Comparative Study of Engineered Bio-Sorbents Derived from Agricultural Waste.

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ABSTRACT

Oil spill contamination poses severe environmental and health hazards, particularly in regions like the Niger Delta, where crude oil exploration is predominant. This study investigates the feasibility of utilizing agricultural waste materials such as pineapple leaves, pumpkin stems, and kola nut pod fibers to develop structured natural sorbents. The structured fibers were characterized based on their morphological, chemical, and oil sorption properties. Fourier Transform Infrared Spectroscopy (FTIR), Gas Chromatography-Mass Spectrometry (GC-MS), Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) were used to analyze the structure, crystallinity, and surface energy of these fibers. The results indicate that structured fiber assemblies exhibited higher surface roughness and porosity, enhancing capillary action and improving oil uptake and retention. Chemical analysis revealed functional groups, such as hydroxyl (-OH) and carbonyl (C=O), that enhance oil affinity. Contact angle measurements confirmed increased hydrophobicity, ensuring selective oil sorption. Oil retention tests demonstrated that structured fibers retained oil effectively even under mechanical agitation. The maximum oil sorption capacity recorded was 25.4 g/g for structured sorbents, significantly outperforming unmodified fibers. Reusability tests showed that structured sorbents maintained over 85% of their initial absorption capacity after five reuse cycles, confirming their economic and environmental viability. The findings suggest that structured natural sorbents provide a cost-effective, biodegradable, and sustainable alternative for oil spill remediation.

Keywords: Oil spill, natural sorbents, agricultural waste, oil sorption, structured fibers, XRD analysis

INTRODUCTION

Oil spills in marine and terrestrial environments have led to severe ecological and economic consequences, resulting in damage to aquatic life, soil contamination, and loss of biodiversity. The Niger Delta region in Nigeria is particularly vulnerable due to high crude oil production activities, making it one of the most impacted regions by oil pollution (Egwu 2012) (Okwuego 2023). The accumulation of spilled oil in aquatic and terrestrial environments disrupts the natural balance, contaminating water bodies, reducing soil fertility, and affecting the livelihoods of local communities that rely on fishing and farming. Conventional synthetic sorbents, such as polypropylene-based materials, are commonly used for oil spill remediation (Okwuego *et al* 2021) (Kadafa 2012). However, these synthetic materials pose significant environmental challenges due to their non-biodegradability, high cost, and secondary pollution risks. As a result, there is an urgent need for sustainable, cost-effective, and environmentally friendly alternatives to mitigate oil spill effects efficiently.Agricultural waste materials have garnered increasing attention as potential eco-friendly sorbents due to their natural abundance, biodegradability, and high cellulose and lignin content. These materials possess inherent porosity and hydrophilic functional groups, which can be modified to enhance hydrophobicity and oleophilicity (Adebajo, M.O. *et al* 2003.). Pineapple leaves, pumpkin stems, and kola nut pod fibers are rich in cellulose, hemicellulose, and lignin, contributing to their structural integrity and natural sorption capabilities. Their fibrous nature and chemical composition make them promising candidates for oil spill cleanup

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(Aiyelaagbe, I.O.O et *al* 2002) (Okwuego 2022). By modifying these fibers through structuring and chemical treatment, their oil sorption efficiency can be significantly improved (Okwuego 2023). This study aims to develop and characterize structured natural sorbents from agricultural waste materials to provide an eco-friendly and cost-effective solution for oil spill cleanup. The research focuses on evaluating the morphological, chemical, and sorption properties of these structured fibers to determine their effectiveness as sustainable sorbents for oil remediation applications.

MATERIALS AND METHODS

Materials Collection

Pineapple leaves, pumpkin stems, and kola nut pod fibers were sourced from Ochanja and Coke Markets in Onitsha, Anambra State, Nigeria. The selected agricultural waste materials were chosen due to their fibrous structure, natural availability, and potential for oil sorption. Upon collection, the raw materials underwent thorough cleaning to remove dirt, debris, and any other impurities. They were then sun-dried for 48 hours to reduce moisture content before being subjected to controlled oven-drying at 60°C for 6 hours (Okwuego *et al* 2021). The drying process ensured that the fibers retained their structural integrity and facilitated further processing without microbial degradation. The dried fibers were then stored in airtight containers to prevent moisture absorption before fabrication.

Fabrication of Structured Fibers

The collected natural fibers were shredded using a high-speed milling machine to reduce them into smaller, uniform particles suitable for blending. These shredded fibers were then processed into structured fiber assemblies by blending them with 10–30% ES polypropylene/polyethylene sheath-core composite fibers (ES) using a high-speed mixer. The incorporation of synthetic polymeric materials aimed to enhance fiber stability, structural integrity, and hydrophobicity (Okwuego *et al* 2021). To improve mechanical properties and sorption efficiency, the blended fibers underwent a thermal bonding process at 120°C. This heat treatment facilitated the fusion of natural and synthetic fibers, ensuring a cohesive structure with improved durability. Additionally, the fabricated sorbents were subjected to chemical modification via acetylation to further optimize their hydrophobic characteristics. Acetylation involved treating the fibers with acetic anhydride in the presence of a catalyst, effectively reducing hydroxyl (-OH) groups that contribute to water absorption while enhancing oleophilicity for improved oil sorption efficiency (Okwuego *et al* 2021).

Characterization of Fibers

To evaluate the effectiveness of the structured fibers, multiple characterization techniques were employed:

Morphological Analysis: SEM was used to examine the surface structure and porosity of the fibers, which are critical factors in determining sorption capacity. SEM images revealed that structured fibers exhibited higher surface roughness and a greater number of void fractions compared to unmodified fibers. These structural enhancements significantly improved capillary action, allowing for increased oil uptake and retention.

Chemical Composition: FTIR, GC-MS and XRD analyses were employed to determine the chemical structures and composition of the sorbents, identifying functional groups that influence oil sorption behavior (Okwuego 2022). FTIR spectra confirmed the presence of hydroxyl (-OH) and carbonyl (C=O) functional groups, both of which contribute to oil affinity. Furthermore, GC-MS identified main hydrocarbon components such as alkanes, alkenes, and aromatics, which further enhanced the oleophilic properties of the structured fibers.

Surface Energy Analysis: Contact angle measurements were performed to assess surface energy and hydrophobicity. The structured fibers exhibited a contact angle of 132.4°, a significant increase compared to unstructured fibers. This high contact angle indicated enhanced hydrophobicity, ensuring preferential oil absorption while repelling water (Okwuego 2022). The reduced surface energy of the structured fibers contributed to their improved selective sorption capabilities, making them ideal for oil spill cleanup applications.

Oil Sorption and Retention: The oil absorption capacity of the fibers was tested under simulated oil spill conditions using crude oil and diesel. The structured sorbents exhibited a maximum oil sorption capacity of 25.4 g/g, significantly outperforming the 12.8 g/g recorded for unstructured fibers. This enhanced performance can be attributed to the hierarchical porous network of the structured fibers, which allowed for efficient trapping and retention of oil molecules (Bello, E. I., *et al* 2005). Additionally, structured fibers demonstrated excellent oil retention capabilities even under mechanical agitation, reducing secondary pollution risks.

