Available online www.worldscientificnews.com

World Scientific News

An International Scientific Journal

WSN 217 (2026) 1-13 EISSN 2392-2192

Application of Moss Plant (*Barbula Indica*) as a Sustainable Material for Oil-Water Separation

Ukachuku Samuel[1,*] and Igiegie Oghenegueke Daniel[2]

[1] Department of Pure and Industrial Chemistry, University of Africa, Toru-Orua, Bayelsa State, Nigeria.

Email: samuel.ukachuku@uat.edu.ng

[2] Department of Environmental Management and Toxicology, Federal University of Petroleum Resources, Effurun, Wari, Delta State, Nigeria.

Email: igiegie.oghenegueke@fupre.edu.ng

[*]Corresponding author's Email: samuel.ukachuku@uat.edu.ng

https://doi.org/10.65770/CPRC7081

ABSTRACT

In this study, the moss plant species, *Barbula indica*, was investigated for its crude oil sorption capacity for a potential application as sorbent for the removal of crude oil from water. Moss samples were pretreated with 10% NaOH (mercerization) and hydrothermally at 100°C and 60°C. Crude oil sorption tests conducted with both untreated and pretreated moss biomass yielded the following results: 1.20gg^{-1}(53.11%), 1.34gg^{-1}(59.56%), 1.61gg^{-1}(71.56%), and 1.91gg^{-1}(84.89%), representing sorption capacity (gg^{-1}) and percentage sorption (%) for untreated moss, 60°C hydrothermally treated moss, 100°C hydrothermally treated moss, and mercerized (10% NaOH) moss, respectively. The results indicated that pretreatment of the moss led to the enhancement of its crude oil sorption performance. Mercerized moss took up crude oil the most, thus confirming mercerization as the most effective pretreatment method for moss in crude oil sorption. In the hydrothermal treatments, temperature of 100°C was more effective than 60°C. Water sorption test results confirmed that the most hydrophobic material had the highest crude oil sorption capacity. The findings reveal that, with or without pretreatment, *Barbula indica* has the potential as an excellent material for crude oil-water separation applications.

Keywords: Moss, Sorbent, *Barbula indica*, oil/water separation, crude oil.

(Received 7 May 2026; Accepted 15 June 2026; Date of Publication 6 July 2026)

1. INTRODUCTION

Oil spill is an accidental or unintentional release of oil into water from a simple shipping boat, tanker, underwater pipeline, or an offshore drilling rig (Zamparas et al., 2020a). These accidents have been observed very frequently for almost three decades (Wolok et al., 2020). The world's biggest spilled oil incident ever was recorded in the Gulf of Mexico in 2010, which lasted for more than 85 days, causing deleterious impacts to the marine ecosystems (Allan et al., 2012).

The world is facing a largescale environmental problem due to petroleum spills, and great attention is currently given to research on various sorbents with potential for application in adsorption of petroleum and its products (Zamparas et al., 2020a). Sorbents are substances that can bind oil hydrocarbons through either absorption or adsorption, or a combination of both phenomena (Porshnov & Klavins, 2017).

Synthetic sorbents for oil-water separation are the most widely applied materials, although they are not the optimal choices from an economic and environmental point of view. These class of sorbents, which are mostly made from polypropylene, polyethylene, polyurethane, and polyester materials (Baruah & Neog, 2025; Gote et al., 2023), are intentionally manufactured to serve as sorption materials to remove hydrocarbons and chemical spills (Mojžiš et al., 2019a). They are processed as high-quality sorption materials. However, they are cost ineffective and carry the potential as environmental pollutants. Given the demerits of these synthetic sorbents, there is a consistent search for alternatives materials which are efficient, cost effective, available, non-toxic, and environment friendly. Peat based materials and plant wastes such as Sphagnum peat moss (Pandey & Alam, 2019a), orange peels (El Gheriany et al., 2020), palm fibers (Abdelwahab et al., 2017), corn stalk (Husseien et al., 2015), walnut shell (Srinivasan & Viraraghavan, 2008a), wheat straw (Lv et al., 2016), sugarcane bagasse (Behnood et al., 2016) amongst others have been reported to be reliable in oil sorption applications (Zamparas et al., 2020b).

