Journal of Renewable Energy and Environment

Research Article

Journal Homepage: www.jree.ir

Mechanical and Microstructural Properties of Bio-composite Produced from Recycled Polystyrene/chicken Feather Biochar

Adewale George Adeniyi[1,2*], Kingsley O. Iwuozor[3], Ebuka Chizitere Emenike[3], Comfort A. Adeyanju[1], Samuel Ogunniyi[1]

[1]*Department of Chemical Engineering, University of Ilorin, P. M. B. 1515, Ilorin, Nigeria*
[2]*Department of Chemical Engineering, Landmark University Omu-aran*
[3]*Department of Pure and Industrial Chemistry, Nnamdi Azikiwe University, P. M. B. 5025, Awka, Nigeria*

PAPER INFO

Paper history:
Received 10 April 2023
Revised 11 May 2023
Accepted 17 June 2023

Keywords:
Biochar
Chicken Feather
Polystyrene Composite
Mechanical Properties

ABSTRACT

Polystyrene waste is a significant environmental problem, and recycling and repurposing it can reduce its impact on the environment. Chicken feather biochar, on the other hand, is a by-product of the poultry industry and can be repurposed to produce bio-composites. The goal of this work was to turn waste chicken feathers into biochar and then, create composites with the biochar acting as the filler and a polystyrene-based resin acting as the matrix. The biochar was prepared with the aid of a top-lit updraft reactor. Composites were fabricated using different mixing ratios of biochar (10-40%) and polystyrene resin. The composites were then analyzed using FTIR, SEM-EDX, and hardness tests. SEM examination demonstrated that the biochar was distributed unevenly throughout the matrix. The alterations and shifts in peak positions shown by FTIR measurement indicated that there was a chemical interaction between the matrix and the biochar. It also revealed the hydrophilic nature of the composite. Hardness test showed that 20% biochar concentration gave the optimum hardness property (139 HRB). The EDX result demonstrated that the matrix as well as the composites consisted majorly of carbon atoms. The results of this study indicate the potential of using chicken feather biochar as a filler material to improve the mechanical and microstructural properties of recycled polystyrene-based bio-composites. This approach can provide a sustainable and environmentally-friendly solution to repurpose waste materials from poultry and plastic industries.

Doi: https://doi.org/10.30501/jree.2023.384691.1553

1. INTRODUCTION

Globally, there is a pressing need to limit the usage of petroleum-based materials and a growing desire to use resources from sustainable and renewable sources to create biomaterials instead [1, 2]. Some attempts have been initiated and are currently being implemented in some countries [3, 4]. These attempts are required to meet the needs of the next generation. The shortcomings of petroleum-based materials for industrial applications have shifted the focus towards the usage of agricultural co-products and by-products [5]. The use of fibres for material production has grown in recent times [6, 7]. Even though synthetic fibres and natural fibres can be used for material development, the latter is preferred due to its ability to facilitate the reduction of CO_2 emissions, lower energy consumption, bio-degradability, low density, low cost of production, and higher usability because they are readily available [8, 9]. Natural fibres can be divided into three major classes: animal fibres, plant fibres, and mineral fibres [10, 11]. According to the United Nation Environmental Program, about 140 billion metric tons of waste from biomass is generated across the globe in the agricultural sector. Annually, approximately 8.5 million tons of chicken feathers are produced worldwide [12]. Chicken feather contains approximately 95-98% protein, primarily β-keratin, as well as numerous functional groups such as carboxyl, hydroxyl, amidogen, and sulfhydryl [13, 14]. The Keratin component of chicken feather makes it non-lignocellulosic, and if theses wastes are not properly managed, they will lead to environmental hazard [15]. Waste Chicken Feather (WCF), a type of animal fibre, has been utilized for composite development due to its mechanical and physical stability [16, 17]. The poultry industry pollutes the environment with lots of WCF [18, 19]. In a bid to minimize this waste, they are usually either burned or buried. However, these waste management techniques have negative impacts on the environment [20, 21]. The use of WCF as a precursor for composite development has emerged because, in addition to solving the environmental crisis relating to its disposal, it produces materials that are biodegradable, renewable, and cheap [22, 23]. It has been demonstrated that adding WCF as a filler to composite materials can add features including hydrophobicity, non-abrasive behavior, acoustical qualities, thermal insulation, and light weight [24]. Although numerous studies have examined the characteristics and uses of WCF-based composites, particularly those with polymeric matrix [25-28], there are still certain limits. One of the issues that has prevented the commercial viability of polymers with natural fibre reinforcement is the presence of hydroxyl groups, which can cause thermal instabilities and poor interfacial bonding to the polymer matrix. It has been demonstrated that the thermal treatment of biomass to create biochar can reduce the amount of hydroxyl groups present in the material [29]. Biochar, which has a porous structure and a high concentration of carbon, is a solid substance made when biomass is thermochemically converted in an air-limited

*Corresponding Author's Email: adeniyi.ag@unilorin.edu.ng
URL: https://www.jree.ir/article_173487.html

environment [30, 31]. It has been utilized as a bio-composite filler due to its superior thermal stability and water resistance properties, in comparison to natural fillers [32, 33]. Polystyrene is among the synthetic polymers that are most frequently found in the environment [34]. It is typically utilized as a material for food packing, refrigerator liners, and as a cushion for goods being transported [35, 36]. However, human ignorance has caused its accumulation in the environment with less regard to health hazards its accumulation could cause. The use of polystyrene for the development of composites not only minimizes its accumulation and negative impacts on the environment, but also produces a material with a wide range of properties. Composites produced from polystyrene have been found to be biodegradable and light-weight, and they have high mechanical and thermal properties [37].