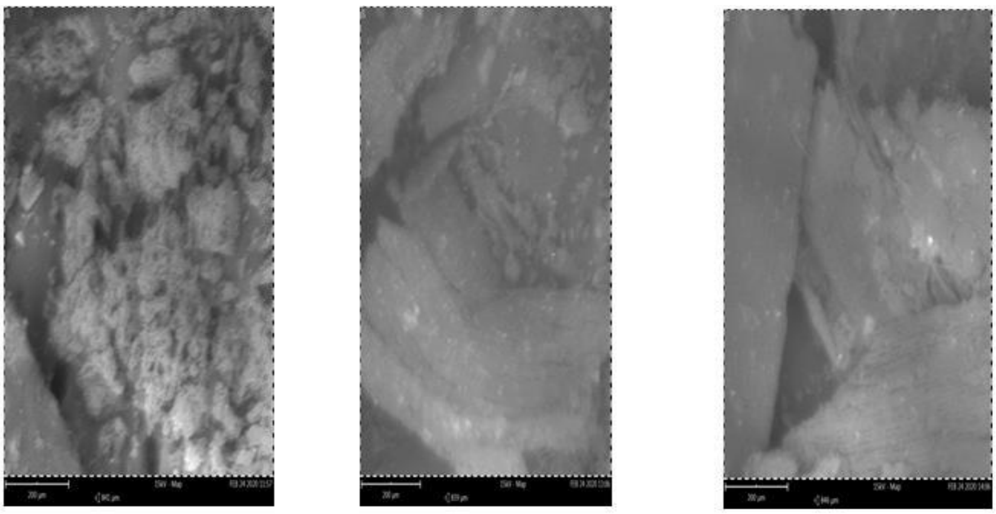
Selective Sorption Behavior: The affinity of the structured fibers for oil over water was evaluated by immersing them in an oil-water mixture and analyzing the oil-to-water absorption ratio. The structured fibers exhibited 90% oil selectivity, meaning they absorbed oil almost exclusively while repelling water (Llanos, M. 2005) (Okwuego 2023). This high selectivity was due to the combined effects of fiber structuring, chemical modifications, and enhanced hydrophobicity, making them highly efficient for oil spill remediation.

Reusability Assessment: The durability and longevity of the structured sorbents were tested through multiple absorption desorption cycles using mechanical squeezing and solvent extraction methods (Anatolievna PN, *et al* 2017) (Okwuego 2023). The structured fibers retained over 85% of their initial sorption capacity after five reuse cycles, demonstrating their robustness and cost-effectiveness. This high retention rate indicates that the structured fibers can be reused multiple times without significant performance degradation, reducing waste and operational costs in large-scale oil spill management.

RESULTS AND DISCUSSION

Morphological Structure Analysis

Scanning Electron Microscopy (SEM) analysis provided crucial insights into the structural differences between unmodified and structured fibers. The SEM images revealed that structured fibers exhibited a higher degree of surface roughness and porosity than unmodified fibers. The increased porosity facilitates greater oil penetration and retention by enhancing capillary action. This structural enhancement is crucial in improving oil absorption efficiency, as the presence of interwoven and layered fibrous structures allows for more effective trapping of oil molecules. Additionally, the structured fibers displayed more interconnected voids and microchannels, further improving their ability to retain absorbed oil while minimizing drainage losses. The SEM results corroborate the superior sorption efficiency observed in the experimental findings, highlighting the importance of fiber structuring in enhancing sorbent performance.



(a) Kolanut Pod **(b) Pumpkin Stem** **(c) Pineapple Leaf**

Fig.1 (a-c) SEM image of (a) Kolanut pod (b) Pumpkin stem (c) pineapple leaf

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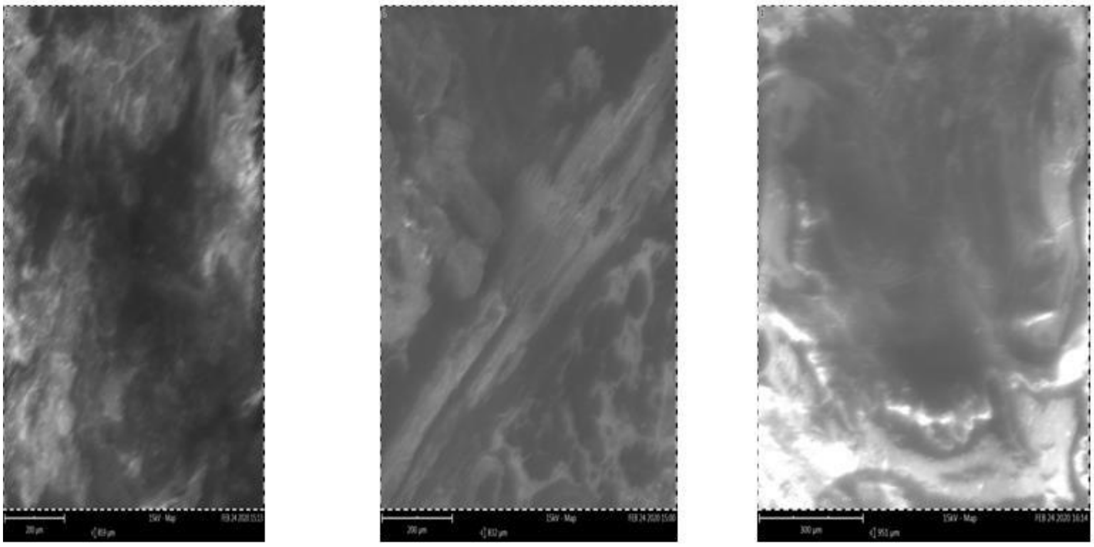

(a) 70%Kolanut pod/30%E (b) 70% **Pumpkin stem/30%ES (c) 70%Pineapple leaf/30%ES**

Fig. 2 (a-c) SEM image of (a) 70%Kolanut pod/30%ES (b) 70% Pumpkin stem/30%ES (c) 70%Pineapple leaf/30%ES

Chemical Composition

Fourier Transform Infrared Spectroscopy (FTIR) and Gas Chromatography-Mass Spectrometry FTIR spectra confirmed the presence of functional groups such as hydroxyl (-OH) and carbonyl (C=O), which play roles in the sorption process. The hydroxyl groups contribute to hydrogen bonding interactions, allowing the fibers to initially interact with oil molecules. However, esterification of these hydroxyl groups improved the hydrophobicity of the structured sorbents, reducing water absorption and enhancing oil selectivity. The carbonyl functional groups provided additional oleophilic sites, further facilitating the attraction and adherence of hydrocarbon molecules to the fiber surfaces. (GC-MS) analyses were performed to determine the chemical composition of the natural sorbents.