Most of the highly efficient materials for oil sorption exhibits properties such as high fluid absorption capacity, rapid uptake of oil, good oil retention quality, sufficient buoyancy, and excellent hydrophobicity/oleophilicity qualities (Ifelebuegu & Johnson, 2017). Among plant materials, Sphagnum peat moss is prominent for its excellent petroleum sorption capabilities, hence, has been applied extensively as an environment friendly and renewable natural product for oil-water separations (Pandey & Alam, 2019; Porshnov & Klavins, 2017). Sphagnum peat moss is characterized by a developed, complex pore system (Porshnov & Klavins, 2017). Its porosity ratio is about 95 %, and the value of its specific surface area is usually greater than 200 m^2/g (Somasundaran, 2014). Despite the structural and anatomical similarities among mosses, no other moss species have received the level of attention given to peat moss in relation to oil-water separation applications. Only a handful of other moss species have been investigated, amongst which are *Ceratodon purpureus* and *Rhytidiadelphus triquetrus* (Mojžiš et al., 2019b). There is the need to diversify investigation to other moss species. This will present other mosses as viable substitute to sphagnum peat moss. It will also promote the local content value of moss species in those regions where sphagnum is not native, reduce over reliance on peat moss, and eliminate challenges of monopolization.

Here, we introduce the moss plant species *Barbula indica,* a native of the study area (Niger Delta subregion, Nigeria). The area plays host to lots of oil production activities and suffers incessant petroleum spills, which has also greatly impacted its ecosystem negatively. The need to develop local content materials for application as petroleum sorbents to aid local oil producers in their efforts to remediate oil contaminated waters and to recover spilled products cannot be overemphasized.

Barbula indica is the most common moss found in the Niger Delta region of Nigeria. It is often found on concrete wall surfaces of abandoned buildings and fences as well as on wet soil surfaces. Their ubitiquous presence in the Niger Delta region is attributed to the fact that *Barbula* mosses thrive in moist habitats. The Niger Delta region records high frequency and volume of rainfall, which creates a highly humid air and moist surfaces for most period of the year (Etim U. U. Ituen & A Folarin Alonge, 2009). Humid condition is favorable for the sprouting and growth of moss plants, which could also be capitalized in setting up moss culture farms for the growing and production of ample quantities of the plant for industrial scale utilization.

2. EXPERIMENTAL PROCEDURES

2.1. List of Materials

Moss biomass sample: Moss biomass samples were picked from a concrete made fence in Yenagoa, Bayelsa State, Nigeria. The sample was then carefully filtered to separate impurities, thereafter washed and rinsed with distilled water, then sun dried. The dry moss biomass was then ground to powder using an electrically powered blender.

Figure 1. Photograph of the Investigated Moss Biomass, *Barbula Indica.*

Crude oil sample: Crude oil sample was collected from an oil field located in Bayelsa State, Nigeria, and stored in a sealed container at room temperature.

Mesh nets: Mesh nets of size 3 μm, made of nylon material, were used as model booms to wrap the sorbents for the petroleum sorption study.

Beakers and measuring cylinders: 200 ml beakers were used as containers for the simulation of petroleum spill. Measuring cylinders were used to transfer volumes of water and crude oil to beakers.

Reagents for moss biomass pretreatment: Analytical grade NaOH procured from Alladin Biological, Shangai China, and was used without further purification to prepare 10 % NaOH solution for pretreatment of moss.

2.2. Pretreatment of Moss Biomass

Hydrothermal treatment: Two sets of moss sample were subjected to hydrothermal treatment. For one set, 5 g of moss was added to a 50 ml distilled water contained in a 100 ml conical flask. This mixture was then heated steadily to a thermometer reading of 100 ^{0}C, after which it was allowed to cool for 3 minutes before filtration. The recovered moss then oven dried at 40 ^{0}C.

For the other set, the same process was repeated, but heating was discontinued at a thermometer reading of 60 °C, allowed to cool for 3 minutes, and the moss recovered via filtration and oven dried at 40 ^{0}C.

Mercerization with 10 % NaOH: Treatment of a sorbent with NaOH is called mercerization. 50 ml 10 % w/v NaOH was prepared by weighing 5 g of NaOH pellets into 45 ml of distilled water. To the 50 ml NaOH solution, 5 g of moss was added and the mixture was heated for 60 minutes. Thereafter, the NaOH treated moss was recovered via filtration, washed with excess distilled water, and oven dried at 40 ^{0}C.

