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To cite this article: Abideen Temitayo Oyewo, Oluleke Olugbemiga Oluwole, Olusegun Olufemi Ajide, Temidayo Emmanuel Omoniyi, Hyunjin Kim, Yong Jun Choi, Young-Kwon Park & Murid Hussain (2023) Optimization of the Factors Influencing Biodegradation and Thermal Stability of Banana Pseudo Stem Fibers in Nigeria, Journal of Natural Fibers, 20:1, 2181909, DOI: [10.1080/15440478.2023.2181909](https://doi.org/10.1080/15440478.2023.2181909)

To link to this article: <https://doi.org/10.1080/15440478.2023.2181909>



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Published online: 27 Feb 2023.



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Optimization of the Factors Influencing Biodegradation and Thermal Stability of Banana Pseudo Stem Fibers in Nigeria

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ABSTRACT

Lignocellulosic fibers, one of natural biopolymers, are derived from abundant banana pseudo stem (BPS) agricultural waste in different parts of Nigeria. In this study, the lignocellulosic fibers of three common banana cultivars, agbagba, paranta, and omini, were investigated to determine their chemical composition and mechanical properties. Furthermore, the experimental investigations were correlated with the corresponding Taguchi L9 orthogonal array design under three factors – fiber treatment, diameter, and cultivar type – to find the optimal factors that are pertinent to the desired biodegradation and thermal stability of the fibers. The optimization results indicated that the fiber treatment followed by diameter and the cultivar type was the most influential of the responses, respectively. However, increased cellulose content led to higher tensile strength and modulus, while higher lignin corresponded to higher elasticity. Meanwhile, the predictions of the biodegradation and thermal stability derived from the Taguchi design via S/N ratio ANOVA and regression modeling correlated adequately with the corresponding experimental observations. Ultimately, the fibers with optimum factors were T3D1C1 and T3D1C3, where T3, D1, C1, and C3 denote that the associated fiber was treated with acetic acid, had a diameter of 60.77 μm , and belong to the cultivar type of agbagba and omini, respectively.

摘要

木质纤维素纤维来源于尼日利亚不同地区丰富的香蕉假茎 (BPS) 农业废弃物。本研究对三个常见香蕉品种 agbagba、paranta 和 omini 的木质纤维素纤维进行了研究, 以确定其化学成分和力学财产。此外, 在三个因素 (纤维处理、直径和栽培品种类型) 下, 将实验研究与相应的田口 L9 正交阵列设计相关联, 以找到与纤维的期望生物降解和热稳定性相关的最佳因素。优化结果表明, 纤维处理对响应的影响最大, 其次是直径和品种类型。然而, 增加的纤维素含量导致较高的拉伸强度和模量, 而较高的木质素对应较高的弹性。同时, 通过 S/N 比 ANOVA 和回归模型从田口设计得出的生物降解和热稳定性预测与相应的实验观察结果充分相关。最终, 具有最佳因子的纤维为 T3D1C1 和 T3D1C3, 其中 T3、D1、C1 和 C3 表示相关纤维用乙酸处理, 直径为 60.77 μm , 分别属于 agbagba 和 omini 品种类型。


KEYWORDS

TGA; biodegradation; Taguchi; banana pseudo stem fiber; optimization; ANOVA

关键词

生物降解; 田口; 香蕉假茎纤维; 优化

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 Supplemental data for this article can be accessed online at <https://doi.org/10.1080/15440478.2023.2181909>

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Introduction

Banana plants have wide varieties that are cultivated in large amounts in different parts of Nigeria. Thus, in many regions of Nigeria, bananas play a pivotal role in terms of their economy and staple food supply and are an integral part of the livelihood of many households (IITA 2021; ProMusa 2020). Notably, Nigeria is the most populous nation in Africa with a total landmass of 45,000 ha available for banana cultivation (ProMusa 2020) and produces approximately 3.09 million metric tons of banana per year, thus making Nigeria the producer of the second highest amount of bananas in Africa after Cameroon (IITA 2021; Kohli, Garg, and Jana 2021). In addition, after harvesting the banana from the banana plant, the remnant banana pseudo stems (BPS), comprising 75% of the plant, are left to decompose naturally in the open space, thereby contributing to environmental pollution. Alternatively, in some regions of Nigeria, BPS fiber is partially used in making rope, sleeping mats, cloth, and agricultural storage bags. Likewise, many reports in the literature have highlighted the potential of BPS fiber as a sustainable source of raw material for several applications (Ferede and Atalie 2022), including polymeric composite making (Abd El-Baky and Attia 2019; Gideon, Atalie, and Nawab 2022; Parre et al. 2020).

In reality, practically, all chemical substances and materials are susceptible to biodegradation, with time being the most important factor. While some materials, like glass and other plastics, take many centuries to decay, things like natural fiber may do so in a matter of days. More than 89% of the original material must be broken down by biological (aerobic bacteria) into CO₂, water, and minerals within 6 months, according to biodegradability criteria employed by the Europeans (Haider et al. 2019). Biodegradation period of solid wastes can also be investigated by the use of respirometry – a process involving CO₂ generation in soil conditions simulation of water, soil, and microbes. Studies on lignocellulosic biomass of banana peels over several days yielded enough CO₂ to validate the degradation process. However, over the same period, similar process for polyethylene plastic failed to yield any CO₂, which suggests that biodegradation might take several years (Raddadi and Fava 2019). Figure 1 details the expected biodegradation duration of materials in a marine environment as reported by Raddadi and Fava (2019). Based on this reality, there is rapid adoption of natural fiber

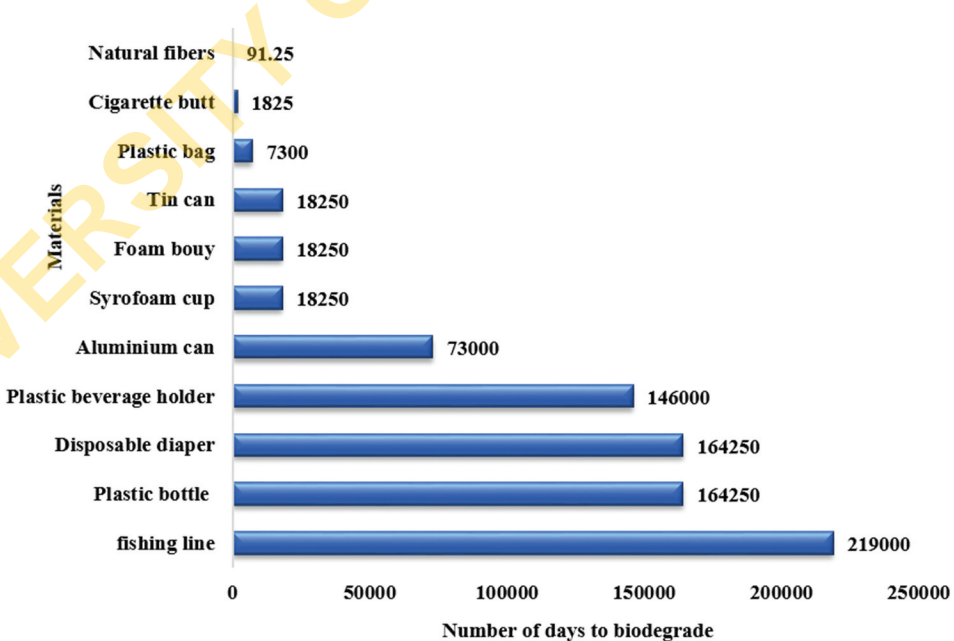


Figure 1. Expected biodegradation duration of some marine debris.

