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Physico-chemical, Thermal and Micro-structural Characterization of Four Common Banana Pseudo-Stem Fiber Cultivars in Nigeria

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ABSTRACT

This study explores Banana pseudo-stem fiber (BPSF) derived from BPF cultivars that are common in Nigeria. The four cultivars are known locally as Agbagba, Omini, Panbola, and Paranta. This study characterized these cultivars to gain insight into their physical, thermal and microstructural properties. The BPSFs were obtained after manual BPS retting and treated with a 2 wt. % sodium hydroxide solution to improve the fiber quality. Data from the characterization revealed the agbagba cultivar to give the highest percentage recovery (3%) and thermal stability at elevated temperatures with a residual char of 14%. The percentage of cellulose, lignin, hemicellulose, and ash content were determined by chemical composition analysis. FTIR spectroscopy showed a lower lignin and hemicellulose absorption band in the agbagba cultivar while scanning electron microscopy supported the FTIR results. Agabagba's crystallinity index (XRD) of 61.7% was higher than other cultivars, and X-ray fluorescence (XRF) and a biodegradation test also showed that only agbagba cultivar contained calcium and had the strongest resilience to microbial attack under simulated soil conditions. Agbagba BPSF may be a viable reinforcement in bio-fiber polymer composites needing high strength due to its balanced qualities that have been demonstrated in comparison to other cultivars.

摘要

本研究探索了尼日利亚常见的香蕉假茎纤维（BPSF）. 这四个品种在当地被称为Agbagba、Omini、Panbola和Paranta. 本研究对这些品种进行了表征, 以了解其物理、热和微观结构特性. BPSFs是在人工BPS脱胶后获得的, 并用2重量%的氢氧化钠溶液处理以改善纤维质量. 表征数据显示, agbagba品种在高温下具有最高的回收率（3%）和热稳定性, 残余炭为14%. 通过化学成分分析确定纤维素、木质素、半纤维素和灰分的百分比. FTIR光谱显示, 巴格巴品种的木质素和半纤维素吸收带较低, 而扫描电子显微镜支持FTIR结果. Agabagba的结晶度指数（XRD）为61.7%, 高于其他品种, X射线荧光（XRF）和生物降解试验也表明, 只有agbagba品种含有钙, 在模拟土壤条件下对微生物攻击具有最强的抵抗力. Agbagba BPSF可能是需要高强度的生物纤维聚合物复合材料中的一种可行的增强材料, 因为与其他品种相比, 它具有平衡的质量.

KEYWORDS

Pseudo-stem fiber; thermal analysis; FTIR; microstructural analysis; fiber yield; bio-fiber polymer composites

关键词

伪茎纤维; 热分析; 微观结构分析; 纤维产量; 生物纤维聚合物复合材料

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Introduction

Bananas are important as a food, income, and employment source for millions of households worldwide (Tenkouanoet al. 2019; undefined). Production of banana fruit spans across all seasons. However, the significant portion of the harvest comes within the dry season between December and March, at a period when large proportion of staple foods in starchy forms are depleted in circulation (Tenkouano et al. 2019). At 127.3 million metric tonnes (MT), banana was reported as one of the fruit crops with highest worldwide production (Panigrahi et al. 2021). Tenkouano et al. (2019) reported that Africa accounts for 62% of banana production worldwide, and Nigeria as the 15th highest producer of bananas globally (ProMusa, 2021). Nigeria has a total landmass of 450, 000 Ha of land for banana cultivation area (ProMusa, 2021) and produces approximately 3.09 MT per year, making Nigeria the second highest producer in west Africa, with Cameroon and Ghana ranking the third and first producers, respectively (Oyewo et al. 2022). However, in sub-Saharan Africa (SSA), Tenkouano et al. (2019) and 2021) reported Nigeria as the 4th largest producer after Uganda, Ghana and Cameroon. Furthermore, after yam and cassava, banana is ranked the third food crop in Nigeria (Tenkouano et al. 2019).

Modern classification places all banana varieties under *Musa paradisiaca*. Therefore, *Musa paradisiaca* is a hybrid of *Musa acuminata* (dessert banana with ploidy, A) and *Musa balbisiana* (cooking banana with ploidy, B). Further classification can also be made through ploidy level – a system that indicates the number of available chromosome sets in each cultivar (Tenkouano et al. 2019). Ploidy level has three categories: diploid, triploid or tetraploid, containing two, three or four chromosomes, respectively. The chromosomes in a diploid hybrid can appear in the form of AA, AB or BB. It should be noted that most tetraploid hybrids are now extinct, whereas triploid hybrids such as AAA, AAB, ABB are widely available and cultivated throughout the world (Divya et al. 2016; Tenkouano et al. 2019). For this reason, all the cultivars considered in this study were triploid. Until now, only botanical nomenclature was used to identify each cultivar. The botanical nomenclature method is not detailed enough to capture the variations with each species (Tenkouano et al. 2019). Therefore, the ploidy level and their subgroup are required for satisfactory identification of each cultivar. Based on this modern method of classification, the cultivars (including their local name) used in this study are classified as presented in Table 1.