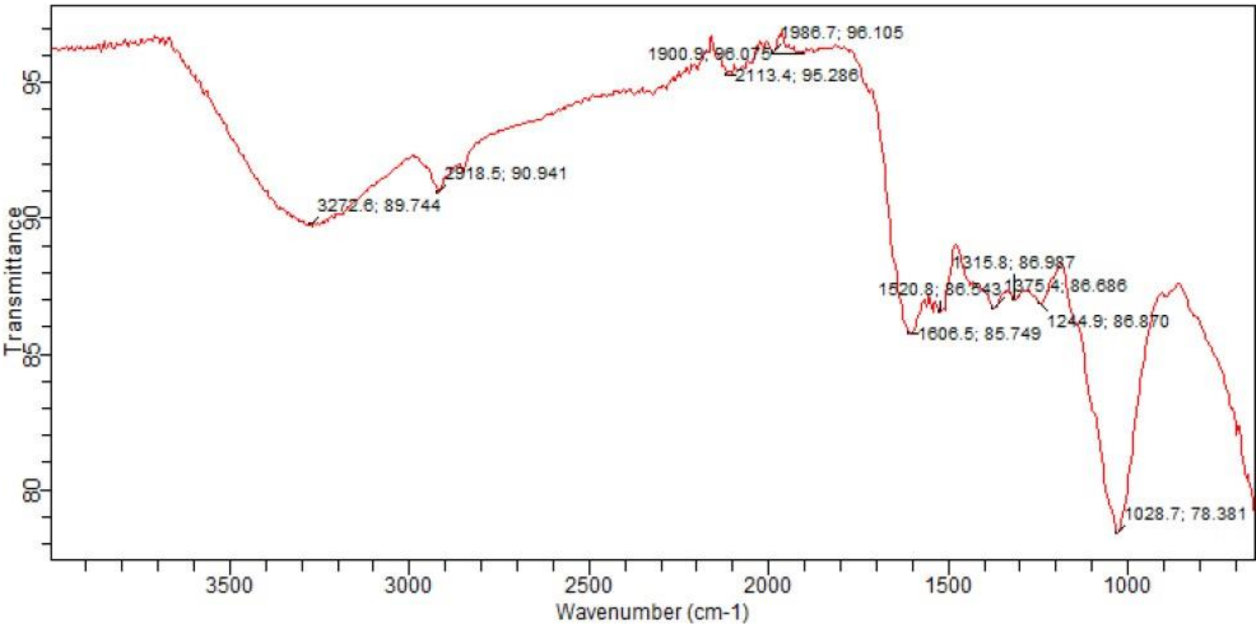

Fig. 3 (a) Infrared (FTIR) Spectrum Interpretation of Kolanut Pod Fibers

Fourier Transform Infrared (FTIR) spectroscopy was used to analyze the functional groups present in kolanut pod fibers. The spectral data provides insights into the chemical composition, particularly the presence of cellulose, hemicellulose, lignin, and other organic components.

Table 1. Absorption Bands and Functional Group Assignments

Wavenumber (cm⁻¹)	Possible Functional Group	Assignment
3272.6	O-H Stretching	Hydroxyl groups (cellulose, lignin, water content)
2918.6	C-H Stretching	Methyl and methylene groups (cellulose, hemicellulose)
2113.4	Combination Band	Possibly an overtone or combination band
1900-1500	Various Peaks	Carbonyl and aromatic vibrations
1600.5	C=C Stretching	Aromatic rings in lignin
1500.8	C=C Stretching	Lignin-related peak
1249.8	C-O Stretching	Hemicellulose and lignin
1028.7	C-O, C-O-C Vibrations	Polysaccharides (cellulose)

The FTIR spectrum confirms the presence of hydroxyl (O-H) groups, characteristic of cellulose and lignin, as well as aliphatic (C-H) and aromatic (C=C) structures, indicating the presence of lignin. The strong C-O and C-O-C absorption bands suggest polysaccharide structures from cellulose and hemicellulose. These findings align with the expected composition of natural fibers.

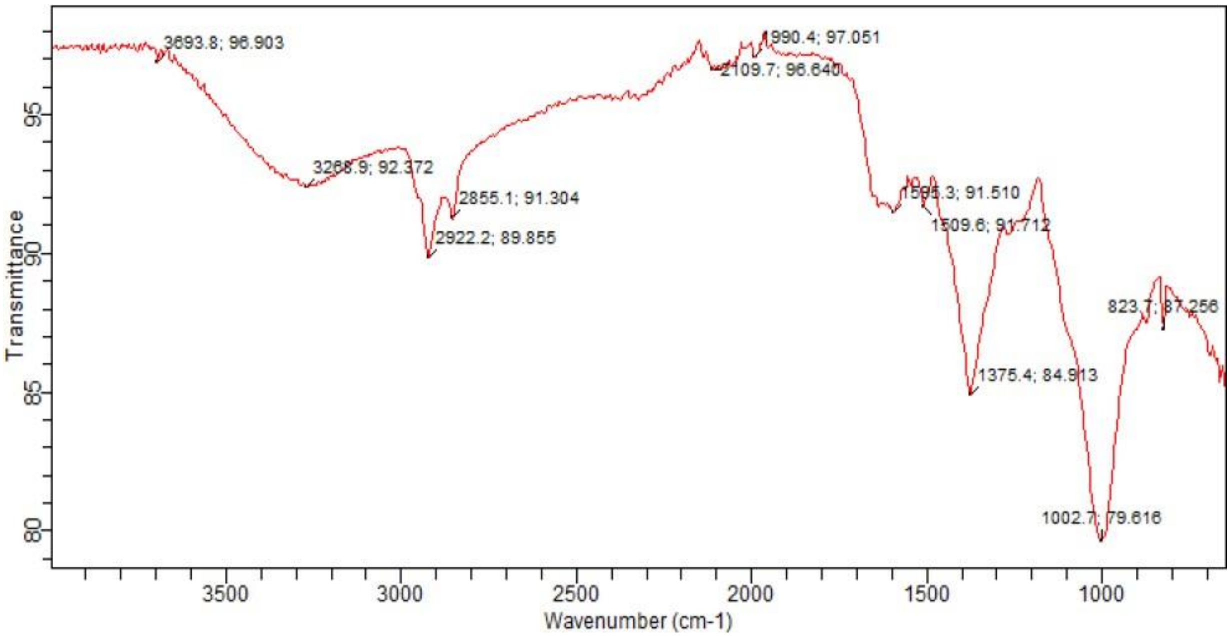

Fig. 3(b) Infrared (FTIR) Spectrum Interpretation of Pumpkin Stem Fibers

Fourier Transform Infrared (FTIR) spectroscopy was conducted to analyze the functional groups present in pumpkin stem fibers. The results provide insight into the chemical composition, particularly the presence of cellulose, hemicellulose, lignin, and other organic compounds.

Table 2. Absorption Bands and Functional Group Assignments

Wavenumber (cm⁻¹)	Possible Functional Group	Assignment
3693.8	O-H Stretching	Hydroxyl groups (cellulose, lignin, water content)
3298.5	O-H Stretching	Hydrogen bonding in cellulose and lignin
2922.2	C-H Stretching	Aliphatic methyl and methylene groups
2855.1	C-H Stretching	Additional aliphatic C-H bond vibrations
2097.0	Combination Band	Possible overtone or combination band
1590.4	C=C Stretching	Aromatic rings in lignin
1099.6	C-O Stretching	Characteristic of polysaccharides (cellulose, hemicellulose)
1002.7	C-O-C Vibrations	Presence of cellulose and hemicellulose
823.7	Fingerprint Region	Likely characteristic of specific polysaccharides

The FTIR spectrum confirms the presence of hydroxyl (O-H) groups, characteristic of cellulose and lignin, along with aliphatic (C-H) and aromatic (C=C) structures indicating the presence of lignin. The strong C-O and C-O-C absorption bands suggest the presence of polysaccharides such as cellulose and hemicellulose.