Simulation of petroleum spill: 200 mL beakers were used as petroleum spill simulation tanks. Five sets of beakers were prepared, each containing 5 mL of crude oil in 80 mL of distilled water, left still and undisturbed.

2.3. Petroleum Sorption Studies

Petroleum sorption test was conducted according to the method provided by the American Society for Testing and Materials, ASTM F726-12, on the use of type II sorbents (loose, or unconsolidated particulate materials) in the removal of non-emulsified, floating and immiscible oils from the surface of water (F20 Committee, n.d.; Bazargan et al., 2015). Crude oil spills were simulated in 200 mL beakers. Empty dry 200 ml beaker was weighed, and the weight recorded. 80 ml volume of distilled water measured with a measuring cylinder was transferred into the weighed 200 ml beaker and the weight of beaker plus distilled water was recorded. 5 ml volume of crude oil (density ~ 0.9gcm$^-$) was measured with a measuring cylinder and added to the distilled water inside the 200 ml beaker, and the weight of beaker plus distilled water plus crude oil was recorded as initial weight. 2 g of moss was wrapped in nylon mesh nets of mesh size 3 μm and dipped into the 200 ml beaker containing oil/water mixture, for oil/sorbent contact. Contact was allowed for 15 minutes, and the wrapped sorbent raised above the beaker for sorbed fluid to drain back into it for 1 minute. After draining, the final weight of beaker and its oil/water contents was recorded (Nwadiogbu et al., 2016). Procedure was repeated once, and weight of absorbed oil was recorded as average value.

Weight of sorbed oil was recorded as initial weight of (beaker + distilled water + crude oil) $-$ final weight of (beaker + distilled water + crude oil) Eq. 1

Oil sorption capacity of the sorbent was estimated as: $\frac{weight\ of\ oil\ sorbed}{weight\ of\ dry\ sorbent}$ Eq. 2

2.4. Water Sorption Test

Water sorption test was conducted in line with ASTM F726-12 (F20 Committee, n.d.). 2 g of each sorbent type was wrapped in a mesh net and dipped into a beaker containing a known weight of distilled water, and allowed to remain for 15 minutes. Thereafter, the sorbent inside the mesh was allowed to drain for 1 minute. The weight of absorbed water was determined by weight difference between initial and final weight of water inside the beaker.

3. RESULTS AND DISCUSSIONS

The results of the petroleum tests for both untreated and pretreated moss biomass are displayed in Table 1 and Figure 2. The results comprise of the crude oil sorption capacity (g/g) and percentage sorption (%). The bar charts in Figure 2 compares the performances of the various pretreated and untreated mosses based on their sorption capacities and sorbed crude oil percentages.

3.1. Crude Oil Sorption Capacity of Untreated and Pretreated Moss Biomass, *Barbula Indica*

The results presented in Table 1 show the crude oil sorption capacities and percentage of sorbed crude oil for the three pretreated moss and the untreated moss. For untreated moss, 60 ^{0}C hydrothermally treated moss, 100°C hydrothermally treated moss, and mercerized moss, we had 1.20, 1.34, 1.61, 1.91 g/g and 53.11, 59.56, 71.56 and 84.89 % respectively. The essence of sorbent pretreatment is to enhance hydrophobicity and, by implication, improve sorbent performance. For crude oil sorption, hydrophobicity is a critical factor for sorbent performance (Nwadiogbu et al., 2016). In this study, the various moss treatment methods were anticipated to enhance the hydrophobicity of the moss and improve their crude oil sorption. The results clearly show the effect of pretreatment on moss performance, as it is observed that all the pretreated moss samples outperformed the untreated sample. This is clearly revealed in the bar charts (Figure 2). It Mercerization with 10 % NaOH provided the best enhancement of moss biomass, with the mercerized moss recording the highest crude oil uptake (84.89 %). This indicated that mercerization with 10 % NaOH was better than hydrothermal treatment. On comparison of the two hydrothermal temperatures, it is observed that the moss biomass pretreated with hydrothermal temperature of 100 ^{0}C, performed better (71.56 %) than that pretreated with hydrothermal temperature of 60 ^{0}C (59.56 %). This indicated that hydrophobicity of the hydrothermally treated moss biomass improved as the treatment temperature of increased, and sorption performance was enhanced. Hydrothermal treatment eliminates cellulosic hydroxyl functions from the surface of a lignocellulosic material, thereby improving its carbon content and making the material more hydrophobic. The results clearly show that moss hydrophobicity increased upon pretreatment with hot water, and the hotter the water, the higher the hydrophobicity generated. This accounted for the higher performance of the moss pretreated hydrothermally with hot water at a temperature of 100 ^{0}C than that pretreated with hot water at 60°C.

