1. Compositions of the epoxy hybridized composite samples.

Sample code	Matrix volume (%)	Fibre reinforcement quantity (%)		
		Glass fibre	Plantain fibre	Raffia palm fibre
CF	60%	40	-	-
CFPF	60%	20	20	-
CFRF	60%	20	-	20
PFRF	60%	-	20	20

Where: CF = Glass fibre reinforced epoxy composite, CFPF = Glass fibre/plantain fibre hybridized epoxy composite, CERF = Glass fibre/raffia palm fibre hybridized epoxy composite, PFRF = Plantain fibre/raffia palm fibre hybridized epoxy composite.

Laboratory analysis of the composite samples

Mechanical properties test

On every predetermined mechanical property testing date (Day 7, 14, 21 and 28), the composite samples were carefully removed from the soil, cleaned with distilled water, and dried at a temperature of 70°C for 5 hours.

The tensile tests were conducted in accordance with ASTM D 3039 on a universal testing machine. The samples of dimensions 100 mm × 10 mm × 5 mm were used for analysis. The sample of 100 mm in length was clamped between the jaws of the machine with each end covering 20 mm of the sample. The tensile load was applied at a constant rate of 1 mm/min until a fracture occurred. Equations 1 and 2 were used to calculate the tensile strength and elongation at the break percentage of the composite samples (Uguru and Oghenerukevwe, 2021).

$$Tensile\ strength, \sigma = \frac{Force_{Max}}{Area} \qquad 1$$

$$Elongation\ at\ Break, EB(\%) = \frac{\Delta L}{L} \qquad 2$$

Where: ΔL is the extension at the break point, L is the original length of the sample, and $F_{\max}$ is the maximum load applied to the sample.

Biodegradation test

The biodegradation tests were carried out in simulated soil according to ASTM G160-03 procedures. Weights of the buried composites samples were taken at a regular interval of 7 days, for an experimental period of 28 days. The biodegradability was calculated by using equation 3.

$$\%\ Biodegradability = \frac{w_i - w_f}{w_f} \times 100 \qquad 3$$

Where: W_i = initial weight, W_f = Final weight

Statistical analysis

The relationship between the biodegradation treatments and the tensile properties of the hybrid composite samples was determined using SPSS statistical software (version 20.0, SPSS Inc, Chicago, IL). The mean was separated using Duncan's Multiple Range Tests (DMRT) at 95% confidence level. All the experiments were replicated four times, and the average values were recorded.

RESULTS AND DISCUSSION

Tensile strength

The ANOVA results presented in Table 2 revealed that the materials used for the composite production and the burial duration had a significant ($p \leq 0.05$) effect on the tensile strength of the composite samples. Furthermore, the ANOVA results (Table 2) revealed that the interaction of the materials and burial duration exhibited a significant ($p \leq 0.05$) effect on the tensile strength of the composite samples.

The findings of this study presented in Figure 1 depicted that the burial time had negative effects on the tensile strength of the composite samples. Figure 1 shows the tensile strength change curve of the CFPF, CFRF and PFRF composites during the soil burial degradation process and compared with that of pure CF composite. It can be observed that with an increase in soil burial duration, the tensile strength of the composites decreased non-linearly. Generally, the composite sample produced solely with natural reinforcement fibres (PF and RF) had the highest tensile strength declining rate (43.86%), while the composite sample produced with solely synthetic fibre (glass fibre) had the minimum tensile strength declining rate (2.18%), at the end of the treatment duration. Furthermore, the study depicted that the composite sample produced through hybridization of glass fibre and plantain fibre, recorded a higher (28.22%) decline in its tensile strength when compared to the 23.55% decline in the tensile strength, recorded in the composite sample produced through hybridization of glass fibre and raffia palm fibre.

As revealed by the study, apart from the CF composite sample, the rate at which the tensile strength of the composites samples declined during the initial 14 burial days (Day 0 to Day 14), was higher when compared to the tensile strength declining rate recorded during the last 14 burial days (Day 14 to Day 28). Similar results were

Table 2. ANOVA results of the effect of materials and burial duration on the tensile strength of the composite samples.

Source of variation	df	Mean square	F	p-value
Material	3	15654.27	125562.30	1.71E-79*
Treatment	4	383.21	3073.68	3.46E-49*
Material * Treatment	12	33.08	265.30	3.75E-34*
Error	40	0.125		
Total	60			

* = significant at 95% confidence level, according to DMRT.