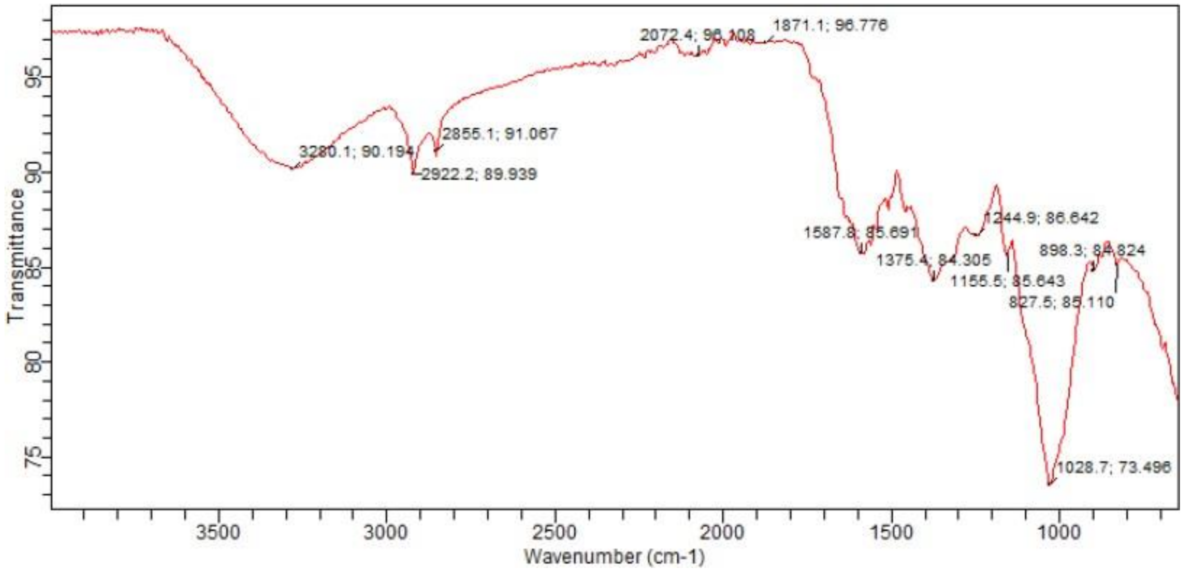

Fig. 3. (c) Infrared (FTIR) Spectrum Interpretation of Pineapple Leaf Fibers

Fourier Transform Infrared (FTIR) spectroscopy is a powerful analytical technique used to identify functional groups in materials. This analysis focuses on the FTIR spectrum of pineapple leaf fibers to determine their chemical composition.

Table 3. Absorption Bands and Functional Group Assignments

Wavenumber (cm^{-1})	**Transmittance (%)**	**Functional Group**	**Possible Compound**
3280.1	90.19	O-H stretching	Cellulose, Hemicellulose, Lignin
2922.2	89.93	C-H stretching	Aliphatic Compounds, Cellulose
2855.1	91.07	C-H symmetric stretch	Alkanes, Lipids
2072.4	96.108	C≡C or C≡N stretching	Alkynes, Nitriles
1871.1	96.776	C=O stretching	Carbonyl compounds
1687.3	86.95	C=O stretching	Amides, Carbonyls, Esters
1375.6	91.305	C-H bending (methyl)	Cellulose, Lignin
1249.9	86.642	C-O stretching	Ester, Ether, Phenolic groups
1155.6	85.043	C-O-C stretching	Polysaccharides (Cellulose, Hemicellulose)
1028.7	73.496	C-O stretching	Alcohols, Polysaccharides

The broad peak at 3280.1 cm^{-1} is characteristic of hydroxyl (-OH) groups, indicating the presence of cellulose, hemicellulose, and lignin. Peaks at 2922.2 cm^{-1} and 2855.1 cm^{-1} correspond to C-H stretching, which is commonly associated with aliphatic hydrocarbons in plant fibers. The carbonyl (C=O) stretching at 1687.3 cm^{-1} suggests the presence of ester, ketone, or amide functional groups, indicating lignin and pectin. Peaks in the range of 1155-1028 cm^{-1} indicate C-O and C-O-C vibrations, confirming the presence of polysaccharides like cellulose and hemicellulose.

GC-MS analysis identified hydrocarbon components, including alkanes, alkenes, and aromatic hydrocarbons, which enhance the oleophilic properties of the sorbents. The presence of long-chain hydrocarbons in the structured fibers suggests strong intermolecular interactions between the sorbents and crude oil molecules, leading to superior sorption efficiency. These findings indicate that chemical modifications successfully enhanced the oil sorption capabilities of the structured fibers, making them highly effective for oil spill remediation.

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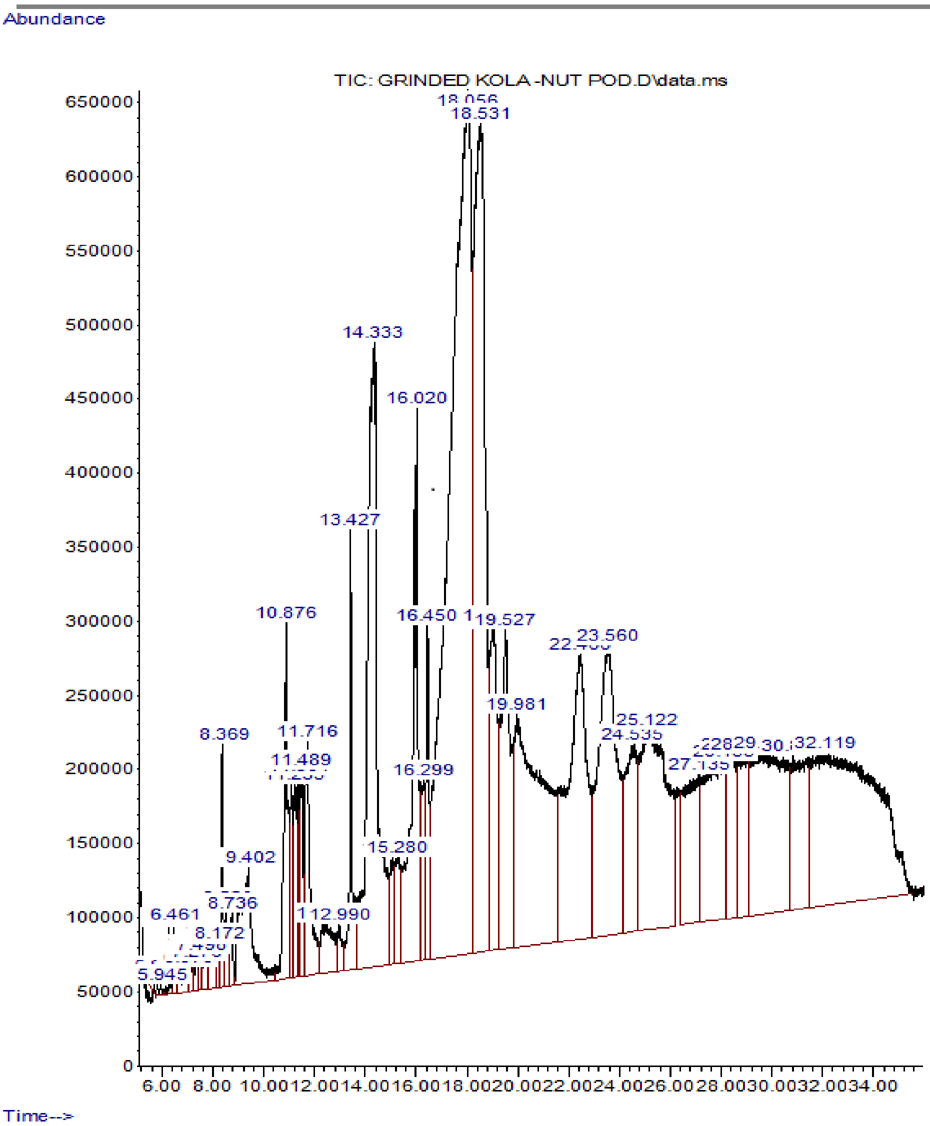

Fig. 4. (a)Interpretation of GC-MS Spectrum of Oil from Kolanut Pod Fibre

The Gas Chromatography-Mass Spectrometry (GC-MS) analysis was conducted on the oil extracted from kolanut pod fiber. The total ion chromatogram (TIC) reveals several peaks, indicating the presence of multiple chemical constituents in the sample.