Banana fiber has traditionally only been used locally, for things like mats, rope production, and handcraft. Importantly, research into the possible uses of banana fiber in textiles and other high-strength applications has been stimulated by the demand for environmentally friendly products (Gangil et al. 2020). Where ductility is necessary, banana fiber can be combined with other natural fibers, including sisal, cotton, ramie, and cotton, to make up for deficiencies in either component. Eswaramoorthi & Ramasamy (2022) examined the impact of hybrid banana/sisal fiber with polypropylene (PP) resin in various combinations with M30-grade concrete. After 7 days of curing, this hybrid composite was contrasted with regular concrete. With the hybrid combinations, a 14–25% increase in compressive, tensile, and flexural strength was noted. Sathish et al. (2021) looked into the usage of natural resin of phenolic origin (Vajram) and banana fiber composite in an effort to create a full-fledged natural composite free of synthetic resins. In a banana/phenolic composite treated with 5% NaOH and 30% fiber volume, superior mechanical characteristics were discovered. The hydrophilicity of natural fiber can be effectively reduced by fiber treatments like sodium hydroxide, benzoylation, maleated coupling agent, and acetylation. Accordingly, fiber that had been chemically

Table 1. Modern classifications of BPSF cultivars.

S/N	Botanical name	Genome (Group)	Subgroup	Cultivar	Local name
1	*Musa acuminata*	AAA	Cavendish	Giant Cavendish	Paranta
2	*Musa acuminata*	AAA	Red	Tall Red	Omini
3	*Musa decrescensde Briey*	AAB	Plantain	False Horn	Agbagba
4	*Musa acuminata ×balbisiana*	ABB	Saba	Saba	Panbola

pre-treated was reported to have better microstructural and mechanical qualities, better thermal and dynamic stability, and excellent fiber–matrix interaction (Hassan et al. 2020; Xu et al. 2015).

The micro structural, thermal and chemical characterization of BPSF have been documented in the form of the extraction method (Xu et al. 2015), different fractions of pseudo-stem (Pereira et al. 2014), study on individual banana species and region (Adeniyi, Ighalo and Onifade 2021) as well as polymeric composites of epoxy (Hassan et al. 2020; Odusote et al. 2016), phenolic (Sathish et al. 2021) and polypropylene (Eswaramoorthi and Ramasamy 2022) resins. The properties of BPSF differ, even within the same species, due to climatic factors, soil, size, age, nutrients, and geographical location (Gangil et al. 2020; Odusote et al. 2016). Therefore, information obtained from one region may not adequately capture the properties of Nigeria BPSF cultivars. No study on the combination of these four cultivars of Nigeria origin has been conducted, which is a motivation for this study. Insight from this work will serve as a gateway for extensive research and utilization of the vast BPS waste. Manual extraction was employed for the BPSF cultivars and the fibers were further treated with sodium hydroxide to improve the fiber quality. The percentage recovery, chemical composition, aspect ratio, and microstructural analysis were examined. The thermal stability at elevated temperatures was also investigated as well as the biodegradation rate under simulated soil conditions. These findings will provide insight and the necessary information for potential development and usefulness in various applications, such as polymer composite, construction and agriculture.

Experimentation

Materials and extraction of BPSF

Four different pseudo-stems of banana cultivars were sourced from the banana plantation of the National Horticultural Research Institute (NIHORT), Ibadan, Nigeria. Sodium hydroxide was procured from Chemical Bond, Ojota, Lagos State, Nigeria. Healthy BPS cultivars were separated into layers called ribbons, as shown in Figure 1a. Details of the extraction process has been reported elsewhere (Oyewo et al. 2022). To improve the BPSF, all cultivars were treated with 2 wt. % sodium hydroxide solution for 30 minutes. Recovered fibers after the immersion period were washed with sufficient water to attain chemical neutrality. Figure 1 presents (a) BPS ribbons and extracted BPSF cultivars of (b) omini (c) panbola (d) agbagba and (e) paranta.

Characterization of banana fiber

Percentage recovery yield

One to two of the outmost layers of the cultivars were removed because they might have been exposed to harsh weather and infection from disease and pests. Subsequently, ribbons were removed from the pseudo-stem strip by strip and approximately 8–9 stripped ribbons (Tuxies) were selected for further processing in each cultivar. Equal 40 g from the ribbon (s) each healthy cultivar (extractable BPS) was measured using a weighing balance, and the measured quantity was individually processed into BPSF to determine the cultivar with highest fiber yield. This test was carried out for each cultivar in three replications while their average means and standard deviations were calculated and recorded. The fiber yield or recovery percentage was calculated using Equation 1:

$$\text{Recovery Percentage} = \frac{\text{Weight of fiber(g)}}{\text{Weight of extractable BPS(g)}} \times 100 \qquad (1)$$

Thermo gravimetric analysis

A TGA/SDTT 991 Melter Tolder instrument was used. The BPSF cultivar samples were observed from 30 to 550°C at a heating rate of 20°C/min. The sample weights varied from 6 to 10 mg. Four samples were tested from each of the BSPF cultivars.

Figure 1. Banana cultivars (a) BPS (b) BPSF Omini (c) BPSF Panbola (d) BPSF Agbagba (e) Paranta.

Fourier transform infrared spectroscopy

Fourier transform infrared (FTIR, Chingnouz FTIR-8150) spectroscopy was performed over the range of 4000–400 cm^{-1} with the BPSF cultivar samples that had been dried in an oven at 90°C for 2 h and stored under vacuum. The dried samples were mixed with KBr in a proportion of 3% (w/w) and pressed (3 tons).

Scanning electron microscopy

A SEM NICON S-3000N (Model 6681) was used to examine the microstructure of the cultivars. A 15 kV accelerating voltage was used to operate the microscope. The tilt was fixed to 0° and a working distance up to 3 mm was used. To make the fiber conductible and acceptable for analysis, a pre-coating with a very thin layer of gold, measuring around 20 nm, was carried out.