The production and disposal of plastic waste, including polystyrene, is a significant environmental problem that has raised concerns about the long-term impact of plastic waste on the ecosystem. Recycling and repurposing of plastic waste can help reduce its impact on the environment. The use of chicken feather biochar, a by-product of the poultry industry, as a filler material for producing bio-composites from recycled polystyrene can provide a sustainable solution to repurpose waste materials from both industries. However, there is a limited scope of research on the mechanical and microstructural properties of such bio-composites. From the authors' extensive search, this is the first study that has utilized chicken waste feather biochar and polystyrene waste for composite development. In this study, the suitability and efficiency of utilizing WCF biochar as the reinforcing material in a polystyrene matrix was investigated. The utilization of WCF biochar as a potential reinforcement for composite production, together with the utilization of polystyrene wastes from the environment, contributes to the novelty of this study.

1. Experimental

1.1. Materials

Waste polystyrene was procured from electrical appliance retailers in Ilorin. Polystyrene is commonly used as a packaging agent to protect electronics and appliances during transit before being discarded. A clean towel was used to clean the waste polystyrene material surface of any dirt. Chicken feathers were derived as poultry waste from Unity Chicken Market in Ilorin, Nigeria. The chicken feathers were rinsed with water to get rid of sand and other contaminants, dried in the sun for 2 hours, and subsequently dried in the oven for three hours at 105 °C. This is to remove all the moisture trapped in the waste [38].

1.2. Biochar Production

A top-lit updraft reactor was used to produce the biochar. The reactor's design and operation were extensively detailed by Adeniyi et al. [39]. Briefly, the dry particles were placed within the reactor's inner chamber and then, properly sealed in order to reduce the amount of oxygen that the feed comes into contact with and to prevent contamination. Following that, the reactor's inner chamber was adequately surrounded by the biomass material employed as fuel. The reactor was then ignited and combustion was encouraged for about two minutes by leaving the reactor uncovered. Thereafter, the oxygen supply was cut off by carefully placing the lid on the reactor. The process lasted for 2 hours, after which the generated biochar was allowed to cool. The system produced biochar with a yield of 28.2 wt% while operating at a high temperature (417.2 °C). The produced biochar material (hereinafter referred to as CFB) was pulverized and sieved using a 100-micron sieve.

1.3. Composite Production

The composite was made by mixing the biochar with polystyrene-based resin (PBR). As previously detailed [40, 41], the PBR was created by saturating Nigerian-grade gasoline with expanded polystyrene at room temperature. The composite was made using cold and hand mixing. A weighed sample of the biochar was mixed with the resin, after which it was mechanically agitated with a rod before being poured into the mold and left to be cured for three days at room temperature. Four different mixing ratios of the resin and biochar were prepared and cured. The materials were tagged as PBR_{100}, $PBR_{90}CFB_{10}$, $PBR_{80}CFB_{20}$, $PBR_{70}CFB_{30}$, and $PBR_{60}CFB_{40}$, representing 100% of the resin, composites having 10% of the biochar, 20% of the biochar, 30% of the biochar, and 40% of the biochar, respectively.

1.4. Material Characterization

For each of the materials created, two main types of characteristics were identified: the mechanical properties (hardness test) and microstructural characteristics (SEM-EDX and FTIR). The functional groups of the composite materials were determined using Fourier transform infrared spectroscopy (Shimadzu, FTIR-8400S, Japan). A scan number of 4 and a scan range of 650–4500 cm^{-1} were used to apply FTIR measurements to the samples after they had been taken and placed on the sample holder of the FTIR machine. The transparent disc was put into the machine's slot after it had been turned on [42, 43]. The automatic analysis was activated along with the graph. Scanning electron microscopy (SEM; Phenom ProX, Phenom-World BV, Netherlands) was used to investigate the resin's and composite's morphology. The material's composition was calculated using dispersive X-ray spectroscopy (EDX) on a hydrogen-free basis. A HTP 1700 integrated palm-sized hardness tester with an integrated probe and controller was used to measure the hardness of the materials. The ASTM D785 Rockwell hardness standard was used to determine the hardness of both the resin and the composites.

2. Results and Discussion

2.1. Materials' Hardness

The matrix and composites' hardness was examined using the ASTM D785 Rockwell hardness test. The findings of a study on the load-bearing capacities of the matrix and composites are shown in **Table 1**. From the table, the mean hardness value of the polystyrene-based resin was 87 HRB. This value is similar to that obtained by Adeniyi et al. [44], but lower than the hardness value of polystyrene (274 HRB) obtained by Adeniyi et al. [45]. The difference in the resin's hardness results from possible differences in the size of the material undergoing the hardness test or the weight of polystyrene dissolved in the solvent. Another reason could be inadequate mixing of the polymer in the solvent [46, 47]. That could make the polymer more concentrated in one part of the material than in another. The mean hardness value dropped from 87 HRB to 65.7 HRB with the addition of 10% biochar made from chicken feathers. Poor interfacial adhesion between the polar biochar material and the non-polar polystyrene matrix could be the cause of this drop [48]. Further addition of the biochar (20%) to the polymeric matrix improved the composite's hardness by more than twice its initial value. This might be brought on by the biochar's increased penetration

modulus in the resin structure. However, when the biochar content in the polymeric resin increased, the composite's hardness declined. This may be due to the aggregation of the biochar that occurred beyond $PBR_{80}CFB_{20}$, which weakened the intercalated structure of the composite and further exposed it to breakage. A similar result was observed with the introduction of clay filler to polystyrene resin, as demonstrated by Adeniyi et al. [45].

Table 1: Mean hardness value of the matrix and composites.