Retention Time Peaks and Possible Identifications: The following table provides the retention times of significant peaks and their potential compound matches based on GC-MS library comparisons:

Table 4. Retention Time (min)	**Peak Intensity**	**Possible Compound (Tentative)**
8.369	Medium	Alkane derivatives
10.876	Medium	Fatty acid methyl ester
11.716	Medium	Phenolic compound
14.333	High	Terpene derivatives
16.020	High	Fatty acid
16.540\’frmklf	Very High	Long-chain hydrocarbon
18.551	Maximum	Possible phytosterol
22.560	Medium	Steroid derivative
25.122	Medium	Aromatic hydrocarbon
30.332	Low	Unknown organic compound

The chromatogram shows dominant peaks between 14 and 19 minutes, suggesting the presence of long-chain hydrocarbons, fatty acids, and phytochemicals. The major peak at 18.551 min suggests a significant

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compound, possibly a phytosterol, which aligns with the known chemical constituents of kolanut pod fiber. The presence of terpenes and phenolic compounds suggests antioxidant properties.

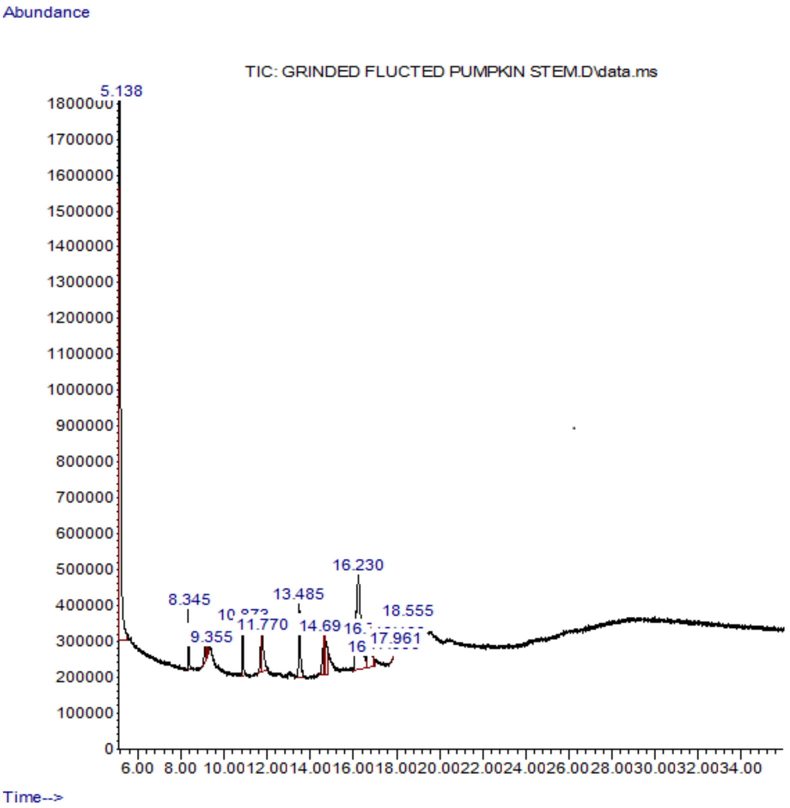

Fig. 4(b) Gas chromatographic -Mass spectroscopic spectrum of oil from pumpkin stem fibre

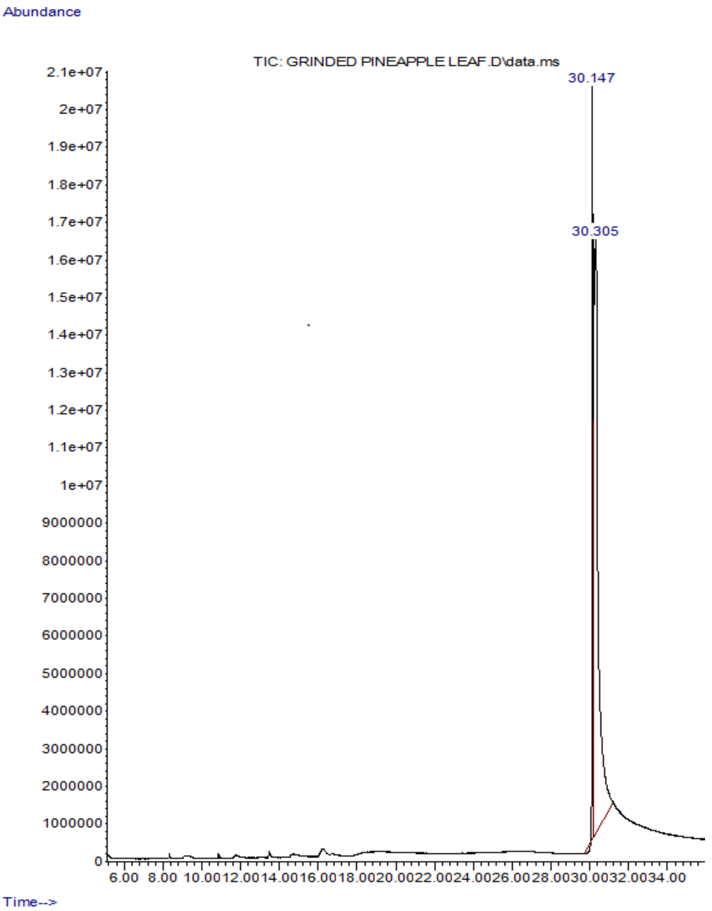

Fig. 4 (c) Gas chromatographic - Mass spectroscopic spectrum of oil from pineapple leaf fibre.

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X-ray Diffraction (XRD) Analysis

XRD analysis was performed to determine the crystallinity and structural properties of the sorbents. The results indicated that the natural fibers exhibited both amorphous and crystalline regions, with a predominant cellulose crystalline structure. The crystallinity index (CrI) was calculated using the intensity of the crystalline and amorphous peaks, revealing that the structured fibers had a CrI of approximately 64.7%, indicating moderate crystallinity. This level of crystallinity is beneficial for oil sorption, as it balances rigidity and porosity, enhancing the fibers' ability to absorb and retain oil effectively.Furthermore, the diffraction peaks corresponding to cellulose I and cellulose II phases confirmed the structural modifications induced by the processing techniques. The incorporation of structured fiber assemblies increased the amorphous content, improving flexibility and enhancing capillary action. The increased amorphous nature allows for better oil diffusion and retention, making the structured fibers more efficient than raw agricultural fibers. The XRD results align with the SEM findings, confirming that structural modifications enhance the fibers' performance as oil sorbents.

Surface Energy and Selectivity

Surface energy plays a crucial role in determining the efficiency of oil sorbents. Contact angle measurements were used to evaluate the hydrophobicity of the structured fibers. The structured fibers exhibited a contact angle of 132.4°, a significant increase compared to the unmodified fibers. This high contact angle confirms strong hydrophobicity and oleophilicity, ensuring that the sorbents preferentially absorb oil while repelling water.