3.2. Water Sorption Performance Of

Water sorption test was conducted to determine the hydrophilicity of the pretreated and the untreated moss samples. 100 g of water was used for the water sorption tests. The results are presented in terms of the percentage of the 100 g of water that was sorbed when the materials were immersed in it. The results were 6.68, 6.06, 5.45, and 3.14 % for untreated moss, 60°C hydrothermally treated moss, 100°C hydrothermally treated moss and mercerized moss, respectively.

The percentage of water sorbed by each of the sorbents represented their hydrophilicity as well as their wettability. Hydrophilic materials are less efficient as sorbents for crude oil removal from water, since they are more attracted to water than the hydrophobic crude oil and tend to repel the crude oil and, as well, reduce their buoyance, after soaking up water. It follows that the more the hydrophilicity of a sorbent, the less efficient it is as a crude oil sorbent.

The bar charts in Figure 3 show the percentage of water taken up by the various pretreated moss biomass and the untreated biomass. It can be deduced clearly from the results that the crude oil sorption performance (Figure 2) and the water sorption performance are inversely correlated, since the order of increasing or decreasing performances are reversed. This shows clearly that the more hydrophobic a material is, the more efficient it is as a sorbent of crude oil and vice versa. From Figure 3, it can be observed that mercerized moss is the least hydrophilic sorbent among the pretreated and the untreated moss samples, which explains why it took up the highest percentage of crude oil in the crude oil sorption test (Figure 2). Untreated moss biomass is the most hydrophilic, as is evident in the results (Figure 3). The hydrothermally treated moss samples also show here that the pretreatment with hot water at 100 ^{0}C is better at making a lignocellulosic material more hydrophobic compared to the pretreatment with hot water at 60 ^{0}C, since the sample pretreated with the former is seen to take up less amount of water than the sample pretreated with the later (Figure 3).

Based on the hydrophilicity test, the order of hydrophobicity and, by extension, crude oil sorption performance of the pretreated and the untreated moss samples can therefore be summarized in increasing order as follows: mercerized moss > 100 ^{0}C hydrothermally treated moss > 60 ^{0}C hydrothermally treated moss > untreated moss.

A comparison of the oil sorption capacity of existing sorbents to the moss based sorbents in this study is presented in Table 2. The table shows that the performances of sorbents in oil sorption may depend on factors such as experimental conditions employed, nature of sorbent, type of oil sorbed, and the modification method employed. The observed sorption performance of the moss based sorbents investigated in this study is good based on the experimental method adopted.

Table 1. Crude Oil Sorption Capacity and Percentage Sorption for the Untreated and Pretreated Moss Biomass.

S/N	**Sorbent type**	**Initial weight of crude oil (g)**	**Final weight of crude oil (g)**	**Weight of sorbed crude oil (g)**	**Crude oil sorption capacity of sorbent (g/g)**	**% crude oil sorbed**
1	Moss	4.5	2.11	2.39	1.20	53.11
2	60 ^{0}C hydrothermal	4.5	1.82	2.68	1.34	59.56
3	100 ^{0}C hydrothermal	4.5	1.28	3.22	1.61	71.56
4	Mercerized moss	4.5	0.68	3.82	1.91	84.89

Table 2. Comparison of Performance of Moss Biomass to Other Sorbents Reported In Previous Studies.