Other tests (X-ray fluorescence, X-ray diffraction and biodegradation)

Xrf test was conducted on 0.5 g of each sample with wavelength dispersive XRF spectroscopy embedded with a Pd anode X-ray tube, operating at 40 pV and 1.2 mA. On the other hand, XRD of different dried powder fractions of the cultivars was carried out using a bench top diffractometer (Rigaku Minilfex 600 C, China) with a Co tube, operating at 40 kV and 40 mA. All the BPSF cultivar samples were scanned from 10 to 80° 2θ. In order to simulate soil condition, the BPSF cultivar samples were weighted and placed in a prepared soil container at room temperature of 28°C. The composition of the soil simulation comprised 31% distilled water, 23% cow manure (organic matter), and 26% loamy soil, all by w/w. The biodegradability was monitored intermittently for a period of 90 days by constantly taking the mass retention measurement. The buried BPSF fibers were removed after 90 days. The fibers were washed under clean running water, dried at room temperature, and measured until the recorded values were constant.

Results and discussion

Percentage recovery

The percentage recovery (fiber yield) was performed to determine the BPSF cultivar that produces the highest fiber percentage recovery. Table 2 lists the percentage recovery or fiber yield for the BPSF cultivar samples. The BPSF weight differs in various cultivars. For BPSF cultivars, 1.5%, 2.0%, 3.0%, and 2.2% were the values of the fiber recovery (fiber yield) for Omini, Paranta, Agbagba and Panbola, respectively. The BPSF considered for this study are triploid – containing three sets of chromosomes to attain a ploidy level of three. The A's is associated with the *Musa acuminate* lineage, while B's belongs to *Musa balbisiana* (Preethi and Balakrishna 2013). Therefore, a cultivar with the genomic group AAA (such as Omini and Paranta) contained three chromosomes of *Musa acuminata*, while a cultivar with genomic group AAB (such as Agbagba) is a hybrid between two chromosomes of *Musa acuminata* and one chromosome of *Musa balbisiana*. In addition, Panbola has an ABB triploid. In BPSF cultivars, observations showed that cultivars containing B genomes, such as Agbagba (AAB) and Panbola (ABB), produced higher fiber yields than the homogenous triploids of Paranta (AAA) and Omini (AAA).

Similarly, it can be inferred that the culinary cultivars (Agbagba and Panbola) showed higher fiber yields than the dessert (Omini and Paranta) cultivars. Divya et al. (2016) also reported a higher percentage yield in the culinary value (0.78%) than the dessert value (0.58%). Factors including greater biomass, robustness, and bulky of the plants may contribute to the greater yield of a cultivar (Preethi and Balakrishna 2013). According to Divya et al. (2016), the genomic constituent was discovered to have little influence on the percentage yield of the fiber and fiber weight. Therefore, Agbagba, Panbola, Paranta, and Omini, listed in decreasing order of their percentage fiber yield, would be useful as adequate information for many purposes, such as composite production.

Thermal analysis

Thermogravimetric analysis (TGA) and derivative thermogravimetric (DTG), as shown in Figure 2 and Figure 3, respectively, help understand the thermal stability of the BPSF cultivars. From Figure 2, the fibers had three main weight loss regions for all the samples throughout decomposition and were within the range of 30 to 550°C. The three stages include initial, middle (50%), and final degradation temperature (called fiber residue). Table 3 lists these stages, as derived from the thermogram curve portion of the BPSF. The temperature at which evaporation and liberation of water molecules occurred was approximately equal for all samples. From 30 to 100°C, there was loss of humidity for all the BPSF cultivars, which was the first region of weight loss (Kumariet al. 2021). At this stage, the percentage weight loss was approximately 6–8%. As the temperature increased, the initial decomposition temperature (IDT) stage set in, which was within the 205–220°C. IDT commenced with Paranta at 205°C, followed by Omini and Panbola at 215°C and Agbagba at 220°C. In the second region, the degradation temperature (50% DT,°C) of the percentage loss of weight was approximately 50%, from 315 to 330°C. The loss at this region can be attributed to the thermal decomposition of α-cellulose and

Table 2. Percentage recovery (fiber yield) for the BPSF cultivars.

Species	Weight of fiber (g)	Weight of extracted fiber (g)	Fiber recovery or yield (%)
Omini	40	0.60 ± 0.011	1.5
Paranta	40	0.80 ± 0.011	2.0
Agbagba	40	1.20 ± 0.013	3.0
Panbola	40	0.88 ± 0.010	2.2

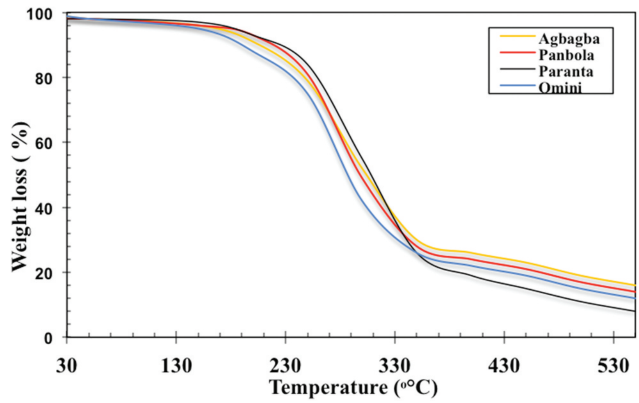

Figure 2. TGA curves of BPSF cultivars.