as the filler in polymer composites in order to reduce environmental pollutions as documented in many studies (Atalie and Gideon 2018; Haider et al. 2019).

Similar to biodegradation, some research suggests that the chemical composition of natural fibers, such as cellulose, hemicellulose, and lignin, affects their thermal behavior. When it comes to thermal stability at high temperatures, natural fiber-reinforced composites perform better than pure natural fibers (Asim et al. 2020; Parre et al. 2020). The treated fibers' thermal properties significantly enhanced because of increased interfacial adhesion between the fibers and matrix. Better fiber–matrix bonds surround the fibers fully and shield them from direct temperature contact, whereas treated fiber-reinforced composites often have smaller residual quantities because some lignin was partially washed away during the treatment process (Kohli, Garg, and Jana 2021; Parre et al. 2020).

BPS fiber-made products, such as agricultural storage bags, are sometimes susceptible to microbial infestation from contaminated agricultural goods and other harsh conditions. Thus, thermogravimetric analysis (TGA) and biodegradation investigation of BPS fibers will help find the optimal values of the factors influencing the fiber that would improve the durability and thermal stability of the products at elevated temperatures. Hence, this study conducted chemical composition and mechanical properties on bpsfs and further examined the biodegradation and thermal stability of the BPS fibers of three banana cultivars common in Nigeria through experiments and the Taguchi optimization technique to optimize the factors influencing the fiber and find the most influencing factors. While experimental studies on biodegradation (Kohli, Garg, and Jana 2021) and thermal properties (Parre et al. 2020; Xu et al. 2015) of banana fibers have been sufficiently documented in the literature, validation of such studies through Taguchi robust analysis is yet to be explored as per the knowledge of the authors. For this reason, three BPS fiber factors were considered in the Taguchi optimization to determine their influence and significance on the biodegradation and thermal stability of the fiber. All factors were processed under three levels, i.e., three fiber treatments (NaOH, acetic acid, and no treatment), diameters (60.77, 82.23, and 105.77 μm), and cultivar types (agbagba, paranta, and omini) were considered in the optimization. Finally, while ranking the influence and significance of the factors, their percentage contribution and significance level were considered (Raddadi and Fava 2019).

Materials and method

Materials

Three different banana cultivars that are common in Nigeria, namely:

Musa acuminata (AAA Group, Cavendish subgroup) cv. Giant Cavendish: Paranta;

Musa acuminata (AAA Group, Red Subgroup) cv. Tall Red: Omini; and

Musa decrescens de Briey (AAB Group, Plantain Subgroup) CV. False Horn: Agbagba were sourced via the National Institute for Horticulture Research (NIHORT), Ibadan, Nigeria.

Subsequently, the BPS of each banana cultivar was made into ribbons (Figure 2 (a)), and the BPS fibers were manually extracted from healthy ribbons by following a procedure similar to the one in the work of Oyewo et al. (2022). The extracted BPS fibers of the banana cultivars are shown in Figure 2 (d)–(f). Furthermore, sodium hydroxide and acetic acid solutions (Figure 2 (b) and (c), respectively) were procured from Bond Chemical Industries Ltd., Lagos, Nigeria.

Experimentation

Chemical composition

According to the procedures outlined in Sanjay et al. (2019), lignin, -cellulose, and other substances that contain fibers were studied in textile materials. Before undergoing chemical treatment, the fibers were heated to 110°C until they attained a constant weight, at which point the moisture content was calculated. The starting weight and ending weight were recorded to calculate the percentage water content. And the E1755–01 method was used to determine the ash content (Sanjay et al. 2019).

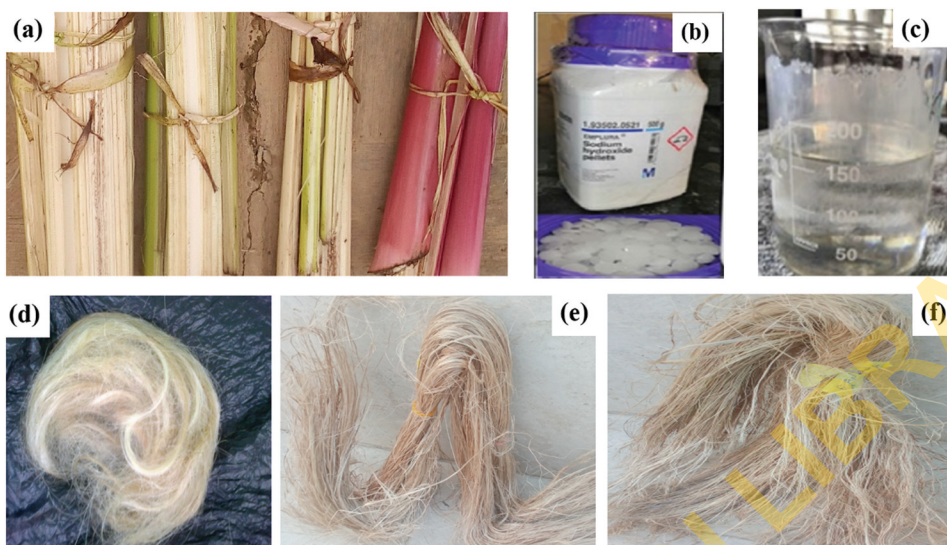


Figure 2. (A) BPS cultivars, (b) sodium hydroxide pellet, (c) acetic acid, (d) omini BPS fiber, (e) paranta BPS fiber, and (f) agbagba BPS fiber.

Mechanical properties

The tensile strength of bpsfs was measured using a universal tensile machine WMS-2 (Ginan Fsid Universal Instrument, Limited, Beijing, China) at 34°C and 60%, controlled temperature and standard humidity, respectively, according to the work by Xu et al. (2015). Ten samples were used to test each cultivar, and the standard deviation of the data was used to calculate the variations.