Material Composition	Mean Hardness value (HRB)
PBR_{100}	87.0
$PBR_{90}CFB_{10}$	65.7
$PBR_{80}CFB_{20}$	139.0
$PBR_{70}CFB_{30}$	106.3
$PBR_{60}CFB_{40}$	96.0

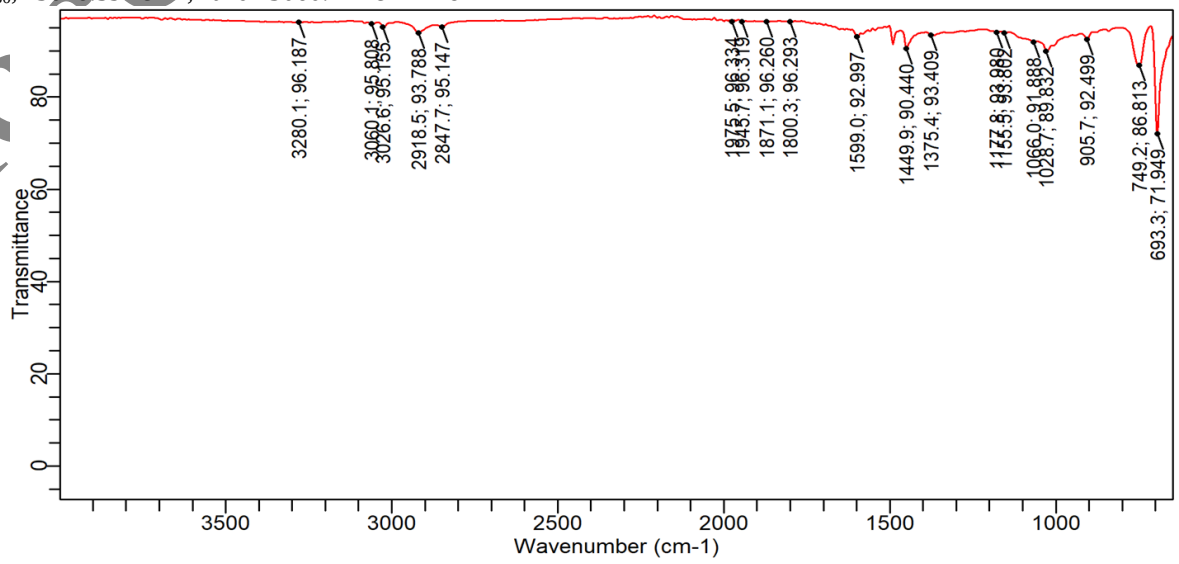
2.2. FTIR Analysis

The functional groups in the resin and composites were studied using FTIR. This was examined in order to draw important conclusions according to the nature of the interactions prevalent in the composites made with various filler concentrations. As CFB filler is added, this can be utilized to monitor changes in polystyrene-based resin (PBR). **Figure 1** displays the composites' FTIR spectra. The spectra show that the peaks of different composites are comparable across the board. In the composites, the peaks at 693.28 cm^{-1}, 1028.74 cm^{-1}, 1449.93 cm^{-1}, 1599.02 cm^{-1}, and 3026.59 cm^{-1} appeared in various composites, but differed in peak strength. Some shifts in peaks were also observed in the comparison of the spectra. For example, the peaks at 2918.50 cm^{-1} and 2847.68 cm^{-1} were observed in the composite having 10%, 20%, and 30% biochar concentrations, but were not present in $PBR_{60}CFB_{40}$ at 2922.23 cm^{-1} and 2851.41 cm^{-1}, respectively. Another shift was observed as the peak at 1155.47cm-1 appeared in $PBR_{90}CFB_{10}$, $PBR_{80}CFB_{20}$, and $PBR_{60}CFB_{40}$. However, the peak appeared at 1151.74 cm^{-1} for the composite having a 30% biochar concentration in the matrix [49, 50].

The alkene stretch of C-H was observed in the polymeric matrix as well as the various composites under study. The band was observed at 3022.87 cm^{-1} for the polymeric matrix, 3026.59 cm^{-1}, and 3060.14 cm^{-1} for $PBR_{90}CFB_{10}$, 3026.59 cm^{-1}, and 3060.14 cm^{-1} for $PBR_{80}CFB_{20}$, 3026.59 cm^{-1} for $PBR_{70}CFB_{30}$, 3026.59 cm^{-1}, and 3060.14 cm^{-1} for $PBR_{60}CFB_{40}$ [48, 51]. C-H bending of alkene was observed in both the matrix and the composites. It was observed in the region 3022.87 cm^{-1} for PBR_{100}; 693.28 cm^{-1}, 749.19 cm^{-1}, and 905.74 cm^{-1} for $PBR_{90}CFB_{10}$; 693.28 cm^{-1}, 752.92 cm^{-1}, 842.37 cm^{-1}, and 905.74 cm^{-1} for $PBR_{80}CFB_{20}$; 693.28 cm^{-1}, 749.19 cm^{-1}, 838.65 cm^{-1}, and 879.65 cm^{-1} for $PBR_{70}CFB_{30}$; and 693.28 cm^{-1}, 749.19 cm^{-1}, 838.65 cm^{-1}, 875.92 cm^{-1}, and 905.74 cm^{-1} for $PBR_{60}CFB_{40}$. The polystyrene utilized, the gasoline solvent, or even both of these factors could be the cause of the alkene C-H bond peak [45, 52].