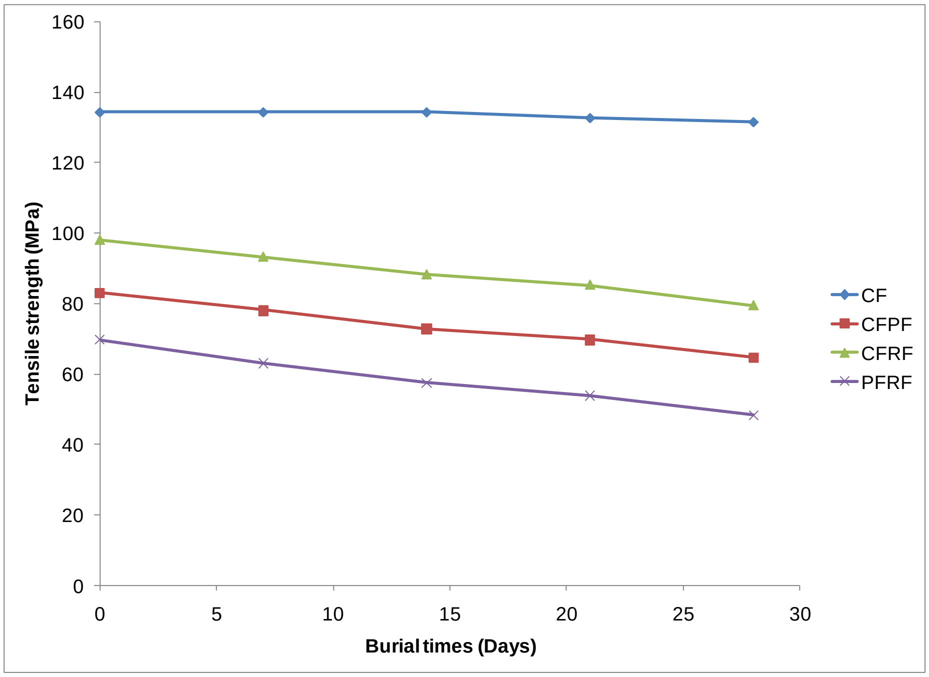

Figure 1. Tensile strength of the composite samples.

reported by Ibrahim *et al*. (2018) that the mechanical properties of green composites experience gradual deterioration during composting. During the soil treatment, the fibre(s) in the composites passed through the biodegradation process, leading to easy breakage of the molecular chains under tensile force. Additionally, microbial activities during the soil treatment tend to weaken the interfacial effect between the organic fibres and the matrix, which will then lead to an acceleration of decreasing rate of the tensile strength of the composites (Phua *et al*., 2011).

Tensile elongation

The ANOVA results of the effect of burial time on the tensile elongation of the composite samples are presented in Table 3. The results revealed that the materials used for the composite production and the burial duration had a significant ($p \leq 0.05$) effect on the tensile elongation of the composite samples. Additionally, the ANOVA results showed that the interaction of the reinforcement materials and the burial duration had a significant ($p \leq 0.05$) effect on the tensile strength of the composite samples.

The mean results of the tensile elongation of the composite samples are plotted in Figure 2. As shown in Figure 2, the natural fibre significantly ($p \leq 0.05$) increased the tensile elongation of the composite samples. It was observed from the results that before the burial of the samples, the tensile elongation of the CF samples was 15.26%, while tensile elongations of 18.21, 23.07 and 20.1% were recorded in the CFPF, CFRF and PFRF reinforced composite samples, respectively.

Interestingly, it was observed from Figure 2 that the tensile elongation decreased slowly during the final stages of the soil burial process, regardless of the reinforcement material. The decrease in the tensile elongation was highest (89.98%) in the PFRF reinforced bio-composite,

Table 3. ANOVA results of the effect of materials and burial duration on the tensile elongation of the composite samples.

Source of variation	df	Mean square	F	p-value
Material	3	85.92	3860.22	2.80E-49*
Treatment	4	69.22	3109.86	2.74E-49*
Material * Treatment	12	7.10	319.11	9.82E-36*
Error	40	0.02		
Total	60			

* = significant at 95% confidence level, according to DMRT.