Fiber treatment

First, each BPS fiber was immersed in a 5 wt. % sodium hydroxide solution for 2 h and washed generously under running water as described elsewhere (Oyewo et al. 2022) for sodium hydroxide treatment, and the above procedure was followed by replacing sodium hydroxide with 2 wt. % acetic acid for the acetic treatment. Furthermore, 20 samples of the BPS fiber of each banana cultivar, with three different diameters, were observed through a digital microscope, and their average diameters were recorded.

Biodegradation

As detailed in Table 2, nine samples were generated from Taguchi optimization due to different combination of controlling. Subsequently, as per the procedure reported in the work of Kohli, Garg, and Jana (2021), 40 g of each fiber sample was buried in a covered container with 25%, 24%, 23%, and 28% of loamy soil, cow dung, sandy soil, and distilled water, respectively, for 90 days at room temperature (29.5 ± 1.1 °C), to incorporate the soil conditions on the sample. Also, the samples were intermittently monitored, and their weight was recorded during burial. At the end of the 90 days period, the samples were recovered, and % weight reduction was calculated.

Thermo gravimetric analysis

Furthermore, the TGA of each sample was carried out by heating 10 mg of the dried sample from 30 to 500 °C with the aid of Saglar TGA/SRT 801 instrument as described in the work of (Parre et al. 2020). So, the thermal stability of the sample through the percentage of leftover (residual mass) from the above heating was calculated by considering the difference between the final and initial mass of the sample as the leftover mass.

Table 1. Process factors and their levels.

S/N	Factors	Unit	Level		
			First	Second	Third
1	Fiber treatment (T)	-	No treatment (1)	NaOH (2)	Acetic acid (3)
2	Diameter (D)	µm	60.71	82.23	105.71
3	Cultivar (C)	-	Omini (1)	Agbagba (2)	Paranta (3)

Table 2. L9 orthogonal array, responses for biodegradation, TGA, and S/N ratio values.

No	Treatment	Diameter (µm)	Cultivar	Designation	Biodegradation (%)	Biodegradation S/N (dB)	TGA (%)	TGA S/N (dB)
1	1	60.77	1	T1D1C1	21.0	26.4444	3.67	11.2933
2	1	82.23	2	T1D2C3	20.0	26.0206	3.29	10.3439
3	1	105.71	3	T1D3C3	23.0	27.2346	2.72	8.6914
4	2	60.77	2	T2D1C2	31.0	29.8272	4.29	12.6491
5	2	82.23	3	T2D2C3	26.7	28.5302	3.91	11.8435
6	2	105.71	1	T2D3C1	27.1	28.6594	3.43	10.7059
7	3	60.77	3	T3D1C3	39.0	31.8213	6.11	15.7208
8	3	82.23	1	T3D2C1	30.0	29.5424	5.37	14.5995
9	3	105.71	2	T3D3C2	31.0	29.8272	4.27	12.6086

Design of experiment and Taguchi method

The control factors affecting BPS fibers and their respective levels selected are presented in Table 1. In addition, using the Minitab 19 software, Table 2 presents the L9 orthogonal array, signal-to-noise ratio (S/N ratio). Additionally, Table 2 presents the percentage mass leftover from thermal stability and biodegradation responses of BPS fibers from the experiments. Notably, the fiber treatment, diameter, and cultivar were designated as T, D, and C, respectively.

Necessarily, the Taguchi method enables experimental work to be validated with corresponding theoretical modeling. In contrast to other validation methods, including the factorial analysis, reduction in experimental quantity for the evaluation/modeling is evident with Taguchi analysis, thereby saving time and the cost of the study. In addition, the noise in the system or S/N ratio of the outputs is also evaluated through the Taguchi method. Generally, a high S/N ratio or noise is unwanted in any system. However, the smaller the better, the normal the better, and the bigger the options in the Taguchi optimization selection for any experiment (Oyewo et al. 2022). In this study, a strong output signal for the fiber responses was desired; hence, the larger the better option was selected and expressed (Equation 1) (Jabbar et al. 2017),

$$\text{the signal – to – noise ratio for larger the better } S/N = -10 \log \frac{1}{n} \sum 1/(X)^2 \quad (1)$$

where n was the observation number(s) and X denoted the observed data of the fiber response.

Analysis of variance

An analysis of variance (ANOVA) was performed on the fiber response data of this study to determine the influential factor(s) among the fiber treatment, diameter, and cultivars. In addition, ANOVA was used to obtain the percentage contribution and significance of each factor. Other means that validated the theoretical modeling of this study included regression analysis, probability plots, confirmation tests, and Pareto charts.

Results and discussions

Chemical composition and mechanical properties of bpsf

The mechanical characteristics of bpsfs are presented in Table 3 along with their chemical compositions. Agbagba, paranta, and omini were discovered to have the highest concentrations of cellulose and hemicellulose, respectively; paranta had the highest concentration of lignin. The mechanical characteristics of natural plant fibers are significantly influenced by the cellulose concentration and cellulose crystallinity of the material. As a result, cellulose content increases along with tensile strength as presented in Table 3. A high lignin concentration has been discovered to improve the natural fibers' capacity to stretch. The same result was attained by Petroudy (2017) who found that leafiran fibers have a lignin content of about 25%, resulting in a higher degree of elongation than kenaf, jute, and pineapple, which have lignin contents of 17%, 9%, and 8.3%, respectively.

Biodegradation

Biodegradation test of the samples is presented in Figure 3 (a). Although all the samples underwent degradation gradually until the duration of the simulation experiment, the degree of biodegradation varies in some samples due to different chemical constituents. However, the percentage leftover mass for each sample after 90 days is presented in Table 2. In essence, sample number 7, T3D1C3 (i.e., treatment level 3, acetic acid; diameter level 1, 60.77 μm ; and cultivar level 3, paranta) had the optimal response, while the least preferred response was that of sample number 3, T1D3C3 in both tests. In terms of microbial susceptibility to biodegradation, hemicellulose, non-crystalline cellulose, cellulose, and lignin come in that sequence, from least to most susceptible. In plants, lignin's primary function is to safeguard the structural integrity of the cell and bind other components to hemicellulose. Due to the presence of aromatic and heterogeneous cross-linked in its structure, biodegradation of lignin is not easily accomplished. Lignin is therefore the component of natural fiber that takes the longest to break down. The pace at which lignin is susceptible to microbial attacks determines how easily fibers can degrade (Luthra et al. 2020).