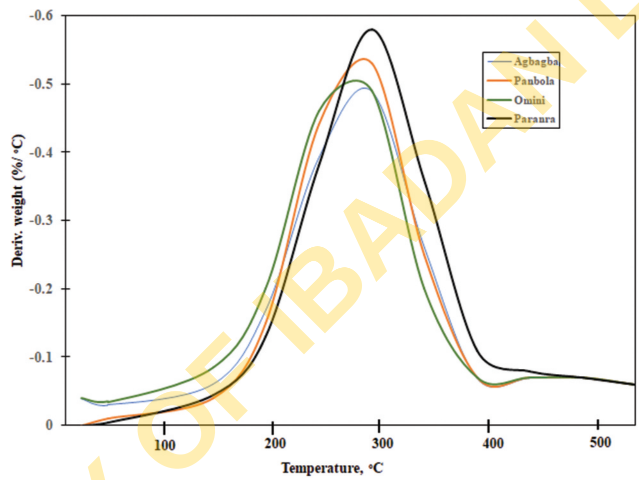

Figure 3. DTG curves of BPSF (a) Agbagba (b) Panbola (c) Omini (d) Paranta.

Table 3. Thermal degradation temperature of the BPSF cultivars.

Degradation parameters				
Cultivar samples	IDT, °C	50 % DT, °C	FDT, °C	% Char yield (residue)
Omini	215	325	373	8
Paranta	205	315	379	12
Agbagba	220	330	392	16
Panbola	215	320	380	14

the depolymerization of hemicellulose (Oyewo et al. 2022). The third region is the final decomposition temperature (FDT). From 373 to 392°C, FDT covered the decomposition of non-cellulosic, such as lignin, the most difficult to decompose constituent of banana fiber. The FDT for Agbagba, Panbola, Omini, and Paranta were 392, 380, 373 and 379°C, respectively. The decomposition of lignin was up to 550°C.

Figure 4 compares the char of BPSF cultivars. The char yields of the BPSF cultivars of Omini, Paranta, Agbagba, and Panbola were 8, 12, 16, and 14%, respectively. The highest residue was obtained from the Panbola and Agbagba cultivars, while the smallest residue was obtained with the Omini cultivar. Therefore, increasing the char yield may reduce the combustible gases formation,

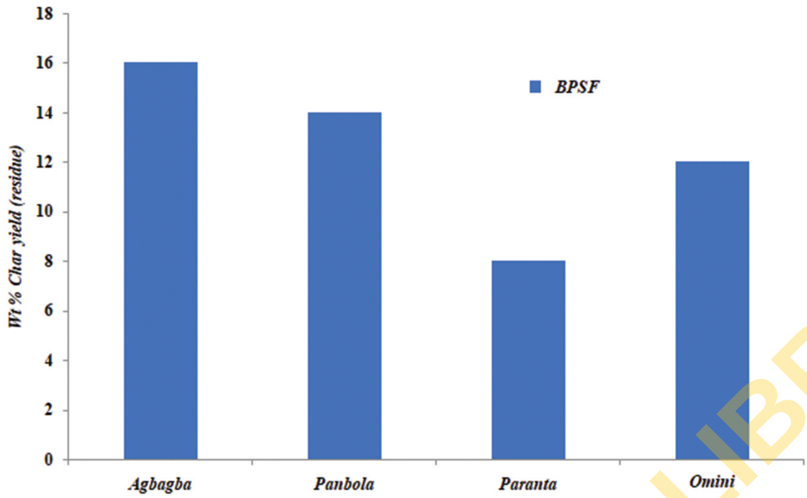

Figure 4. Comparison of the char (residue) of BPSF cultivars.

conductivity (thermal) of burning materials and exothermicity of the pyrolysis reaction (Chen et al. 2020). Thus, the rate of flame retardancy would increase in the fiber with a higher char percentage. Kumari et al. (2021) reported a similar observation of higher char percentage, revealing that the surface treatment was effective for hemicellulose reduction, leading to the lignin-cellulose complex formation, in which the new formation attains better stability and increment of residual weight (Kumari et al. 2021). The temperature of the BPSF cultivars through DTG (Figure 3) was correlated with the TGA results. Figure 3 shows the major peak and different decomposition temperatures of all BPSF cultivars. Observation of wide peaks as a result of loss curve from the first derivatives in the cultivars may be attributed to various combustion such as carbon (Xu et al. 2015).

A higher percentage residue always led to higher crystallinity (Cecen et al. 2017). Therefore, the higher value of the BPSF cultivars indicates higher crystallinity. Upon heating, the possibility of moisture liberation reduces because of the moisture that are firmly held in the pack structure, resulting in higher FTD, as observed with the Agbagba and Panbola cultivars. The decreased amount of water absorbed in these can be attributed to the removal of alkali-sensitive sites with higher alkali concentrations, which are also active sites for moisture absorption (Rajesh et al. 2020). Furthermore, the higher thermal stability of Agbagba and Panbola cultivars was probably due to better removal of lignin, wax and hemicelluloses from the fiber surface (Rajesh et al. 2020).

A higher percentage residue of Agbagba BPSF cultivars might be justified by the larger amount of hydrogen bonds between cellulose that can lead to more ordered and packed cellulose regions. The ordered region increases the thermal stability of natural fibers because the cellulose is immobile due to strain and weakened hydrogen bonds in their cellulose (Rajesh et al. 2020).

Fourier transform infrared spectroscopy

Table 4 lists the transmittance peaks for BPSF cultivars and various validations by other papers. The table shows the spectra recorded using the transmittance method in the 4000–600 cm^{-1} region (wavelength), presented in BPSF cultivars.

The main constituents of the natural fibers are cellulose, lignin, and hemicelluloses. Thus, the FTIR band results were attributed and confined to these components. The results are presented in Figure 5. The major absorption bands were observed at 3256, 2744, 2545, 1719, 1693, 1442, 1129, 951, and 720 cm^{-1}. The broadband at 3256 cm^{-1} for the banana fibers corresponds to the hydroxyl group (O – H) stretching vibrations of cellulose, hemicellulose, and absorbed moisture (Adeniyi, Ighalo and Onifade

Table 4. Transmittance peaks obtained from the BPSF cultivars.