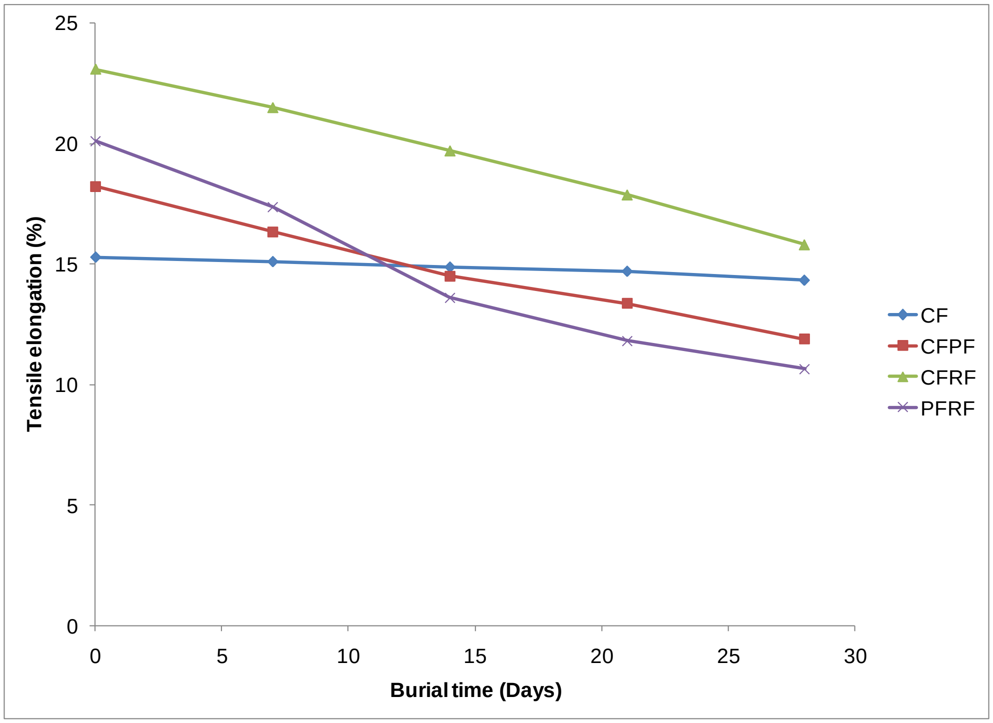

Figure 2. Tensile elongation at break of the composite samples.

when compared to the 53.28% and 45.92% respectively, recorded in the CFPF and CFRF reinforced bio-composites. It was observed from the results that the tensile elongation of the CF reinforced composite had the lowest tensile elongation declining rate (6.48%), signifying that the artificial fibre (glass fibre) was resistant to biodegradation. Phua *et al*. (2012) reported a similar decline in the tensile elongation of bio-composite samples and attributed it to the decrease in the random chain scission of the composites. Similarly, Huang *et al*. (2018) reported that organic fibre causes a rapid reduction in the tensile elongation of bio-composites during the soil burial process.

Biodegradability

Table 4 presents the ANOVA findings of the effect of the burial time on the biodegradability of the composite samples. The outcomes of the ANOVA results revealed that the materials used for the composite production and the burial duration had a significant ($p \leq 0.05$) effect on the biodegradability of all the tested composites. Additionally, the ANOVA results revealed that the interaction of the reinforcement materials and the burial duration exhibited a significant ($p \leq 0.05$) influence on the biodegradability of the composite samples.

Figure 3 displays the weight loss results of the composites using the soil treatment. It can be observed from the results that as the soil burial duration increases, the weight loss increases, and it was more substantial in the bio-composites, compared to the glass fibre reinforced composite. The PFRF bio-composite had the highest (46.4%) weight loss, and was closely followed by the CFPF bio-composite which recorded 41.27% weight loss during the 28 days of soil burial duration. Furthermore, it was

Table 4. ANOVA results of the effect of materials and burial duration on the biodegradability of the composite samples.

Source of variation	df	Mean square	F	p-value
Material	3	1354.96	165914.04	6.48E-82*
Treatment	4	1909.78	233850.89	8.77E-87*
Material * Treatment	12	152.75	18704.46	5.52E-71*
Error	40	0.01		
Total	60			

* = significant at 95% confidence level, according to DMRT.