Thermo gravimetric analysis

The percentage mass residual obtained from the biodegradation and TG analyses of the BPS fibers are presented in Table 2. According to Figure 3 (b), the degradation of the fibers took place between 31°C and 550°C and had three primary weight loss zones for all samples. Like the biodegradation test, the highest leftover mass residue was found in sample number 7, while the least was found with sample number 3. The degradation temperature is divided into three stages: initial, middle (50%), and final (called fiber mass residue). All three stages can be visualized in Figure 3 (b). Final decomposition temperature covered the breakdown of non-cellulosic materials of lignin, the component of banana fiber that is hardest to break down (Asim et al. 2020). Due to the removal of alkali-sensitive sites with greater alkali concentrations, which are also active sites for moisture absorption, the amount of water absorbed in these decreased. Additionally, improved lignin, wax, and hemicellulose removal from the

Table 3. Chemical composition and mechanical properties of bpsf.

Properties	Omini	Agbagba	Paranta
Cellulose (%)	64.81	68.61	65.17
Hemicellulose (%)	13.77	14.24	14.17
Lignin (%)	7.51	6.05	6.95
Water content (%)	3.23	3.17	3.88
Other extractives (%)	10.68	92.07	90.17
Tensile strength (MPa)	321 \pm 21	382 \pm 33	337 \pm 27
Modulus of elasticity (GPa)	8.04 \pm 2.54	15.11 \pm 3.33	8.20 \pm 2.07
Percentage elongations (%)	2.33 \pm 0.7	1.66 \pm 0.45	2.48 \pm 0.34

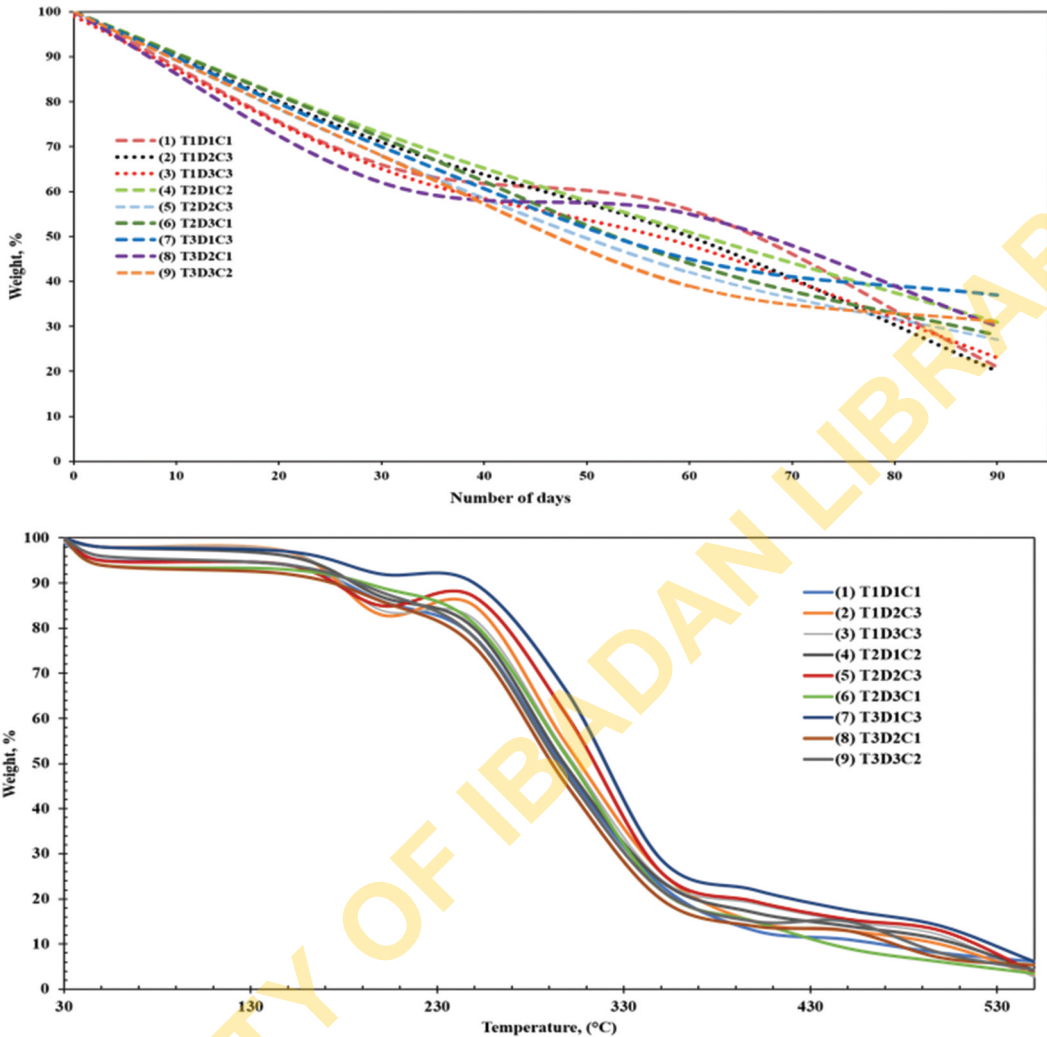


Figure 3. (a) Biodegradation and (b) thermogravimetric analysis curve.

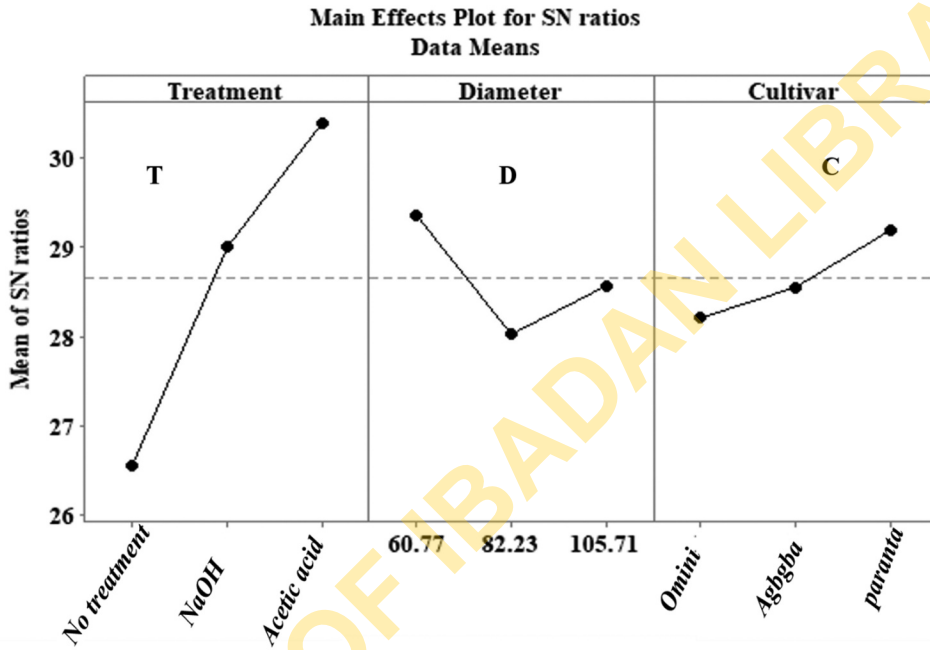
fiber surface is likely what contributed to the sample number 7's higher thermal stability. Because there are stronger hydrogen bonds between the cellulose molecules of paranta, more organized and densely packed cellulose regions result in an greater percentage residue. Since cellulose in natural fibers is immobile as a result of strain and weaker hydrogen bonds, the organized region boosts the thermal stability of such fibers (Asim et al. 2020).