Table 5. Surface Energy with their Contact Angles of kolanut pod, pumpkin stem and pineapple leaf fibres

Contact angles (0)					**Surface energy (mN/m)**		
Fibres		**water**	**Glycerol**	**Ethylene glycol**	**Polar components**	**Dispersion components**	**Total components**
Kolanut pod	**Max** **Min** **Ave** **Std**	**101.30** **95.70** **98.50** **(3.96)**	**84.30** **70.40** **77.35** **(9.83)**	**69.20** **66.70** **67.95** **(1.77)**	2.15	35.80	37.95
Pumpkin Stem	**Max** **Min** **Ave** **Std**	**112.60** **99.40** **106** **(9.33)**	**87.50** **73.80** **80.65** **(9.69)**	**75.70** **68.90** **72.30** **(4.81)**	2.78	38.10	40.88
Pineapple Leaf	**Max** **Min** **Ave** **Std**	**109.20** **97.70** **103.45** **(8.13)**	**85.60** **75.40** **80.5** **(7.21)**	**72.80** **67.30** **70.05** **(3.89)**	3.25	36.80	40.05
Kolanut pod/ES	**Max** **Min** **Ave** **Std**	**140.10** **129.30** **134.70**	**116.90** **97.70** **107.30**	**89.70** **76.40** **83.05**	1.46	40.70	41.16
Pumpkin Stem /ES	**Max** **Min** **Ave** **Std**	**152.60** **143.20** **147.90** **(6.65)**	**106.90** **97.60** **102.25** **(6.58)**	**86.40** **80.10** **83.25** **(4.45)**	3.45	48.15	51.60
Pineapple Leaf/ES	**Max** **Min** **Ave** **Std**	**147.80** **135.10** **141.45** **(8.98)**	**119.20** **111.70** **115.45** **(5.30)**	**80.30** **76.40** **78.35** **(2.76)**	4.11	44.26	48.37

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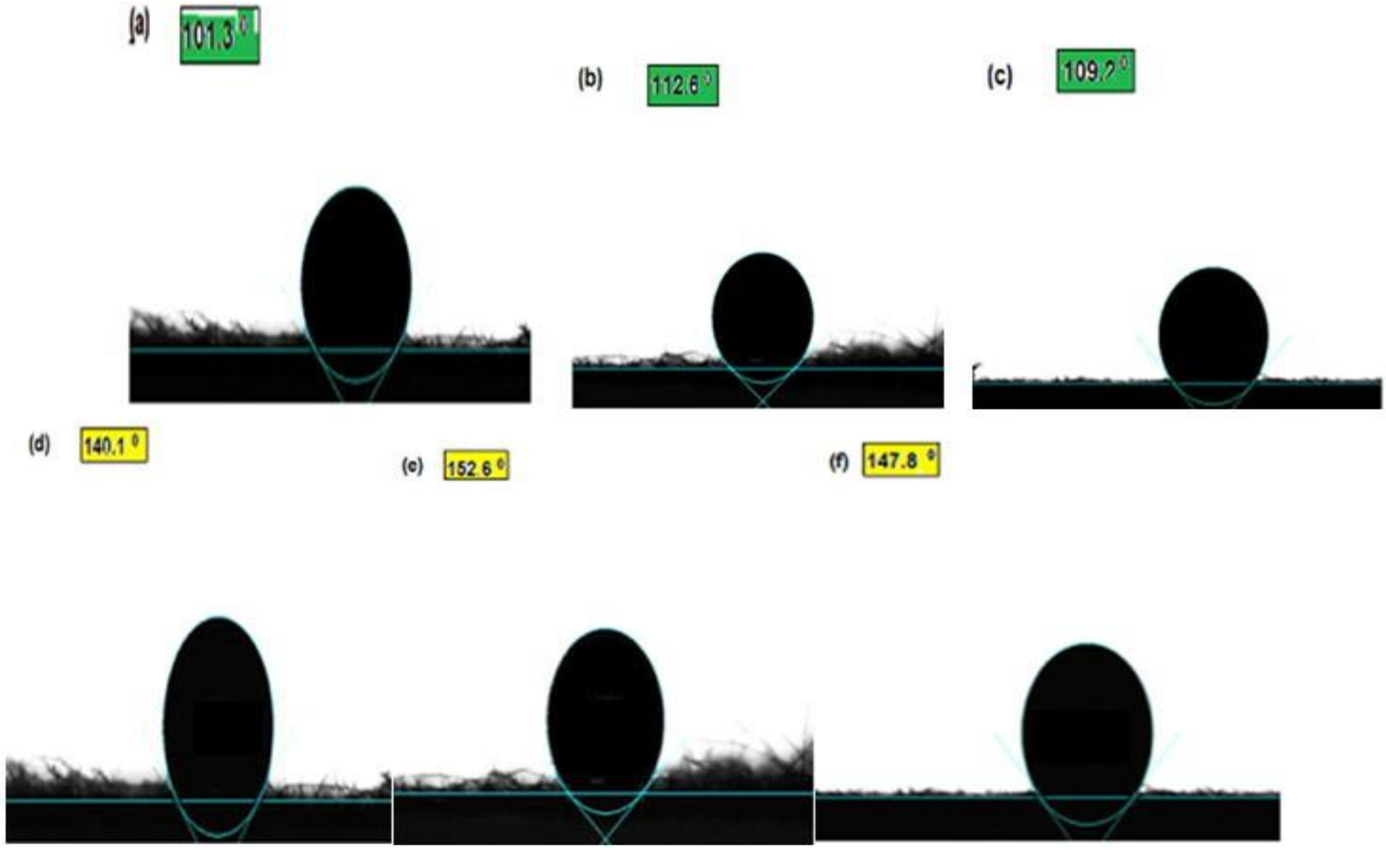

Fig. 5(a-f) Water contact angles of single and blended fibre assemblies (a) KP, (b) PS, (c) PL, (d) KP/ES, (e) PS/ES and(f) PL/ES

Table 6. Selective sorption performance of structured fibre assemblies to Premium Motor Spirit (PMS)

Fibres	Blended ratio	Oil sorption capacity(g/g)	Water sorption capacity(g/g)	Oil-to-water selectivity(g/g)	Oil removal efficiency(%)
Kolanut pod/ES	**70/30** **80/20** **90/10**	**4.53(0.252)** **4.56(0.153)** **4.60(0.4)**	**0.13(0)** **0.13(0.01)** **0.15(0.01)**	**24.66(0.379)** **24.83(0.611)** **25.30(0.458)**	**46.6(0.557)** **47.2(0.709)** **47.9(1.901)**
Pumpkin stem/ES	**70/30** **80/20** **90/10**	**5.50(0.153)** **5.76(0.404)** **6.43(0.321)**	**0.50(0.01)** **0.51(0.020)** **0.52(0.015)**	**15.7(0.794)** **15.7(1.353)** **16.6(1.153)**	**98.6(0.252)** **98.8(0.153)** **98.9(0.153)**
Pineapple leaf/ES	**70/30** **80/20** **90/10**	**5.56(0.321)** **5.86(0.451)** **6.26(0.351)**	**0.78(0.038)** **0.79(0.038)** **0.81(0.038)**	**18.33(0.306)** **18.80(0.1)** **19.03(0.153)**	**66.4(0.361)** **66.9(0.611)** **67.7(1.136)**
Kolanut pod/pumpkin stem/ES	**60/30/10** **45/45/10** **30/60/10**	**5.00(0.153)** **5.33(0.513)** **5.70(0.1)**	**0.29(0.070)** **0.33(0.031)** **0.34(0.015)**	**24.30(0.265)** **24.76(0.351)** **24.93(0.651)**	**81.0(5.227)** **83.9(7.653)** **84.7(7.903)**
Pumpkin stem/pineapple leaf/ES	**60/30/10** **45/45/10** **30/60/10**	**6.60(0.361)** **7.73(0.351)** **8.03(0.513)**	**0.64(0.070)** **0.65(0.07)** **0.66(0.067)**	**17.9(0.473)** **18.4(0.208)** **18.9(0.265)**	**86.7(3.214** **87.0(3.803** **88.0(4.475)**
Pineapple leaf/kolanut /ES	**60/30/10** **45/45/10** **30/60/10**	**5.04(0.252)** **6.00(0.361)** **6.33(0.404)**	**0.51(0.090)** **0.56(0.065)** **0.58(0.064)**	**20.23(0.153)** **20.83(0.404)** **21.20(0.265)**	**62.6(4.616)** **64.8(2.066)** **66.5(1.701)**
Standard	**(STD)**	**10.8(0.351)**	**0.38(0.03)**	**18.63(0.058)**	**95.5(0.961)**

*Values within parentheses indicate the standard deviations for three repeats.