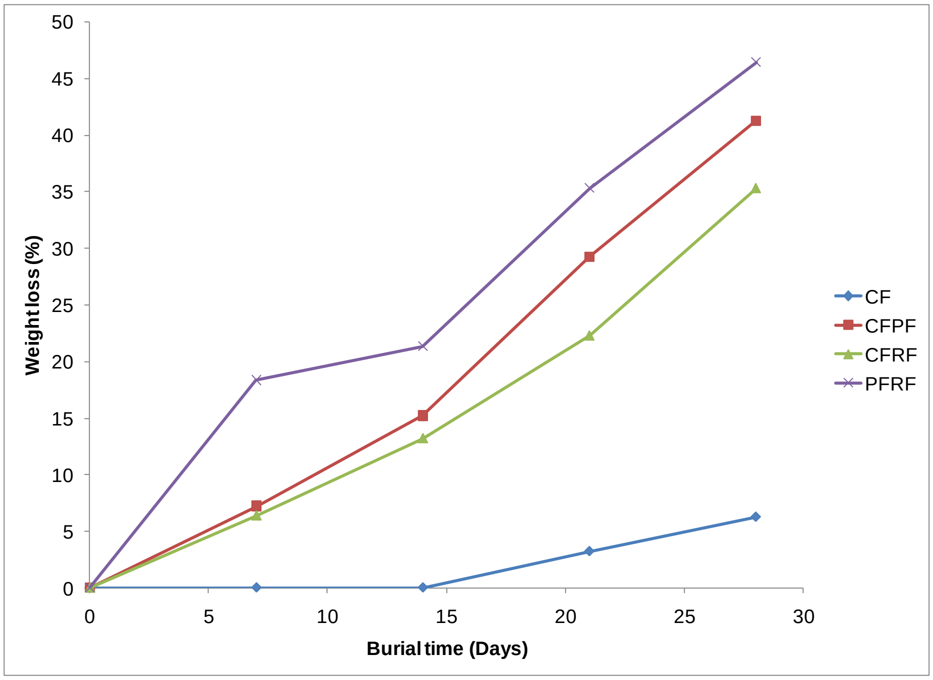

Figure 3. Weight loss of the composites.

observed that the CFRF bio-composite had a weight loss of 35.3%, than the glass fibre reinforced composite recorded the lowest weight loss (6.23%) at the end of the 28 days soil treatment duration. These results affirmed earlier research reports (Farag, 2017; Ibrahim *et al*., 2018), that the introduction/incorporation of natural fibre could accelerate the degradation of composite samples.

Degradation bio-composites is mainly due to the hydrolysis of amorphous area of the composites, which is facilitated by microbial actions in the soil (Thellen *et al*., 2005). Microorganisms secrete enzymes on the composites, which help to degrade organic reinforcement materials into lower molecular weight fragments, resulting in the disintegration of the composite (Phua *et al.,* 2011). Similar results were obtained by Ibrahim *et al*. (2018), where the weight loss of the composites was gradual during the burial period. By the end of the test (6 weeks), the residual weights were 59, 47, 46, and 35% for flax, palm, banana, and bagasse composites, respectively.

Furthermore, Figure 3 revealed that the composites exhibited gradual degradation during the first 14 days, and the rate sharply increased after the 21st day. Luo and Netravali (2003) stated that these variations are due to changes in microbial activity in which the consortium of microorganisms increases over time until reaching a maximum and then decreasing. The biodegradability of composites in different environmental conditions does not only affect their weight but causes significant alterations in their mechanical properties (Tsuji and Suzuyoshi, 2002).

Biodegradable composites can provide a more environmental and sustainable alternative to the synthetic polymer. The importance of biodegradable composites is not limited to the positive environmental effect; the production of such materials can also provide opportunities to improve the standard of life for people around the world. The results of this study revealed that plantain fibre and raffia fibre are environmentally friendly, and had appreciable tensile properties; hence, they can be used to produce composite for automobile parts.

Conclusion

This study was carried out to ascertain the environmental friendliness of some synthesized and natural (organic) fibres. Four epoxy composite samples were produced through hybridization of glass fibre, plantain fibre and raffia palm fibre. All the composite samples were produced and tested (mechanical and biodegradability tests) in accordance with ASTM International accepted procedures. The statistical analysis revealed that soil treatment and organic fibre reinforcement had a significant effect on the bio-composites produced ($p \leq 0.05$). Furthermore, the findings showed that tensile strength, tensile elongation of the bio-composites, declined non-linearly during the soil treatment; and the declining rate was higher in the organic fibres reinforced composite, when compared to the synthetized fibre. It was observed that the pure natural fibres (PFRF) exhibited more pronounced weight loss; while the sample with the pure synthesized fibre (CF) exhibited more resistance to biodegradation. The higher biodegradability observed in the CFPF, CFRF and PFRF epoxy composites could be attributed to the presence of organic fibres, which facilitates biodegradation. The study results demonstrated that plantain fibre and raffia fibre are environmentally friendly, and had appreciable tensile properties; hence, they can be used to produce composite for automobile parts.

Recommendations

Based on the findings of this study, the following recommendations were made.

1. This study was based on only two natural fillers; more research should be done on the combination of more natural fillers, in order to have robust data.
2. Only the tensile properties of the hybrid composite produced were tested, more mechanical and thermal tests should be carried out on the hybridized composite by future researchers.
3. Only 28 burial days were used in this study, the burial time should be increased to 120 days by future researchers.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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