Signal-to-noise ratio

The rank and order of the factors influencing the BPS fiber (fiber treatment, diameter, and cultivar) on the experimental fiber response, as well as the optimal level of each factor, were obtained via the S/N ratio. In particular, after finding the difference between the highest and the lowest levels of each factor (known as delta), the factors with the highest positive delta were ranked as the most important factor (Oyewo et al. 2022). Via delta ranking, the order of influential factors is determined as treatment (first), diameter (second), and cultivar type (third). Accordingly, the S/N ratio of the biodegradation response of the BPS fibers is presented in Table 4. Furthermore, Figure 4 presents the optimal level for

Table 4. Biodegradation response table for signal-to-noise ratios (larger is better).

Level	Treatment	Diameter (μm)	Cultivar
1	26.57	29.36	28.22
2	29.01	28.03	28.56
3	30.40	28.57	29.20
Delta	3.83	1.33	0.98
Rank	1	2	3

**Figure 4.** S/N ratio for biodegradation (larger is better).

each factor. The optimal level for biodegradation is T3D1C3 – which can be considered as the treatment at level 3 (acetic acid), diameter at level 1 (60.77 μm), and cultivar level 3 (paranta). Prediction of T3D1C3, as obtained from S/N ratio, satisfactorily corresponds to the results obtained from biodegradation experimentation (sample number 7).

Furthermore, the S/N ratio from the TGA of the BPS fibers was used to determine the order of the influential factors (Table 5) and the optimal level of each of these factors (Figure 5). Similarly, in the order of importance, the S/N ratio of TGA also ranks fiber treatment, diameter, and cultivar type, as the influential factors. Thus, the optimal level for TGA is T3D1C1 – which can be interpreted as the treatment at level 3 (acetic acid), diameter at level 1 (60.77 μm), and cultivar level 1 (omini). Notably, Taguchi optimization analysis prediction of T3 and D1 was the same value obtained with the

Table 5. TGA response table for signal-to-noise ratios (larger is better).

Level	Treatment	Diameter (μm)	Cultivar
1	10.11	13.22	12.20
2	11.73	12.26	11.87
3	14.31	10.67	12.09
Delta	4.20	2.55	0.33
Rank	1	2	3

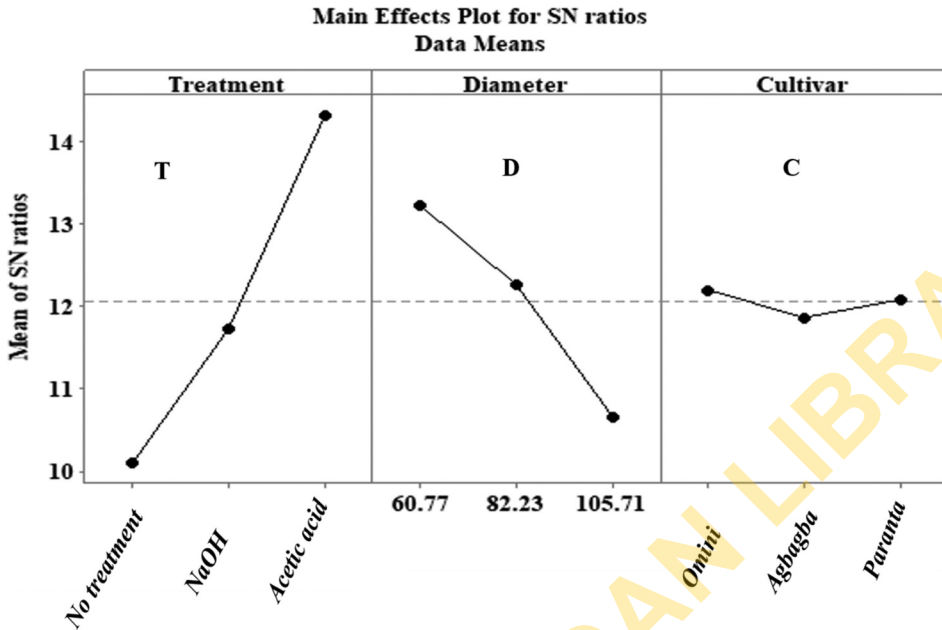


Figure 5. S/N ratio of TGA (larger is better).

biodegradation experimental results. However, cultivar type gave C3 (paranta) in experimentation and C1 (omini) in the optimization.

Analysis of variance (ANOVA)

The results of the ANOVA of the S/N ratios from TGA and biodegradation of BPS fibers are presented in Table 6. The confidence interval for the ANOVA of the S/N ratios of the BPS fiber responses was 95%, and the remaining 5% (0.05) was regarded as the probability of failure (p-value). Thus, a parameter that showed the significance of each level of the factors influencing the fibers was the p-value. So, since a 95% confidence interval was used, a factor that had a p-value less than 0.05 was considered significant, and subsequently, the null hypothesis was discarded. In contrast, when the p-value of a factor was greater than 0.05, the factor was considered insignificant, and the null hypothesis was accepted. Meanwhile, the p-value and the contribution percentage of individual factor

Table 6. Analysis of Variance for SN ratios for TGA and Biodegradation.