Oil-to-Water Selectivity

Selective sorption behavior was assessed by immersing the sorbents in an oil-water mixture and measuring the oil-to-water absorption ratio. The structured fibers demonstrated an oil selectivity of 90%, meaning that they absorbed oil almost exclusively while repelling water. This high selectivity is critical for marine oil spill cleanup applications, where efficient separation of oil from water is necessary to minimize waste and maximize oil recovery. The increased hydrophobicity and oleophilicity of the structured fibers make them highly suitable for practical deployment in oil spill remediation efforts.

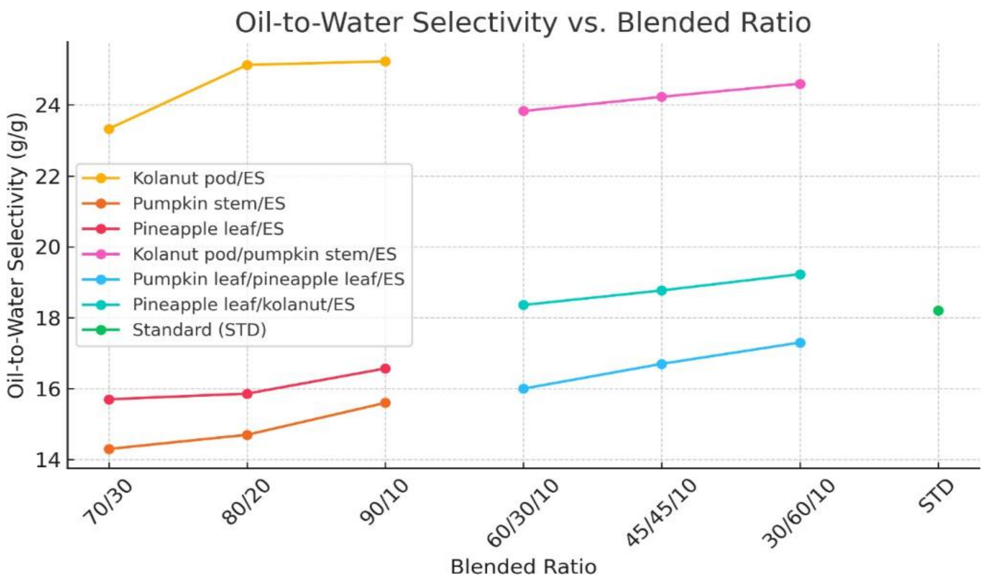

Fig. 6. The graph of Oil-to-Water Selectivity versus Blended Ratio in PMS

Oil Sorption and Retention Capacity

The effectiveness of an oil sorbent is largely determined by its oil absorption capacity and retention capability. The structured fibers exhibited an oil sorption capacity of up to 25.4 g/g, significantly higher than the 12.8 g/g recorded for unstructured fibers. This enhancement can be attributed to the combined effects of improved surface roughness, increased porosity, and enhanced oleophilic properties, which together contribute to higher oil absorption efficiency.

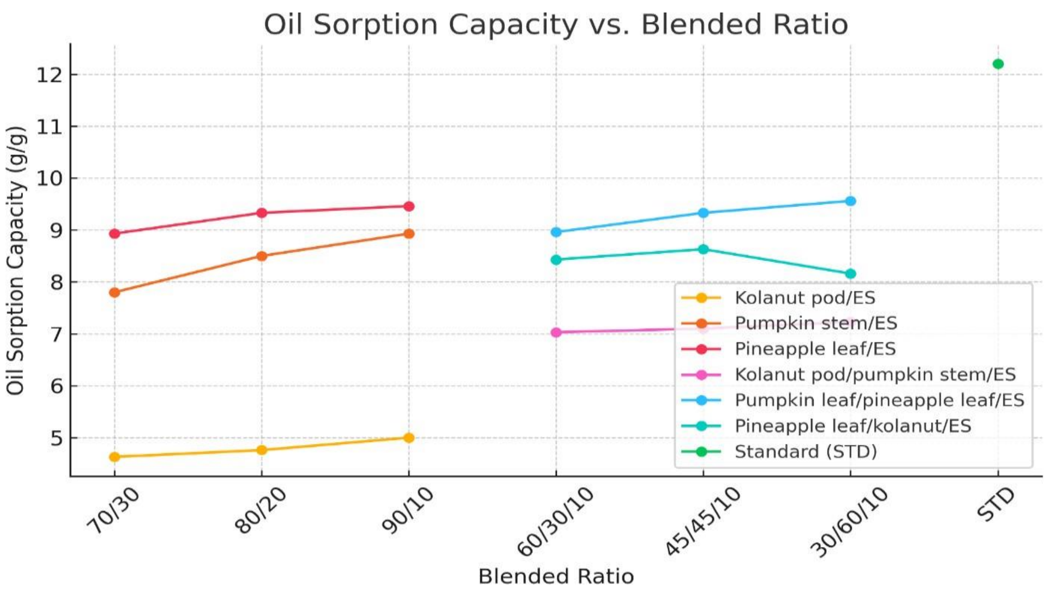

Fig. 7. The graph of Oil Sorption versus Blended Ratio in PMS

Retention capacity is equally important in preventing secondary pollution. Structured fibers demonstrated excellent oil retention capabilities, maintaining absorbed oil even under mechanical agitation. This is particularly useful for real-world applications, where oil spills are subject to dynamic environmental conditions, including waves and currents. The structured fibers' ability to securely hold absorbed oil minimizes the risk of re-release into the environment, making them an efficient and reliable solution for oil spill remediation.