It was discovered that both the matrix and the composites contained the hydroxyl stretch of alcohol or carboxylic acid. The peak was observed at 2881.23 cm^{-1} for PBR_{100}; 2918.50 cm^{-1} for $PBR_{90}CFB_{10}$, and $PBR_{80}CFB_{20}$; 3183.14 cm^{-1}, and 3615.51 cm^{-1} for $PBR_{70}CFB_{30}$; and 3160.78 cm^{-1} and 3567.06 cm^{-1} for $PBR_{60}CFB_{40}$. The peaks at 1360.48 cm^{-1} for PBR_{100}, 1375.38 cm^{-1} for $PBR_{90}CFB_{10}$, 1371.66 cm^{-1} for $PBR_{80}CFB_{20}$, 1375.38 cm^{-1} for $PBR_{70}CFB_{30}$, and 1267.29 cm^{-1} for $PBR_{60}CFB_{40}$ were attributed to the C-O-H bending mode. The C-O stretch of alcohol or ether was also observed to be present in the matrix as well as the composite. It occurred at the peaks 1181.57 cm^{-1} for PBR_{100}; 1028.74 cm^{-1}, 1066.01 cm^{-1}, 1155.47 cm^{-1}, and 1177.83 cm^{-1} for $PBR_{90}CFB_{10}$, and $PBR_{80}CFB_{20}$; 1028.74 cm^{-1}, and 1151.74 cm^{-1} for $PBR_{70}CFB_{30}$; and 1028.74 cm^{-1}, 1069.74 cm^{-1}, and 1155.47 cm^{-1} for $PBR_{60}CFB_{40}$ [53].

The -C≡N stretch was responsible for the peaks at 2351.95 cm^{-1} for PBR100, 2374.31 cm^{-1} for PBR80CFB20, 2370.58 cm^{-1} for PBR70CFB30, and 2374.31 cm^{-1} for PBR60CFB40. The alkene stretch of C=C may be responsible for the bands at 1513.80 cm^{-1} for PBR100, 1599.02 cm^{-1} for PBR90CFB10, PBR70CFB30, and PBR60CFB40, and 1654.93 cm^{-1} for PBR80CFB20. For PBR90CFB10 and PBR80CFB20, the peaks at 3280.05 cm^{-1} and 3242.78 cm^{-1}, respectively, were attributed to the C-H stretch of the alkyne group. The aldehyde stretch of C-H was assigned the peaks at 2847.68 cm^{-1} for PBR90CFB10, PBR80CFB20, and PBR70CFB30, and 2751.41 cm^{-1} for PBR60CFB40 [54]. The FTIR spectra of the composites indicate that the shift in peaks as well as changes in peaks (disappearance and appearance) may be caused by chemical interactions between the CFB and the polymeric matrix. The existence of hydroxyl groups in the different composites suggests that the nature of the composites is hydrophilic.



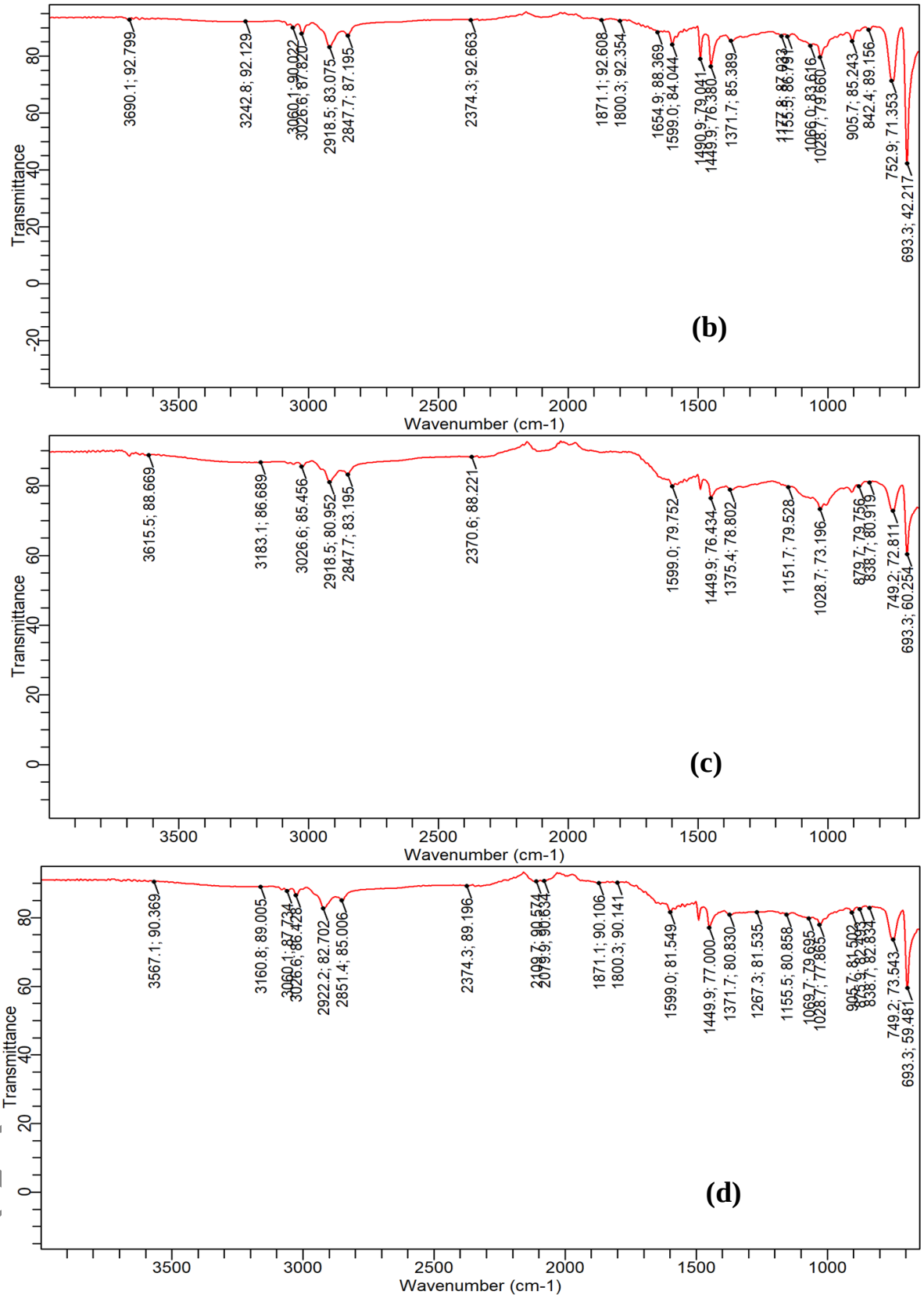


Figure 1: FTIR spectra of (a) $PBR_{90}CFB_{10}$, (b) $PBR_{80}CFB_{20}$, (c) $PBR_{70}CFB_{30}$, (d) $PBR_{60}CFB_{40}$ composites.