Source	Response	Treatment	Diameter	Cultivar	Residual error	Total
DF	TGA	2	2	2	2	8
	Biodegradation	2	2	2	2	8
Seq SS	TGA	26.9156	9.9744	0.1711	0.1976	-
	Biodegradation	22.5576	2.6970	1.4837	0.6830	-
Adj SS	TGA	26.9156	9.9744	0.1711	0.1976	-
	Biodegradation	22.5576	2.6970	1.4837	0.6830	-
Adj MS	TGA	13.4578	4.9872	0.0855	0.0988	-
	Biodegradation	11.2788	1.3485	0.7419	0.3415	-
F	TGA	136.18	50.46	0.87	-	-
	Biodegradation	3.03	3.95	2.17	-	-
P	TGA	0.007	0.019	0.536	-	-
	Biodegradation	0.029	0.0202	0.315	-	-
% Contribution	TGA	69.24	23.77	4.459	2.53	100
	Biodegradation	72.26	19.84	5.41	2.49	100

toward the optimization outcome were instrumental in the ANOVA. Table 6 also gives the percentage contribution of the factors obtained from the TGA of the fibers. While the S/N ratio is used to determine the order of influential factors, it cannot be used to evaluate the percentage contribution of each factor. Both tests have the highest percentage contributions in fiber treatment (up 72.26%), followed by diameter (up 23.77%) and cultivar type (2.53%), which supports the order determined by the S/N ratio. Additionally, Table 6 shows the p-values for TGA and biodegradation. The null hypothesis is disapproved in both cases where the fiber treatment and diameter p-values are less than 0.05. The cultivar type, however, is more than 0.05, hence the null hypothesis is rejected.

Regression modeling

Regression equations for the optimization of the influencing factors of the BPS fibers based on the TGA and biodegradation of the fibers are the Equations (2) and (3), respectively. In particular, in the regression modeling of the BPS fiber responses, the confidence of determination (R^2) in the TGA responses of the fibers was 93.75%, whereas that of the biodegradation responses of the fibers was 88.59%. In both cases, R^2 was within the acceptable range. Furthermore, for each response, the values of all the factors were inserted into the corresponding regression equation to generate the predicted values, called the fits. The fits were then correlated with the corresponding experimental values to determine the exactness, variation, and accuracy of the modeling and are presented in Table 7. In particular, the percentage modeling error was calculated by dividing the difference between the experimental value and the fit, called the residual, by the experimental value. So, for the TGA and biodegradation, the percentage error was within -0.70 – 9.98 and -0.46 – 10.511% , respectively. These errors, within 10%, were acceptable according to Oyewo et al. (2022); (Abd El-Baky and Attia 2019). As such, there was a sufficient correlation between both the experiments and the modeling, given the fiber responses.

The regression equation for the TGA of the BPS fibers:

$$4.253 + 1.012 \text{ fiber treatment} - 0.02713 \text{ fiber diameter} + 0.045 \text{ fiber cultivar} \quad (2)$$

The regression equation for the biodegradation of the BPS fibers:

$$18.02 + 6.00 \text{ fiber treatment} - 0.0713 \text{ fiber diameter} + 1.77 \text{ fiber cultivar} \quad (3)$$

Probability plot and Pareto chart

The normal probability plots of the TGA and biodegradation of the BPS fibers are given in Figure 6 (a) and (b), respectively. Furthermore, the regression equation efficacy and the significance of the factors influencing the fibers in relation to the fiber responses were validated with the help of the probability plots. So, at α equal to 0.05, there was a 5% probability of error between the experimental and the

Table 7. Comparison between experiment and regression modeling equation.

TGA					Biodegradation			
No	Exp.	Fit	RES	%	Exp.	Fit	RESI	%
1	3.67	3.662	0.01	0.23	21.0	21.456	-0.46	-2.171
2	3.29	3.124	0.17	5.03	20.0	21.692	-1.69	-8.462
3	2.72	2.532	0.19	6.90	23.0	21.785	1.22	5.283
4	4.29	4.718	-0.43	-9.98	31.0	29.223	1.78	5.733
5	3.91	4.181	-0.27	-6.93	26.7	29.459	-2.76	-10.334
6	3.43	3.454	-0.02	-0.70	27.1	24.252	2.85	10.511
7	6.11	5.775	0.34	5.49	39.0	36.989	2.01	5.156
8	5.37	5.103	0.27	4.98	30.0	31.926	-1.93	-6.419
9	4.27	4.511	-0.24	-5.64	31.0	32.018	-1.02	-3.285

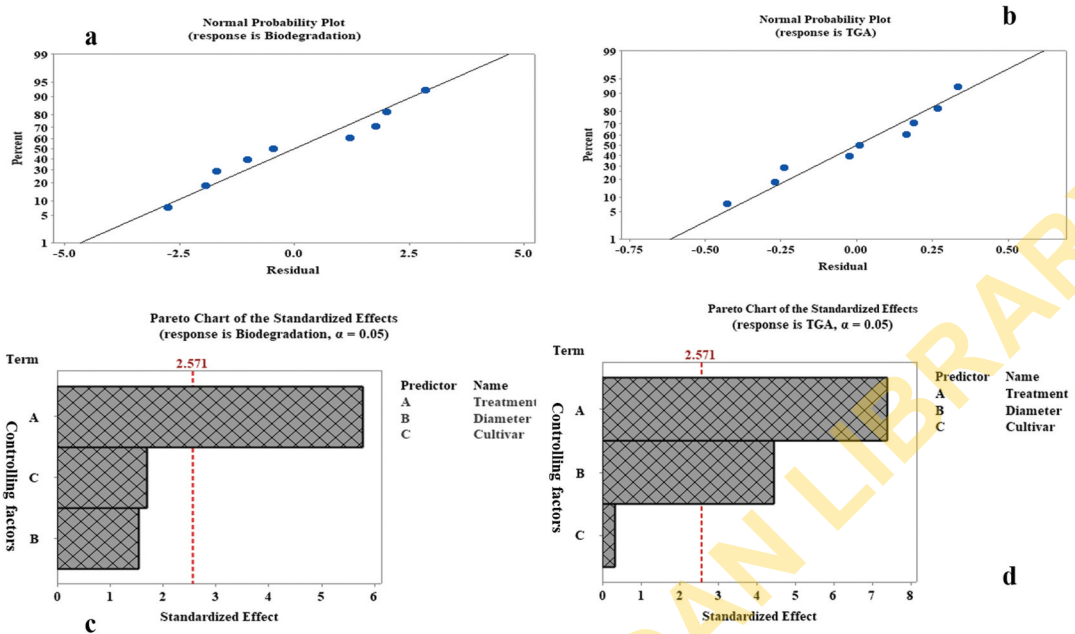


Figure 6. (A) Probability plot for biodegradation. (b) Probability plot for TGA. (c) Pareto chart for biodegradation. (d) Pareto chart for TGA.

model predictions of the responses, that is, the confidence interval (CI) remained at 95%. Next, at this CI, a linear probability plot was generated between the residual and the percentage probability of the responses. Meanwhile, according to Oyewo et al. (2022) and Arıcı, Çelik, and Keleştemur (2021), the residuals must be adequately fitted with a linear probability plot without many outliers. Here, the residuals in Figure 6 (a) and (b) for the fiber responses from the TGA and biodegradation of the fibers, respectively, were very close to the linear probability plot without undue variations. Furthermore, the Pareto charts for the BPS fiber responses from the TGA and biodegradation of the fibers are shown in Figure 6 (c) and (d). Unlike the linear probability plot, the Pareto chart is used to determine the significance of the influential factors by corroborating the S/N ratios and the ANOVA of the fiber responses. Procedurally, first, a standardized reference line (2.571) was generated automatically in the Pareto chart which is useful to determine the significance of a factor. Then, any bar above this reference line was considered to correspond to a significant factor; otherwise, the bar was considered to correspond to an insignificant factor.