Type of sorbent	**Sorption method employed**	**Oil/sorbent contact time (minute)**	**Sorption capacity gg^{-1}**	**Type of oil**	**References**
Pretreated Sphagnum moss	**ASTM**	**20**	**22.756**	**Crude oil**	Ren et al., 2025
Untreated Banana peel	**ASTM**	**15**	**5**	**Gas oil**	Alaa El-Din et al., 2018
Thermally treated rice husk	**ASTM**	**30**	**15**	**Crude oil**	(Kudaybergenov et al., 2013)
Untreated rice husk	**N/A**	**N/A**	**1.25**	**Engine oil**	(Razavi et al., 2014)
Acetylated oil palm empty fruit bunch	**N/A**	**N/A**	**7**	**Crude oil**	(Asadpour et al., 2016)
Untreated Jute fibre	**ASTM**	**60**	**2.6**	**Engine oil**	(Teli & Valia, 2013)
Acetylated Jute fibre	**ASTM**	**60**	**21.8**	**Engine oil**	(Teli & Valia, 2013)
Untreated granulated walnut shell	**N/A**	**N/A**	**0.30-0.58**	**Mineral oil, vegetable oil**	(Srinivasan & Viraraghavan, 2008b)
Untreated Luffa fiber	**N/A**	**N/A**	**1.9**	**Crude oil**	(Annunciado et al., 2005)
Mercerized moss biomass (*Barbula indica*)	**ASTM**	**15**	**1.91**	**Crude oil**	**Present study**
Hydrothermally treated (100 ^{0}C) moss biomass (*Barbula indica*)	**ASTM**	**15**	**1.61**	**Crude oil**	**Present study**
Untreated moss biomass (*Barbula indica*)	**ASTM**	**15**	**1.20**	**Crude oil**	**Present study**

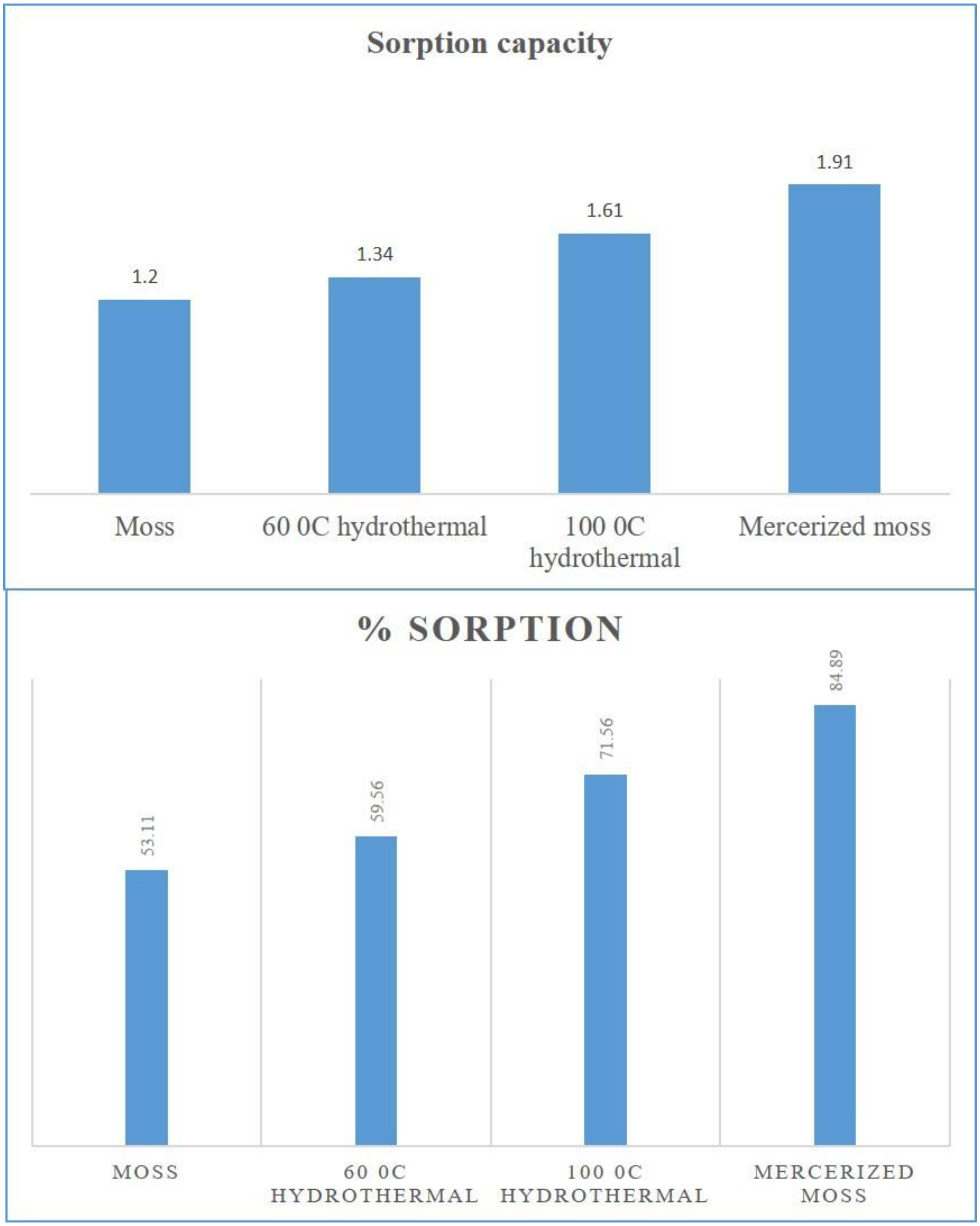

Figure 2. Bar Charts of Sorption Capacity (Above) and Percentage Sorption (Below) for Untreated and the Various Pretreated Moss Biomass.