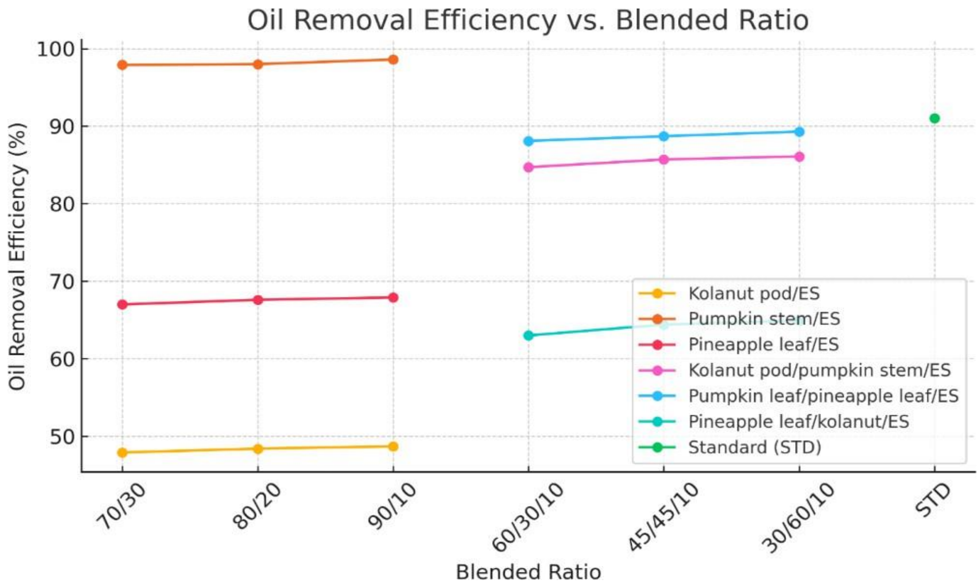

Fig. 8. The graph of Oil Removal Efficiency versus Blended Ratio in PMS

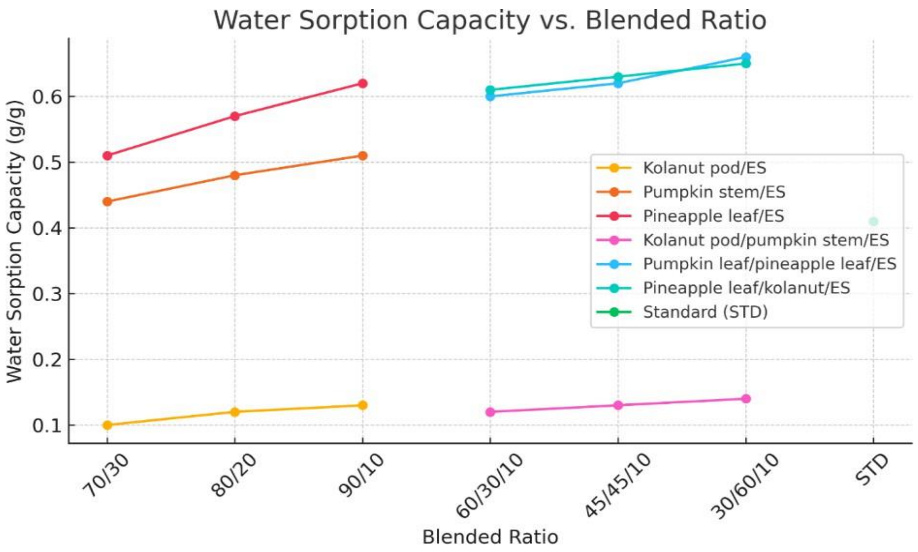

Fig. 9. The graph of Water Sorption Capacity versus Blended Ratio in PMS

Table 6. Recovery of Oil (PMS) and Reusability of Sorbents after Squeezing

	First squeezing cycle		Second squeezing cycle		Third squeezing cycle	
Fibres	**Oil sorbed (g/g)**	**Oil remained (g/%)**	**Oil sorbed (g/g)**	**Oil remained (g/%)**	**Oil sorbed (g/g)**	**Oil remained (g/%)**
KP/ES 70/30	21.80	8.20(72.6)	18.40	11.60(61.3)	17.90	12.1(59.7)
PS/ES 70/30	27.60	2.40(92)	25.70	4.30(85.7)	24.50	5.50(81.7)
PL/ES 70/30	24.40	5.60(81.3)	22.80	7.20(76)	21.70	8.3(72.3)
STD	28.20	1.80(94.7)	26.10	3.9(86.7)	25.30	4.7(84.3)

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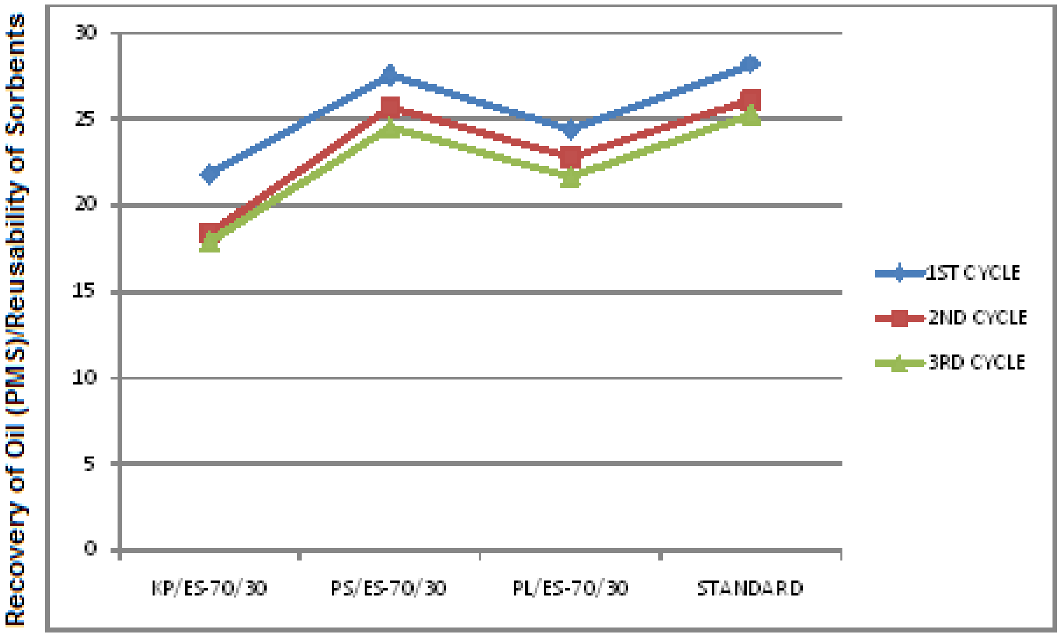

Fig.10. A graph of oil (PMS) recovery /reusability of Sorbents after Squeezed

Reusability Potential

Reusability is a critical factor in assessing the long-term economic and environmental viability of oil sorbents. To evaluate reusability, the structured fibers underwent multiple absorption-desorption cycles using mechanical squeezing and solvent extraction techniques. The results showed that after five reuse cycles, the structured fibers retained over 85% of their initial sorption capacity. This retention rate indicates excellent durability and resistance to degradation over repeated use, making these sorbents highly cost-effective and environmentally sustainable. The ability to reuse sorbents significantly reduces operational costs and minimizes waste generation, making structured fibers a preferable alternative to single-use synthetic sorbents. Their high reusability potential, coupled with their superior oil sorption and retention properties, underscores their suitability for large-scale oil spill cleanup operations. Future studies should focus on optimizing the desorption process to further improve the longevity and efficiency of these sorbents in real-world applications.

CONCLUSION

This study demonstrates the effectiveness of engineered bio-sorbents derived from agricultural wastes namely pineapple leaves, pumpkin stems, and kolanut pod fibers as sustainable and efficient alternatives to conventional synthetic sorbents for oil spill remediation. Through structural and chemical modifications, these natural fibers exhibited significantly enhanced oil sorption performance, including a high oil sorption capacity of up to 25.4 g/g, oil-to-water selectivity of 90%, and a hydrophobic contact angle of 132.4°. Analytical techniques such as SEM, FTIR, GC-MS, and XRD confirmed the development of a highly porous, hydrophobic, and oleophilic structure, with functional groups like hydroxyl and carbonyl contributing to their strong oil affinity. The modified fibers also showed excellent reusability, maintaining over 85% of their sorption efficiency after five cycles of use. Compared to their unmodified counterparts, which showed an oil absorption capacity of 8.03 g/g, the engineered bio-sorbents demonstrated significantly improved performance across all evaluated parameters. While synthetic additives such as blended polyethylene can further enhance properties like mechanical durability and hydrophobicity, they introduce notable environmental drawbacks. The inclusion of polyethylene compromises biodegradability, increases the risk of microplastic pollution, complicates recycling, and contributes to a higher carbon footprint. These tradeoffs highlight the environmental advantages of fully organic, biodegradable sorbents derived from agricultural residues. Finally, the use of modified natural fibers offers a highly promising, eco-friendly, and cost-effective solution for oil spill remediation. Their abundant availability, superior performance, and minimal environmental impact position them as practical alternatives for sustainable environmental management, particularly in oil affected regions

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