Confirmation test

Validation of the experimental and Taguchi model-predicted BPS fiber responses via a confirmation test was necessary to ensure their usability. As such, an improvement in the S/N ratio of the responses toward finding the optimal influencing factors of the biodegradation and thermal stability of the fibers was achieved using the following Equation 5.

$$\theta_{\text{predicted}} = \alpha_1 + \sum_{i=1}^y (\alpha_0 - \alpha_i), \quad (4)$$

where α_1 indicated the mean S/N ratio, α_0 was the mean S/N ratio at the optimal level of the influencing factor, and y represented the number of influencing factors. Therefore, for the confirmation test, the average value representing the fiber responses from the experiment was compared with the corresponding experimental and the model predicted values. Eventually, the TGA and

Table 8. Confirmation test using average, experimentation, and prediction values.

Responses	Designation	Unit	Average value T2D2C3	Experimental T3D1C3	Prediction T3D1C1
TGA	Test	%	3.9100	5.3700	5.5700
	S/N	dB	11.8435	15.7208	15.6289
	Mean	%	3.9100	5.3700	5.8611
	Regression	%	4.181	5.1027	5.6853
Biodegradation	Test	%	26.7000	39.000	39.00
	S/N	dB	28.5302	31.8213	31.8213
	Mean	%	26.7000	39.000	39.000
	Regression	%	29.4591	36.9893	36.9971

biodegradation responses had the experimental and predicted values compared to the average value, T2D2C3. In addition, since the optimum fiber predicted from the TGA (T3D1C1) was not experimented with before in this study, a new experiment with T3D1C1 was run, and the comparison was made with the best experimental value (T3D1C3) and average value. So, this new test (T3D1C1), i.e., the optimum prediction from Taguchi analysis, showed an improvement of 3.72% with the experimental value and 29.8% with the average value. Equally, a comparison made using regression analysis of experimental, Taguchi prediction, and average value is presented in Table 8. Finally, the confirmation test was performed based on a mean with,

$$\beta = T + d + C - 2Y, \quad (5)$$

where β was the mean value of the response parameter; T, d, and C were the fiber treatment, diameter, and cultivar at the optimal level, respectively; and Y was the mean of the response parameter. The comparison between the average value of the experimental and model-predicted BPS fiber response parameters from the biodegradation and TGA of the fibers is presented in Table 8. In general, a reduction in the S/N ratio improves the efficiency of the optimization process (Oyewo et al. 2022). Following diameter and cultivar selection as determined by ANOVA analysis (% contribution) and s/n ratio, fiber treatments had the greatest impact on all outputs. The thermal stability and biodegradation of natural fibers are thus governed by a number of important elements, some of which include chemical treatments and fiber diameter. In affirmation to this claim, the study of Ezeamaku et al. (2022), investigating the effectiveness of some chemical treatments on banana fiber, also found improvement in tensile strength with acetic acid-treated banana fiber (79.67%) than potassium permanganate (77.78%) and sodium hydroxide (60.71%), the least. Similar to chemical treatments, the effect of lower diameter on natural fiber has been outlined in this study. Additionally, a study by Gangil et al. (2020); Masood et al. (2018) and microscopy research by Jaafar et al. (2019) demonstrate that smaller diameter fibers have better fiber dispersion in the matrix than larger diameter fibers, making them suitable for textile applications (Shaker et al. 2020), and a potent challenger to synthetic fibers (Shaker, Nawab, and Jabbar 2020).

In addition to the above results, the results of the validation of the experimental and Taguchi optimization method-predicted responses of the fibers in the form of 2-dimensional contour and 3-dimensional surface plots are shown in the **supplementary data** section of this article.

Conclusion

The work aimed at studying and analyzing the optimal values of the factors influencing the biodegradation and thermal stability of banana pseudo stem (BPS) of three common banana cultivars of Nigerian origin using theoretical modeling and experiments. All bpsf fibers were first examined for chemical composition and mechanical characterization. The three principal chemical components were cellulose, hemicellulose, and lignin. Agbagba and omini had the highest amounts of cellulose and hemicellulose (68.61% and 65.17%), while omini had the highest lignin content (7.51%). The chemical

composition and mechanical characteristics showed a strong association, with higher lignin concentration corresponding to higher elasticity and higher cellulosic content corresponding to higher tensile strength and tensile modulus. In particular, three influencing factors were selected: fiber treatment, diameter, and fiber cultivar in the study/analysis. The subsequent prediction from the optimization using the Taguchi method indicated that the fiber treatment was the most influential factor of thermal stability while fiber treatment and diameter were the most influential factors of biodegradation of the fibers. Next, the optimal factors, found using the S/N ratio and Pareto charts, correspond to samples T3D1C1 and T3D1C3 for the biodegradation and thermal stability of the fibers, respectively; with T3 denoting 5 wt. % NaOH-treated fiber, D1 denoting a fiber diameter of 60.77 μm , and C1 and C2 denoting agbagba and omini, respectively. Finally, the experimental fiber response parametric values were found to be well correlated with the model predicted fiber response parametric values via probability plot and regression modeling, as the percentage error between the experimental and predicted values was less than 10%.

Acknowledgments

The authors gratefully acknowledge the support provided by The World Academy of Science (TWAS), Italy, and the Department of Chemical Engineering, COMSATS University Islamabad (CUI), Lahore Campus, Pakistan. Young-Kwon Park acknowledges for the support from the National Research Foundation of Korea (NRF-2021R1A2C3011274). This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Plastic-Free Specialized Graduate School funded by Korea Ministry of Environment (MOE).

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Funding

The authors gratefully acknowledge the support provided by The World Academy of Science (TWAS), Italy, and the Department of Chemical Engineering, COMSATS University Islamabad (CUI), Lahore Campus, Pakistan. Young-Kwon Park acknowledges for the support from the National Research Foundation of Korea (NRF-2021R1A2C3011274). This work was supported by Korea Environment Industry & Technology Institute (KEITI) through Plastic-Free Specialized Graduate School funded by Korea Ministry of Environment (MOE).