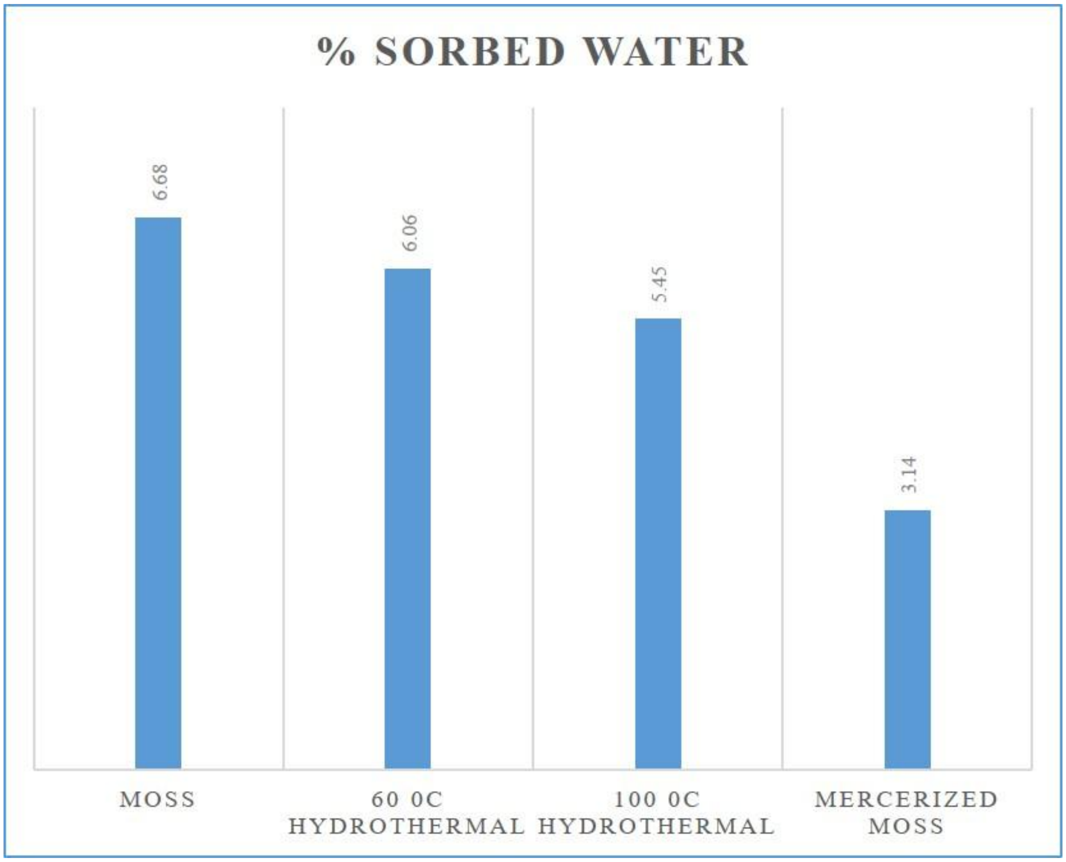

Figure 3. Bar Charts of Percentage Water Sorption by the Untreated and Pretreated Moss Biomass, *Barbula Indica.*

4. CONCLUSION

The profiling of moss plant, *Barbula indica*, as a potential sorbent for the removal of crude oil from water has been carried out. The crude oil sorption test was based on determination of the effect of pretreatment on the performance of moss, as well as comparison of the effectiveness of various pretreatment methods. Moss biomass pretreatments were performed via mercerization with 10 % NaOH, and hydrothermally at temperatures of 100 ^{0}C and 60 ^{0}C. The method provided by the American Society for Testing and Materials (ASTM F726-12) (F20 Committee, n.d.) was applied for crude oil sorption test. 2 g of each of the pretreated and the untreated moss samples were dipped into simulated oil spill tanks represented by 200 ml beakers, where contact was maintained for 15 minutes with 5 ml of crude oil (weight ~ 4.5 g, density ~ 0.9 gcm^{-1}) floating on 80 ml of water. Weight of crude oil taken up by sorbents were obtained by mass difference. Water sorption tests were also conducted for each of the moss samples to determine their hydrophilicity and their suitability as crude oil sorbents.