		Banana Peduncle (cm^{-1})				
Functional group	Possible assignment	Omini	Paranta	Agbagba	Panbola	References
O-H stretching (H-bonded)	Water, Cellulose, Hemicellulose and lignin	3239	3252	3232	3237	(Adeniyi et al. 2020)
C-H stretching (aromatic)	Cellulose, lignin, carboxylic acids	2582 2327	2578	2568	2753 2576	(Adeniyi et al. 2020; Kumari et al. 2021)
C=C stretching (ester, aromatic ring, ketone) OH bending/C=O stretching	Hemicellulose (sometimes lignin). Lignin/water	1699	1722	1741	1856 1693	(Kumari et al. 2021; Preethi and Balakrishna 2013)
C-H_2 bending (deformation) OH, in Plane deformation.	Cellulose, lignin Cellulose	1370	1467 1371	1377	1434	(Preethi and Balakrishna 2013; Xu et al. 2015)
C-O (stretching vibration)	Lignin, hemicellulose	1095	1141	1125	1114	(Adeniyi et al. 2021; Kumari et al. 2021)
C=O stretch (C-O-C asymmetric stretch)	Cellulose	-	-	-	922	(Adeniyi et al. 2021; Xu et al. 2015)
β-glycosidic linkages of glucose ring of cellulose C-H out-of-plane deformation	*β*-glycosidic linkages between the monosaccharides. Lignin	790	793	843		(Preethi and Balakrishna 2013; Xu et al., 2015)

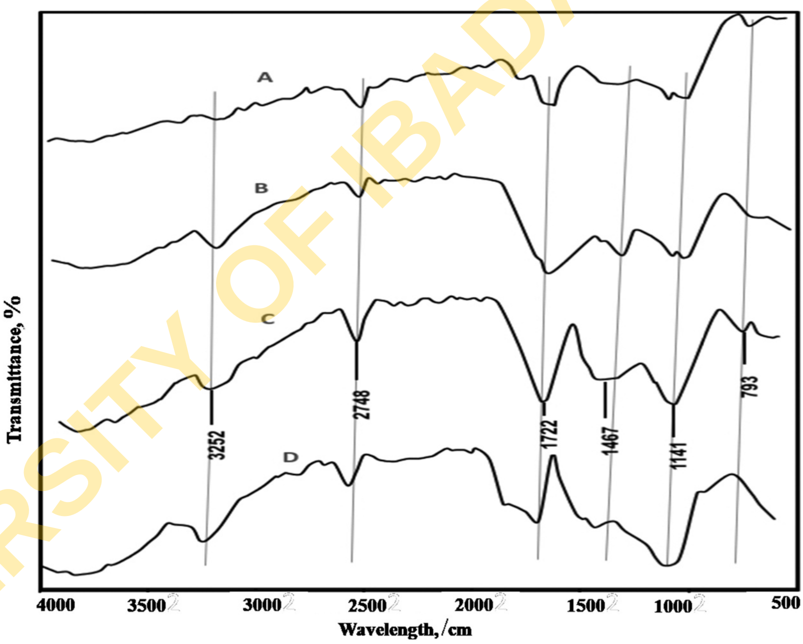

Figure 5. Fourier transform infrared spectroscopy of BPSF cultivars (a) Agbagba (b) Omini (c) Paranta and (d) Panbola.

2021; Xu et al. 2015). This indicates a weak absorbance for all BPSF, while Agbagba was the weakest at this wavelength. Therefore, a weak absorption band at 3237–3252 cm^{-1} reflects the breakage of hydrogen bonding between the O – H group of cellulose and hemicellulose, which was probably induced by the chemical treatment and may promote the hydrophobicity of the fibers. In addition, Xu et al. (2015) also reported that the peak at 2921 to 2700 cm^{-1} was attributed to the C-H stretching vibration from the – CH_2 group of cellulose and hemicellulose. Adeniyi, Ighalo and Onifade (2021) attributed the above range to the asymmetric and symmetric C-H stretching of the methyl and methylene units of cellulose (Adeniyi, Ighalo and Onifade 2021).

The peak around 2900 cm^{-1} for BPSF was absent, indicating the absence of asymmetric C – H stretching vibrations of the alkyl group in cellulose. On the other hand, symmetric stretching vibrations of the above at 2758 cm^{-1} were present, approximately at the same level for all the BSPF cultivars. The absorption band at 1756 cm^{-1} and 1693 cm^{-1} may be due to stretching of the carbonyl (C=O) ester and carboxyl groups of hemicellulose and possibly fatty acids from lignin (Pereira et al. 2014). The absence or presence of the characteristic peaks at 1722 cm^{-1}, is associated with the removal of hemicellulose and lignin, particularly hemicellulose, which are easy to remove (mostly with an alkali treatment) (Pereira et al. 2014). The vibrational stretching at this stage (1736 to 1722 cm^{-1}) is conspicuous in all the cultivars except for the Agbagba cultivars in BPSF, which was weakly reflected. The disappearance or weak vibrational stretch at this band indicated the removal of most hemicelluloses (Xu et al. 2015). The chemical composition (**supplementary data**) with a lower percentage of hemicellulose in these cultivars is substantiated by the results of this section, suggesting hemicellulose as a key component responsible for water absorption. In particular, Agbagba BPSF showed a significant decrease in absorption during the chemical treatment. The bands at 1638, 1514, 1424, and 1383 cm^{-1} were assigned to the aromatic skeletal vibrations and were associated with C – O stretch in lignin (Xu et al. 2015). This weak band was similar in all cultivars but was very weak in the Agbagba cultivar. Lignin cements other components of the natural plant fiber together, making it the most difficult component to decompose (Dorezet al. 2014). Therefore, the absence or weakness of vibrational band in BPSF (Agbagba cultivar) indicates lignin removal, which may result in higher strength of natural fibers (Xu et al. 2015). The strong absorption at 1059 $cm^{-1}$was attributed to the C – O stretching vibration in cellulose and hemicellulose (Xu et al. 2015). The small absorption band at 921–793 cm^{-1} may be ascribed to the β-glucoside linkages found with the sugar units in cellulose as well as the hemicellulose. Xu et al. (2015) and Pereira et al. (2014) attributed this stage to the C – H out-of-plane deformation of lignin (Xu et al. 2015).