2.3. SEM-EDX analysis

SEM-EDX was utilized to gather more information pertaining to the resin and the composites. For this, only one composite sample ($PBR_{60}CFB_{40}$) was analyzed as a representative of the composites to distinguish it from the pure polystyrene resin. The energy dispersive X-ray spectrophotometer is a useful technique for composite characterization as it helps to quantitatively determine the elemental composition of the composite. The EDX analyses of the polystyrene resin and chicken feather filled polystyrene resin are presented in **Table 2** and **Table 3,** respectively. EDX analysis of the polystyrene resin (**Table 2**) showed that the elements carbon, oxygen, and silicon were present in the resin. A similar composition of pure polystyrene resin was reported by Adeniyi et al. [45]. The EDX result of $PBR_{60}CFB_{40}$ (**Table**

3) showed that the composite sample was made up majorly of carbon at a higher concentration (84.3%) than that of the polystyrene resin (67.7%), which is due to the presence of the biochar sample [55, 56]. In addition, the composite showed a decrease in the concentration of oxygen from 28% in the matrix to 6% in the composite. This can be the result of the biochar filling up any open pores in the structure of the composite. In addition, it was found that the composite contained trace amounts of additional elements like silicon, potassium, and aluminum. These elements could be as a result the chicken feather biochar, which was reported in a study by Adeniyi et al. [57].

The SEM micrograph of the polymeric matrix, as presented in **Figure 2**, indicates that its surface is smooth, slivery, and shiny. However, beneath this surface, tiny micro-fillers were observed, which may be particles of polystyrene that remained undissolved in the solvent. In addition, the micrograph showed that the cured resin was not homogenous as the surrounding structure of the material looked different (lighter) in comparison with the centre (darker). A similar observation was made for the cured polystyrene resin by Adeniyi et al. [44]. The SEM micrograph of the $PBR_{60}CFB_{40}$ composite (**Figure 3**) depicts the presence of a rough surface having some crevices. It also clearly depicts the presence of the polystyrene resin, observed in the slivery portion of the micrograph, and the biochar, observed in the darker portion of the micrograph. It could be seen that the mixing of the biochar in the matrix was not properly done, and this could be due to the hand-mixing method or the curing at room temperature. Though curing at room temperature saves both cost and energy, it produces less homogenized composite materials than thermally cured composites. When stress or load is applied, the composite fissures may enable an elongation break, increasing the composite durability. Moreover, the gaps might facilitate the movement of oxygen between the materials beneath and the surrounding air, which would increase the materials' flammability.

Table 2: EDX result of PBR_{100}.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	74.75	67.73
8	O	Oxygen	23.27	28.09
14	Si	Silicon	1.98	4.19

Table 3: EDX result of $PBR_{60}CFB_{40}$.

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
6	C	Carbon	91.20	84.32
8	O	Oxygen	4.90	6.04
19	K	Potassium	1.60	4.80
13	Al	Aluminium	1.64	3.41
14	Si	Silicon	0.66	1.43

Figure 2: The SEM micrograph of PBR_{100}.