The results were presented in terms of crude oil sorption capacity (g/g) and percentage of crude oil sorbed by the materials. The obtained values were 1.20 g/g (53.11 %), 1.34 g/g (59.56 %), 1.61 g/g (71.56 %), and 1.91 g/g (84.89 %) for untreated moss, 60 ^{0}C hydrothermally treated moss, 100 ^{0}C hydrothermally treated moss, and mercerized moss, respectively, which indicated that pretreatment of the moss *Barbula indica*, towards improving its hydrophobicity, led to enhancement of its crude oil sorption performance. Further, the results confirmed that mercerization was the most effective method for moss biomass pretreatment, with the mercerized moss having highest crude oil sorption capacity. Hydrothermal treatment at 100 $^{\circ C}$ was found to be more effective than that at 60 °C. The findings clearly reveal that the moss plant *Barbula indica* is a potentially significant plant for a possible application as a sorbent for oil-water separation, and that its hydrophobicity can be chemically or physically enhanced for the same purpose for optimal sorption performance.

Funding:

This research was not funded by any external body.

Data Availability:

The data are available upon request from the corresponding author.

Declaration of Conflicts of Interest:

The authors have no conflict of interest to declare.

AI Disclosure statement:

The authors declare the nonuse AI tool in the preparation of this article.

Authors	Email id	Orcid id
Ukachuku Samuel	samuel.ukachuku@uat.edu.ng	0000-0003-2120-9375
Igiegie Oghenegueke Daniel	igiegie.oghenegueke@fupre.edu.ng	0009-0003-6823-5244

Reference

[1] Abdelwahab, O., Nasr, S. M., & Thabet, W. M. (2017). Palm fibers and modified palm fibers adsorbents for different oils. *Alexandria Engineering Journal*, *56*(4), 749–755. https://doi.org/10.1016/j.aej.2016.11.020

[2] Alaa El-Din, G., Amer, A. A., Malsh, G., & Hussein, M. (2018). Study on the use of banana peels for oil spill removal. *Alexandria Engineering Journal*, *57*(3), 2061–2068. https://doi.org/10.1016/j.aej.2017.05.020

[3] Allan, S. E., Smith, B. W., & Anderson, K. A. (2012). Impact of the deepwater horizon oil spill on bioavailable polycyclic aromatic hydrocarbons in Gulf of Mexico coastal waters. *Environmental Science & Technology*, *46*(4), 2033–2039. https://doi.org/10.1021/es202942q

[4] Annunciado, T. R., Sydenstricker, T. H. D., & Amico, S. C. (2005). Experimental investigation of various vegetable fibers as sorbent materials for oil spills. *Marine Pollution Bulletin*, *50*(11), 1340–1346. https://doi.org/10.1016/j.marpolbul.2005.04.043

[5] Asadpour, R., Sapari, N. B., Isa, M. H., & Kakooei, S. (2016). Acetylation of oil palm empty fruit bunch fiber as an adsorbent for removal of crude oil. *Environmental Science and Pollution Research International*, *23*(12), 11740–11750. https://doi.org/10.1007/s11356-016-6349-2

[6] Baruah, S., & Neog, D. (2025). Adsorption analysis of organic and chemical sorbents for oil spill management on land. *Results in Engineering*, *26*, 105167. https://doi.org/10.1016/j.rineng.2025.105167

[7] Bazargan, A., Tan, J., & McKay, G. (2015). Standardization of Oil Sorbent Performance Testing. *Journal of Testing and Evaluation*, *43*(6), 20140227. https://doi.org/10.1520/JTE20140227

[8] Behnood, R., Anvaripour, B., Jaafarzadeh, N., & Farasati, M. (2016). Oil spill sorption using raw and acetylated sugarcane bagasse. *Journal of Central South University*, *23*(7), 1618–1625. https://doi.org/10.1007/s11771-016-3216-8