Scanning electron microscopy

Cecen et al. (2017) reported that the rougher surface of bio-fiber indicated higher crystallinity, a situation where the crystals in the fiber structure are more oriented. Therefore, the Agbagba BPS (Figure 6a) cultivar was rougher than the other BPS cultivar, probably due to the high crystallinity, cellulose content, and the effect of alkalization, which could be more pronounced in the fiber structure (Cecen et al. 2017). However, smooth surface was noticed in omini but more prominent in panbola, indicating the presence of impurities which has not been totally removed by the mercerization action. The high crystallinity of the natural fiber was attributed to the absence or slight presence of lignin and hemicellulose binding a bundle of an individual cell (Cecen et al. 2017). A rough surface can also be achieved when the hydrogen bonds that cement lignin and hemicellulose with the cellulose (causing immobility of hydroxide groups in the cellulose) is broken due to the mercerization action, which in turn shrinks the tuberous cellulose fibers to a more compact, better packing and rearranges cellulose cell (Xu et al. 2015). Consequently, there would be an increase in surface area of the fibers and the large area of contact between the fiber and the matrix, leading to an increase in tensile strength, crystalline rougher surface, and displacement of large hydroxide group in the cellulose. Natural fibers with a rough surface increase the number of sites available for matrix interaction, reduction in weakness of the fiber and water absorption affinity, improves reaction with hydrophilic polymer and enhanced mechanical interlocking (Cecen et al. 2017).

X-ray fluorescence analysis

Table 5 lists the main elements in the BPSF cultivar ashes. Potassium (K) was the main element for all fractions, followed by chlorine (Cl), phosphorous (P), magnesium (Mg), silicon (Si), and sulfur (S). Calcium (Ca) was detected only in the Omini BPSF at 9.12% and Agbagba BPSF at 7.07%, whereas Mg, Si, S, and P were present as minor elements. Adeniyi, Onifade and Ighalo et al. (2020) and Pereira et al.

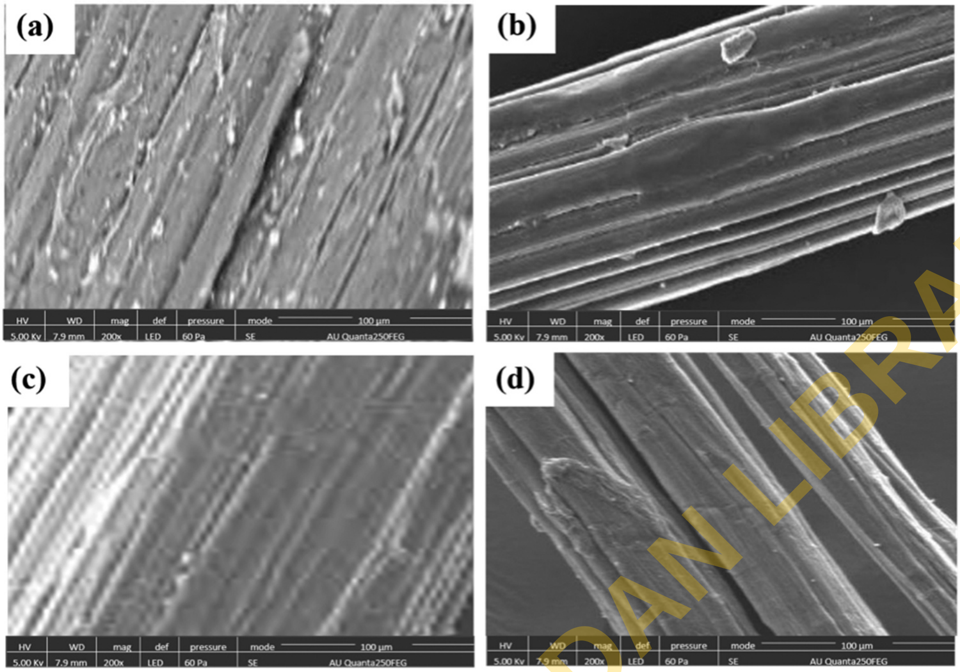

Figure 6. Longitudinal view of SEM images of BPS cultivars of (a) Agbagba (b) Omini (c) Paranta (d) Panbola.

Table 5. Elemental composition of BPSF cultivars (percentage, % w/w).