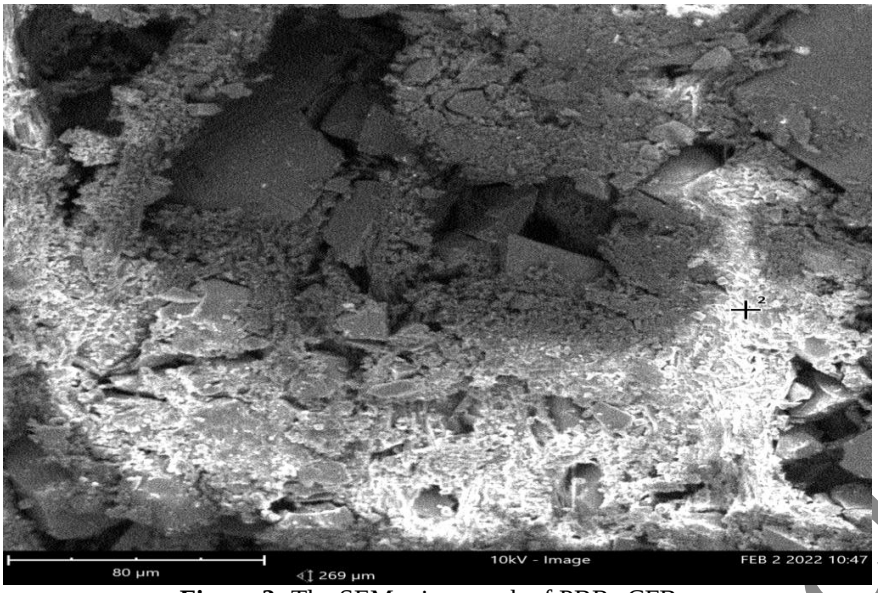


Figure 3: The SEM micrograph of $PBR_{60}CFB_{40}$

3. Conclusion

In this study, the authors investigated the mechanical and microstructural properties of a bio-composite produced from recycled polystyrene and chicken feather biochar. A top-lit updraft reactor was used to thermochemically convert the waste chicken feathers (WCF) into biochar. Hand lay-up and manual mixing techniques were utilized to create the composites, which were then allowed to be cured at room temperature. The chicken feather biochar-polystyrene resin composites were created utilizing various biochar-polystyrene resin mixing ratios. The composites were analyzed through FTIR, SEM-EDX, and hardness tests. The SEM examination revealed that the biochar was unevenly distributed in the matrix. FTIR analysis demonstrated the chemical interaction between the biochar and polystyrene matrix, as demonstrated by changes and shifts in peak positions, highlighting the composite's hydrophilic nature. The results showed that the addition of chicken feather biochar to recycled polystyrene improved the mechanical properties of the composite, as evidenced by the increase in the material hardness. The improvement of mechanical properties can be attributed to the good interfacial bonding between the biochar and polystyrene matrix, as observed in the SEM images. The findings of this study have important implications for the repurposing of waste materials from both the plastic and poultry industries. The use of chicken feather biochar as a filler material can provide a sustainable solution for both industries while also reducing the environmental impact of plastic waste. The improved mechanical and microstructural properties of the bio-composite from this study make it a promising material for use in various industries, including automotive, construction, and packaging. In lieu of this, further studies are needed to investigate the potential of this material for other applications and to optimize its properties for specific uses.

Disclosure statements

Conflict of Interest: The authors declare that there are no conflicts of interest.

Funding: There was no external funding for the study.

Compliance with Ethical Standards: This article does not contain any studies involving human or animal subjects.

Acknowledgements

The laboratory supports and services rendered by Mr. Tijani are duly acknowledged

References

1. Susmiati Y. The prospect of bioethanol production from agricultural waste and organic waste. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2018),7(2):67-80.
2. Gabriel AA, Solikhah AF, Rahmawati AY, Taradipa YS, Maulida ET. Potentials of Edible Canna (Canna edulis Kerr) Starch for Bioplastic: A Review. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2021),10(2):182-91.
3. Afifah H, Hidayat N, Wignyanto W. Penentuan Isolat Bakteri Asetogenik yang Mampu Menghasilkan Total Asam Tertinggi pada Pengolahan Limbah Cair Tahu secara Anaerob. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2018),7(1):47-56.
4. Rusdianto AS, Septyatha F, Choiron M. Analisis kelayakan finansial industri bio-pellet kulit kopi di Kabupaten Jember. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2018),7(2):89-94.
5. Tesfaye T, Sithole B, Ramjugernath D, Chunilall V. Valorisation of chicken feathers: Characterisation of chemical properties. ***Waste Management***, (2017),68:626-35.
6. Rajak DK, Pagar D, Behera A, Menezes PL. Role of Composite Materials in Automotive Sector: Potential Applications. ***Advances in Engine Tribology***, (2022):193-217. doi: https://doi.org/10.1007/978-981-16-8337-4_10.
7. Mochane M, Mokhena TC, Mokhothu T, Mtibe A, Sadiku E, Ray SS, et al. Recent progress on natural fiber hybrid composites for advanced applications: A review. (2019).
8. Wijana S, Dewi IA, Setyowati EDP. Aplikasi pewarna batik pada tenun dari serat daun nanas (kajian proporsi jenis benang dan jenis pewarna). ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2016),5(1):30-8.
9. Rilek NM, Hidayat N, Sugiarto Y. Hidrolisis lignoselulosa hasil pretreatment pelepah sawit (Elaeis guineensis Jacq) menggunakan H2SO4 pada produksi bioetanol. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2017),6(2):76-82.
10. Adeniyi A, Abdulkareem S, Ndagi M, Abdulkareem M, Ighalo J. Effect of fiber content on the physical and mechanical properties of plantain fiber reinforced polystyrene composite.