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References

- Abd El-Baky, M., and M. Attia. 2019. Water absorption effect on the in-plane shear properties of jute-glass-carbon-reinforced composites using Iosipescu test. *Journal of Composite Materials* 53:3033–45. doi:10.1177/0021998318809525.
- Arıcı, E., E. Çelik, and O. Keleştemur. 2021. An analysis of the engineering properties of mortars containing corn cob ash and polypropylene fiber using the Taguchi and Taguchi-based grey relational analysis methods. *Case Studies in Construction Materials* 15:e00652. doi:10.1016/j.cscm.2021.e00652.
- Asim, M., M. T. Paridah, M. Chandrasekar, R. M. Shahroze, M. Jawaid, M. Nasir, and R. Siakeng. 2020. Thermal stability of natural fibers and their polymer composites. *Iranian Polymer Journal* 29:625–48. doi:10.1007/s13726-020-00824-6.

- Atalie, D., and R. K. Gideon. 2018. Extraction and characterization of Ethiopian palm leaf fibers. *Research Journal of Textile and Apparel* 22 (1):15–25. doi:10.1108/RJTA-06-2017-0035.
- Ezeamaku, U. L., O. D. Onukwuli, M. E. Ezech, I. O. Eze, N. E. Odimegwu, and C. P. Agu. 2022. Experimental investigation on influence of selected chemical treatment on banana fibre. *Industrial Crops and Products* 185:115135. doi:10.1016/j.indcrop.2022.115135.
- Ferede, E., and D. Atalie. 2022. Mechanical and water absorption characteristics of sisal fiber reinforced polypropylene composite. *Journal of Natural Fibers* 19 (16):1–14. doi:10.1080/15440478.2022.2069188.
- Gangil, B., L. Ranakoti, S. Verma, T. Singh, and S. Kumar. 2020. Natural and Synthetic Fibers for Hybrid Composites. In *Hybrid Fiber Composites: Materials, Manufacturing, Process Engineering*, ed. A. Khan, S. M. Rangappa, M. Jawaid, S. Siengchin, and A. M. Asiri. Wiley-VCH Verlag GmbH & Co. KGaA. ISBN: 9783527824571. doi:10.1002/9783527824571.ch1.
- Gideon, R., D. Atalie, and Y. Nawab. 2022. Mechanical and water absorption properties of Jute/Palm leaf fiber-reinforced recycled polypropylene hybrid composites. *International Journal of Polymer Science* 2022:2022. doi:10.1155/2022/4408455.
- Haider, T. P., C. Völker, J. Kramm, K. Landfester, and F. R. Wurm. 2019. Plastics of the future? The impact of biodegradable polymers on the environment and on society. *Angewandte Chemie International Edition* 58:50–62.
- IITA. 2021. 'Banana and plantain', international institute for training and agriculture, Accessed 3rd December, 2021. <https://www.iita.org/cropsnew/banana-plantain/>.
- Jaafar, J., J. P. Siregar, S. Mohd Salleh, M. H. Mohd Hamdan, T. Cionita, and T. Rihayat. 2019. Important considerations in manufacturing of natural fiber composites: A review. *International Journal of Precision Engineering and Manufacturing-Green Technology* 6:647–64.
- Jabbar, M., K. Shaker, M. Umair, and Y. Nawab. 2017. Optimizing the performance of woven protective gloves using grey relational analysis. *The Journal of the Textile Institute* 108:1715–19.
- Kohli, D., S. Garg, and A. K. Jana. 2021. Physical, mechanical, optical and biodegradability properties of polyvinyl alcohol/cellulose nanofibrils/kaolinite clay-based hybrid composite films. *Indian Chemical Engineer* 63:62–74.
- Luthra, P., K. K. Vimal, V. Goel, R. Singh, and G. S. Kapur. 2020. Biodegradation studies of polypropylene/natural fiber composites. *SN Applied Sciences* 2:1–13.
- Masood, Z., S. Ahmad, M. Umair, K. Shaker, Y. Nawab, and M. Karahan. 2018. Mechanical behaviour of hybrid composites developed from textile waste. *Fibres & Textiles in Eastern Europe* 26 (1): 46–52. doi:10.5604/01.3001.0010.7796.
- Oyewo, A. T., O. O. Oluwole, O. O. Ajide, T. E. Omoniyi, M. H. Hamayun, and M. Hussain. 2022. Experimental and theoretical studies to investigate the water absorption behavior of carbon/banana fibre hybrid epoxy composite. *Materials Chemistry and Physics* 285:126084.
- Parre, A., B. Karthikeyan, A. Balaji, and R. Udhayasankar. 2020. Investigation of chemical, thermal and morphological properties of untreated and NaOH treated banana fiber. *Materials Today: Proceedings* 22:347–52.
- Petroudy, S. D. 2017. Physical and mechanical properties of natural fibers. *Advanced High Strength Natural Fibre Composites in Construction*. Amsterdam: Elsevier. ISBN: 9780081004111.
- ProMusa. 2020. 'Banana producing countries', Accessed 4th December, 2021. <https://www.promusa.org/Nigeria>.
- Raddadi, N., and F. Fava. 2019. Biodegradation of oil-based plastics in the environment: Existing knowledge and needs of research and innovation. *The Science of the Total Environment* 679:148–58.
- Sanjay, S., J. P. Siengchin, M. Jawaid, C. I. Pruncu, and A. Khan. 2019. A comprehensive review of techniques for natural fibers as reinforcement in composites: Preparation, processing and characterization. *Carbohydrate Polymers* 207:108–21.
- Shaker, K., R. M. W. U. Khan, M. Jabbar, M. Umair, A. Tariq, M. Kashif, and Y. Nawab. 2020. Extraction and characterization of novel fibers from Vernonia elaeagnifolia as a potential textile fiber. *Industrial Crops and Products* 152:112518.
- Shaker, K., Y. Nawab, and M. Jabbar. 2020. Bio-composites: Eco-friendly substitute of glass fiber composites. In *Handbook of Nanomaterials and Nanocomposites for Energy and Environmental Applications*, ed. O. V. Kharissova, L. M. T. Martínez, and B. I. Kharisov, 151–175. Cham: Springer International Publishing. ISBN: 978-3-030-36267-6. https://link.springer.com/referenceworkentry/10.1007/978-3-030-36268-3_108
- Xu, S., C. Xiong, W. Tan, and Y. Zhang. 2015. Microstructural, thermal, and tensile characterization of banana pseudo-stem fibers obtained with mechanical. *Chemical, and Enzyme Extraction* 10:12.