Elemental composition of BPSF and BPF (percentage, % w/w)				
Elemental composition	Omini	Paranta	Agbagba	Panbola
Potassium (K)	57.58	64.67	67.23	47.04
Chlorine (Cl)	22.65	22.81	28.56	30.75
Calcium (Ca)	9.12	-	7.07	-
Phosphorous (P)	1.58	2.86	4.68	3.76
Magnesium (Mg)	2.36	3.12	3.90	3.28
Silicon (Si)	2.98	2.02	4.55	3.77
Sulfur (S)	0.23	0.25	0.12	0.11

(2014) detected similar compositions in their investigation, reporting K as main ash component, and the presence of Ca, Si, P, and Mg. In addition to the above mentioned elements. Adeniyi et al. (2020) detected indium (In) in the *Musa paradisiaca* ashes. Each element detected can be assessed for many applications.

Ca and K are useful in soil remediation (Adeniyi et al. 2020). These results suggest that the BPSF cultivars should consider the sole material for extracting fibers or other materials and a major source of molecules for both technological advances. They can also find applications in the bio-refinery area in which biomass is converted to fuels and other useful products. Variations in the elemental composition of plants may be due to the soil content in the geographical area in which the plant was grown (Dorez et al. 2014; Adeniyi et al. 2020).

X-ray diffraction

Figure 7 presents the XRD pattern of the cultivar samples. The peak at 16.5° 2θ is assigned to the (2 0 0) plane, while the peak at 23.5° 2θ was attributed to the (1 0 0) crystallographic plane (Xu et al. 2015). Estimation of crystallinity index was carried out with Equation (2) (Xu et al. 2015):

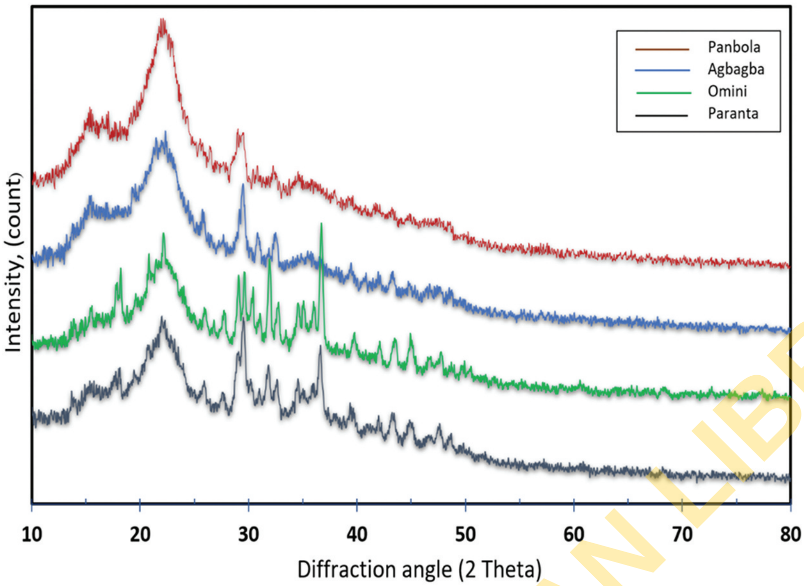

Figure 7. XRD pattern of BPSFs: (a) Omini (b) Paranta (c) Agbagba (d) Panbola.

$$Crystalllinity\ Index(CI) = H_{23.5} - H_{16.5}/H_{23.5} \quad (2)$$

Where $H_{23.5}$ is the peak at 23.5° 2θ and is the contribution of both crystalline and amorphous fractions. $H_{16.5}$ is the diffracted intensity at 16.5° 2θ, and was assigned to the amorphous fraction (Manimaran et al. 2019). The crystallinity indices of Omini, Paranta, Agbagba, and Panbola were calculated to be 56.2, 55.5, 61.7, and 59.1%, respectively, which agrees with the cellulose composition of each BPSF cultivar. The Agbagba cultivar has the highest crystallinity index, while Omini has the lowest. The higher crystallinity index of the Agbagba cultivar may be due to the higher cellulosic content and enhancement of the crystalline fraction (supplementary data). Method of fiber extraction, including chemical and enzymatic methods may lead to higher crystallinity because of the fiber surface, which has been modified, respectively, by the chemical and enzymatic action. Xu et al. (2015) reported a higher CI for chemical (60.2%) and enzyme (61.2%) extracted banana fibers while the CI of mechanical extraction was (56.6%). In this study, all cultivars were also pretreated with sodium hydroxide. The CI obtained from these BPSF cultivars were higher than the bio-fibers reported by Manimaran et al. (2019), i.e.,*C. pangorei* (41%), *Acacia leucophloea* (51%), and *Acacia Arabica* (51.72%) but lower than jute (71%) (Manimaran et al. 2019). Xu et al. (2015) attributed the higher CI of the natural fiber to the amorphous component, reduction in hemicellulose due to surface modification, and improved crystalline fraction. Other intense peaks (diffraction angle), such as ~29° 2θ and ~39° 2θ, were attributed to the presence of inorganic components, including Cl, K, and Ca, from XRF spectroscopy. The diffraction angle, 39° 2θ, was more prominent in Agbagba and Omini and was ascribed to the presence of Ca, as revealed by XRF. Pereira et al. (2014) assigned the narrow peaks to inorganic substances.