Advances in Materials and Processing Technologies, (2022),8(4):4244-56. doi: https://doi.org/10.1080/2374068X.2022.2054583.
11. Adeniyi AG, Abdulkareem SA, Adeyanju CA, Ighalo JO. Recycling of delonix regia pods biochar and aluminium filings in the development of thermally conducting hybrid polystyrene composites. ***Journal of Polymers and the Environment***, (2022),30(8):3150-62. doi: https://doi.org/10.1007/s10924-022-02413-5.
12. Joardar J, Rahman M. Poultry feather waste management and effects on plant growth. ***International Journal of Recycling of Organic Waste in Agriculture***, (2018),7(3):183-8.
13. Chen H, Li W, Wang J, Xu H, Liu Y, Zhang Z, et al. Adsorption of cadmium and lead ions by phosphoric acid-modified biochar generated from chicken feather: selective adsorption and influence of dissolved organic matter. ***Bioresource technology***, (2019),292:121948.
14. Tuna A, Okumuş Y, Celebi H, Seyhan AT. Thermochemical conversion of poultry chicken feather fibers of different colors into microporous fibers. ***Journal of Analytical and Applied Pyrolysis***, (2015),115:112-24.
15. Al-Khatib IA, Eleyan D, Garfield J. A system dynamics model to predict municipal waste generation and management costs in developing areas. ***The Journal of Solid Waste Technology and Management***, (2015),41(2):109-20.
16. Aranberri I, Montes S, Azcune I, Rekondo A, Grande H-J. Fully biodegradable biocomposites with high chicken feather content. ***Polymers***, (2017),9(11):593.
17. Rangappa SM, Parameswaranpillai J, Siengchin S, Jawaid M, Ozbakkaloglu T. Bioepoxy based hybrid composites from nano-fillers of chicken feather and lignocellulose Ceiba Pentandra. ***Scientific reports***, (2022),12(1):1-18.
18. Joardar J, Rahman M. Poultry feather waste management and effects on plant growth. ***International Journal of Recycling of Organic Waste in Agriculture***, (2018),7:183-8. doi: https://doi.org/10.1007/s40093-018-0204-z.
19. Muduli S, Champati A, Popalghat HK, Patel P, Sneha K. Poultry waste management: an approach for sustainable development. ***Int J Adv Sci Res***, (2019),4:08-14.
20. Chaturvedi V, Agrawal K, Verma P. Chicken feathers: a treasure cove of useful metabolites and value-added products. ***Environmental Sustainability***, (2021),4:231-43. doi: https://doi.org/10.1007/s42398-021-00160-2.
21. Karuppannan SK, Dowlath MJH, Raiyaan GD, Rajadesingu S, Arunachalam KD. Application of poultry industry waste in producing value-added products—A review. ***Concepts of Advanced Zero Waste Tools***, (2021):91-121.
22. Amulya K, Katakojwala R, Ramakrishna S, Mohan SV. Low carbon biodegradable polymer matrices for sustainable future. ***Composites Part C: open access***, (2021),4:100111.
23. Rajeshkumar G, Seshadri SA, Devnani G, Sanjay M, Siengchin S, Maran JP, et al. Environment friendly, renewable and sustainable poly lactic acid (PLA) based natural fiber reinforced composites–A comprehensive review. ***Journal of Cleaner Production***, (2021),310:127483.
24. Okonkwo E, Daniel-Mkpume C, Ude S, Onah C, Ijomah A, Omah A. Chicken feather fiber—African star apple leaves bio-composite: Empirical study of mechanical and morphological properties. ***Materials Research Express***, (2019),6(10):105361.
25. Ali MF, Hossain MS, Moin TS, Ahmed S, Chowdhury AS. Utilization of waste chicken feather for the preparation of eco-friendly and sustainable composite. ***Cleaner Engineering and Technology***, (2021),4:100190.
26. Ghani SA, Tan SJ, Yeng TS. Properties of chicken feather fiber-filled low-density polyethylene composites: The effect of polyethylene grafted maleic anhydride. ***Polymer-Plastics Technology and Engineering***, (2013),52(5):495-500.
27. Mendez-Hernandez ML, Salazar-Cruz BA, Rivera-Armenta JL, Estrada-Moreno IA, Chavez-Cinco MY. Preparation and characterization of composites from copolymer styrene-butadiene and chicken feathers. ***Polímeros***, (2018),28:368-72.
28. Supri AG, Aizat AE, Yazid M, Masturina M. Chicken feather fibers–recycled high-density polyethylene composites: The effect of ε-caprolactam. ***Journal of Thermoplastic Composite Materials***, (2015),28(3):327-39.
29. Onyekachi OE, Iwuozor KO. Mechanical and water absorption properties of polymeric compounds. ***American Journal of Mechanical and Materials Engineering***, (2019),3(2):36-46. doi: DOI: 10.11648/j.ajmme.20190302.12.
30. Emenike EC, Iwuozor KO, Agbana SA, Otoikhian KS, Adeniyi AG. Efficient recycling of disposable face masks via co-carbonization with waste biomass: a pathway to a cleaner environment. ***Cleaner Environmental Systems***, (2022),6:100094.
31. Emenike EC, Ogunniyi S, Ighalo JO, Iwuozor KO, Okoro HK, Adeniyi AG. Delonix regia biochar potential in removing phenol from industrial wastewater. ***Bioresource Technology Reports***, (2022),19:101195. doi: https://doi.org/10.1016/j.biteb.2022.101195.
32. Adeniyi A, Iwuozor K, Emenike E, Amoloye M, Aransiola E, Motolani F, et al. Prospects and problems in the development of biochar-filled plastic composites: a review. ***Functional Composites and Structures***, (2023).
33. Adeniyi AG, Abdulkareem SA, Ighalo JO, Abdulkareem MT, Iwuozor KO, Emenike EC. A study on the hybrid polystyrene composite filled with elephant-grass-biochar and doped-aluminium-content. ***Functional Composites and Structures***, (2022),4(3):035006.
34. Adeniyi AG, Amusa VT, Emenike EC, Iwuozor KO. Co-carbonization of waste biomass with expanded polystyrene for enhanced biochar production. ***Biofuels***, (2022):1-9.
35. Taib N-AAB, Rahman MR, Bakri MKB, Matin MM, Sanaullah K. Recycled industrial plastics' fine waste incorporated into biocomposites. Recycled Plastic Biocomposites. Elsevier; 2022. p. 213-28.
36. DeFlorio W, Liu S, White AR, Taylor TM, Cisneros-Zevallos L, Min Y, et al. Recent developments in antimicrobial and antifouling coatings to reduce or prevent contamination and cross- contamination of food contact surfaces by bacteria. ***Comprehensive Reviews in Food Science and Food Safety***, (2021),20(3):3093-134.
37. Ismawanti RD, Putri WDR, Murtini ES, Purwoto H. Edible Film Made of Corn Starch-Carrageenan-Rice Bran: The Characteristic of Formula's Viscosity, Water Content, and Water Vapor Transmission Rate. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2020),9(3):173-83.
38. Sumanti DM, Hanidah I-I, Abdullatif MA. Physical, Chemical, and Functional Characteristics of Composite Flours from Banana Corm and Tempeh. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2022),11(2):139-50.
39. Adeniyi AG, Adeyanju CA, Iwuozor KO, Odeyemi SO, Emenike EC, Ogunniyi S, et al. Retort carbonization of bamboo (Bambusa vulgaris) waste for thermal energy recovery. ***Clean***