Biodegradability

Banana fibers are lignocellulosic fibers, and their biodegradation is contingent upon some conditions, including the degradative strength of the microbial population (Pereira et al. 2014). Figure 8 presents the result of the fiber biodegradability subjected to microbial exposure in soil simulation for 90 days. The omini cultivar had the highest mass retention, followed by agbagba cultivar while the lowest was obtained with the panbola and paranta cultivar. Exposure to microbial action in the soil simulation led

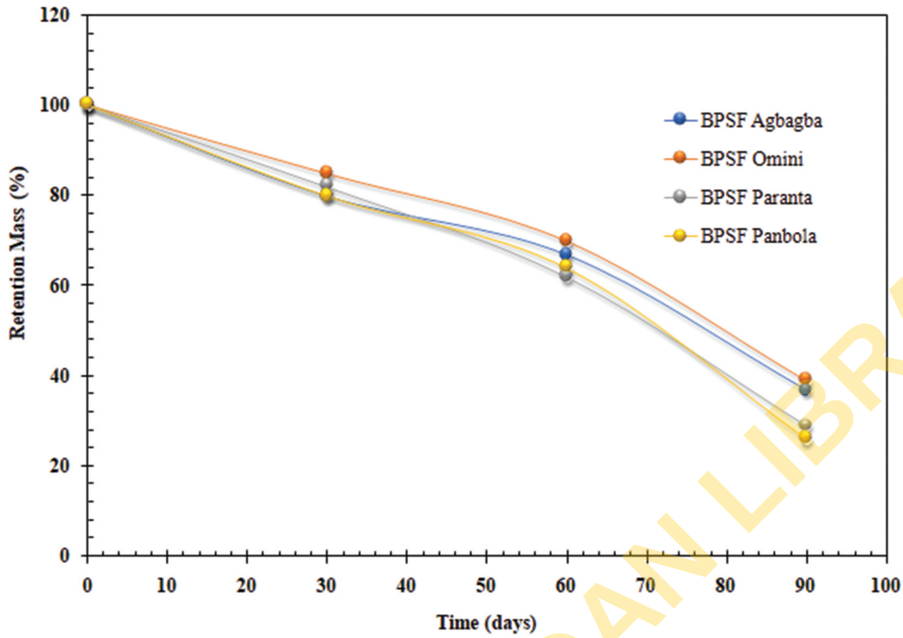

Figure 8. Mass retention (%) in soil simulation of BPSF cultivar.

to the production of enzymes, where all BPFS were affected (Pereira et al. 2014; Pérez et al., 2002). The loss of weight was attributed to the action of microorganisms of fungi and bacteria, which are best-known for degrading the polymer of cellulose, lignin and hemicellulose. Microorganisms are classified into two categories based on external enzymatic action: hydrolases are produced from a hydrolytic system, responsible for the degradation of cellulose and hemicellulose, whereas the extracellular ligninolytic system depolymerizes lignin (Kumar et al. 2020).

Hemicellulose is comprised of short lateral chains of different sugars that can be hydrolyzed conveniently. Hemicellulose is regarded as the component in the natural fiber with highest susceptibility to microbial attack because of their location in the non-crystalline region and partly solubility in water with lower molecular weight (Kumar et al. 2020). Hemicellulose, followed by non-crystalline cellulose, cellulose, and lignin, respectively, are the order of microbial susceptibility to biodegradation. Unlike crystalline cellulose, few non-crystalline celluloses in the plant cell suffered degradation after hemicellulose. This was attributed to weak hydrogen bonds between its cells. The chain of cellulose located in crystalline regions relates via strong hydrogen bonds and Van der Waal forces, which alter their biodegradation properties considerably in comparison with the non-crystalline sections (Kumar et al. 2020; Pereira et al. 2014). The main role of lignin in plant is to provide structural protection and binding of other components with hemicellulose. Biodegradation of lignin is not easily achieved due to the presence of aromatic and heterogeneous cross-linked in its structure. Because of its non-water soluble and lowest water absorption rate, the lignin structure adopts the cellulosic microfibrils to form a protective fortress against the advances of foreign microorganisms (Dorez et al. 2014; Kumar et al. 2020). Therefore, lignin is the most difficult to decompose among the constituents of natural fiber. The susceptibility of fibers to biodegradation depends on the rate at which lignin is vulnerable to microbial attack (Dorez et al. 2014). Thus, Omini BPSF with higher lignin content, as presented in the chemical composition (**supplementary**), resists microbial attack at various degrees than other BPSF cultivars. This probably occurs due to the increasing superficial surface (exposure of the cellulosic chains to enzymes produced by microorganisms) of the Omini cultivar.

All fibers reduced their mass content until the final day, but omini cultivars with the highest hemicellulose and lignin content suffered the least microbial attack, followed by agbagba, paranta and panbola. The highest mass retention found in omini and agbagba indicated that the microbial attack was least pronounced, and that the cultivars were more durable without losing significant strength during storage.

Conclusions

BPSF cultivars, agbagba, omini, panbola, and paranta, were obtained using the manual retting method and subjected to different characterization techniques. The highest percentage recovery (3%) was obtained from the agbagba BPSF cultivar, followed by panbola (2.2%), paranta (2.0%) and omini (1.5%). In addition, SEM revealed the structural arrangement and arch fibers in the BPSF cultivars. Thermal analyses, through the residual char, suggested that agbagba was stable at elevated temperatures, while FTIR spectroscopy showed that lignin and hemicellulose were reduced in agbagba than other BPSF cultivars. Percentage of lignin, cellulose, hemicellulose, water and ash content were determined by chemical composition analysis in which the highest cellulose percentage, 69.21%, was found in agbagba (supplementary data). Data from X-ray diffraction analysis revealed that increased in cellulose content led to increased crystallinity index and mechanical properties, whereas omini and agbagba cultivars were least degraded and vulnerable to microbial attack in simulated soil due to lower lignin content (supplementary data). Furthermore, in addition to the main elemental compositions of all cultivars – potassium, chlorine and phosphorous – X-ray fluorescence test also detected calcium in omini and agbagba cultivars. The presence of calcium can be explored in soil remediation and other applications. Among all cultivars, agbagba BPSF cultivar exhibited the most balanced properties and has the greatest potential for use as reinforcement in the polymer composite.

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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.

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