Technologies and Environmental Policy, (2023),25(3):937-47. doi: https://doi.org/10.1007/s10098-022-02415-w.
40. Adeniyi AG, Abdulkareem SA, Odimayomi KP, Emenike EC, Iwuozor KO. Production of thermally cured polystyrene composite reinforced with aluminium powder and clay. ***Environmental Challenges***, (2022),9:100608.
41. Adeniyi AG, Abdulkareem SA, Odimayomi KP, Iwuozor KO, Emenike EC. Microstructural and thermal properties of thermally cured calcined cow bone/kaolin filled hybrid polystyrene composites. ***Asia‐Pacific Journal of Chemical Engineering***, (2023):e2898. doi: https://doi.org/10.1002/apj.2898.
42. Adeniyi AG, Adeyanju CA, Emenike EC, Otoikhian SK, Ogunniyi S, Iwuozor KO, et al. Thermal energy recovery and valorisation of Delonix regia stem for biochar production. ***Environmental Challenges***, (2022),9:100630. doi: https://doi.org/10.1016/j.envc.2022.100630.
43. Adeniyi AG, Amusa VT, Iwuozor KO, Emenike EC. Thermal recycling strategy of Coca-Cola PVC label films by its co-carbonization with Terminalia ivorensis leaves. ***Cleaner Engineering and Technology***, (2022),11:100564. doi: https://doi.org/10.1016/j.clet.2022.100564.
44. Adeniyi AG, Abdulkareem SA, Emenike EC, Abdulkareem MT, Iwuozor KO, Amoloye MA, et al. Development and characterization of microstructural and mechanical properties of hybrid polystyrene composites filled with kaolin and expanded polyethylene powder. ***Results in Engineering***, (2022):100423.
45. Adeniyi AG, Abdulkareem SA, Ighalo JO, Oladipo-Emmanuel FM, Adeyanju CA. Microstructural and mechanical properties of the plantain fiber/local clay filled hybrid polystyrene composites. ***Mechanics of Advanced Materials and Structures***, (2021):1-11.
46. Adeniyi AG, Abdulkareem SA, Emenike EC, Abdulkareem MT, Iwuozor KO, Amoloye MA, et al. Development and characterization of microstructural and mechanical properties of hybrid polystyrene composites filled with kaolin and expanded polyethylene powder. ***Results in Engineering***, (2022),14:100423. doi: https://doi.org/10.1016/j.rineng.2022.100423.
47. Adeniyi AG, Abdulkareem SA, Iwuozor KO, Abdulkareem MT, Adeyanju CA, Emenike EC, et al. Mechanical and microstructural properties of expanded polyethylene powder/mica filled hybrid polystyrene composites. ***Mechanics of Advanced Materials and Structures***, (2022):1-10.
48. Adeniyi AG, Emenike EC, Iwuozor KO, Saliu OD. Solvated polystyrene resin: a perspective on sustainable alternative to epoxy resin in composite development. ***Materials Research Innovations***, (2023):1-13.
49. Odeyemi SO, Iwuozor KO, Emenike EC, Odeyemi OT, Adeniyi AG. Valorization of waste cassava peel into biochar: An alternative to electrically-powered process. ***Total Environment Research Themes***, (2023),6:100029.
50. Aringbangba OE, Oluwafemi F, Kolapo AL, Adeogun AI, Popoola TO. Elimination of Aflatoxins from Two Selected Nigerian Vegetable Oils using Magnetic Chitosan Nanoparticles. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2021),10(1):1-11.
51. Adeniyi AG, Abdulkareem SA, Ighalo JO, Saliu OD, Amosa MK, Momoh RO. Crystallographic, functional group and microstructural properties of oil palm biochar reinforced hybrid polystyrene composite doped with aluminium. ***Advances in Materials and Processing Technologies***, (2022),8(3):2893-904. doi: https://doi.org/10.1080/2374068X.2021.1945288.
52. Pulungan MH, Santoso ESM. Ice cream cup production using purple sweet potato (Ipomoea batatas L. Poir) as a substitute ingredient. ***Industria: Jurnal Teknologi dan Manajemen Agroindustri***, (2020),9(3):184-94.
53. Adeniyi A, Odimayomi K, Emenike EC, Iwuozor K, Ndagi M. Preparation of activated carbon monolith from waste biomass using solvated polystyrene-based binder. ***Advances in Materials and Processing Technologies***, (2023):1-13.
54. Adeniyi AG, Abdulkareem SA, Adeyanju CA, Abdulkareem MT, Iwuozor KO, Emenike EC, et al. Mechanical and morphological analyses of flamboyant seed pod biochar/aluminium filings reinforced hybrid polystyrene composite. ***Journal of the Indian Academy of Wood Science***, (2023):1-9.
55. Adeniyi AG, Abdulkareem SA, Iwuozor KO, Ogunniyi S, Abdulkareem MT, Emenike EC, et al. Effect of salt impregnation on the properties of orange albedo biochar. ***Cleaner Chemical Engineering***, (2022),3:100059. doi: https://doi.org/10.1016/j.clce.2022.100059.
56. Adeniyi AG, Iwuozor KO, Emenike EC, Ogunniyi S, Amoloye MA, Sagboye PA. One-step chemical activation for the production of engineered orange peel biochar. ***Emergent Materials***, (2023),6(1):211-21. doi: https://doi.org/10.1007/s42247-022-00442-3.
57. Adeniyi GA, Abdulkareem SA, Adeyanju CA, Iwuozor KO, Ogunniyi S, Kawu KY, et al. Recovery of Metallic Oxide Rich Biochar from Waste Chicken Feather. ***Low-carbon Materials and Green construction***, (2022),Accepted Manuscript.