[9] El Gheriany, I. A., Ahmad El Saqa, F., Abd El Razek Amer, A., & Hussein, M. (2020). Oil spill sorption capacity of raw and thermally modified orange peel waste. *Alexandria Engineering Journal*, *59*(2), 925–932. https://doi.org/10.1016/j.aej.2020.03.024

[10] Etim U. U Ituen & A Folarin Alonge. (2009). Niger Delta Region of Nigeria, Climate Change and the way Forward. *Bioenergy Engineering, 11-14 October 2009, Bellevue, Washington*. Bioenergy Engineering, 11-14 October 2009, Bellevue, Washington. https://doi.org/10.13031/2013.29162

[11] F20 Committee. (n.d.). *Test Method for Sorbent Performance of Adsorbents*. ASTM International. https://doi.org/10.1520/F0726-12

[12] Gote, M. G., Dhila, H. H., & Muley, S. R. (2023). Advanced Synthetic and Bio-Based Sorbents for Oil Spill Clean-up: A Review of Novel Trends. *Nature Environment and Pollution Technology*, *22*(1), 39–61. https://doi.org/10.46488/NEPT.2023.v22i01.004

[13] Husseien, M., Amer, A. A., Maghraby, A. E., & Hamedallah, N. (2015). Oil spill removal from water by using corn stalk: Factors affecting sorption process. *International Journal of Environment and Waste Management*, *16*(4), 281. https://doi.org/10.1504/IJEWM.2015.074907

[14] Ifelebuegu, A. O., & Johnson, A. (2017). Nonconventional low-cost cellulose- and keratin-based biopolymeric sorbents for oil/water separation and spill cleanup: A review. *Critical Reviews in Environmental Science and Technology*, *47*(11), 964–1001. https://doi.org/10.1080/10643389.2017.1318620

[15] Kudaybergenov, K. K., Ongarbayev, E. K., & Mansurov, Z. A. (2013). Petroleum Sorption by Thermally Treated Rice Husks Derived from Agricultural Byproducts. *Eurasian Chemico-Technological Journal*, *15*(1), 57–66. https://doi.org/10.18321/ectj141

[16] Lv, E., Xia, W., Tang, M., & Pu, Y. (2016). Preparation of an Efficient Oil-Spill Adsorbent Based on Wheat Straw. *BioResources*, *12*(1), 296–315. https://doi.org/10.15376/biores.12.1.296-315

[17] Mojžiš, M., Bubeníková, T., Zachar, M., Kačíková, D., & Štefková, J. (2019a). Comparison of natural and synthetic sorbents' efficiency at oil spill removal. *BioResources*, *14*(4), 8738–8752. https://doi.org/10.15376/biores.14.4.8738-8752

[18] Mojžiš, M., Bubeníková, T., Zachar, M., Kačíková, D., & Štefková, J. (2019b). Comparison of natural and synthetic sorbents' efficiency at oil spill removal. *BioResources*, *14*(4), 8738–8752.

[19] Nwadiogbu, J. O., Ajiwe, V. I. E., & Okoye, P. A. C. (2016). Removal of crude oil from aqueous medium by sorption on hydrophobic corncobs: Equilibrium and kinetic studies. *Journal of Taibah University for Science*, *10*(1), 56–63. https://doi.org/10.1016/j.jtusci.2015.03.014

[20] Pandey, S., & Alam, A. (2019a). Peat moss: A hyper-sorbent for oil spill cleanup - a review. *Plant Science Today*, *6*(4), 416–419. https://doi.org/10.14719/pst.2019.6.4.586

[21] Pandey, S., & Alam, A. (2019b). Peat moss: A hyper-sorbent for oil spill cleanup - a review. *Plant Science Today*, *6*(4), 416–419. https://doi.org/10.14719/pst.2019.6.4.586

[22] Porshnov, D., & Klavins, M. (2017). Sorption of Hydrocarbons on Peat, and Possibilities for Using Peat-Based Oil Sorbent for Treatment of Polluted Areas. *Linnaeus Eco-Tech*, 1032–1045. https://doi.org/10.15626/Eco-Tech.2010.109

[23] Razavi, Z., Mirghaffari, N., & Rezaei, B. (2014). Adsorption of crude and engine oils from water using raw rice husk. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, *69*(5), 947–952. https://doi.org/10.2166/wst.2013.804

[24] Ren, J., Yang, X., Wang, Y., Zhang, S., & Zhou, J. (2025). Sustainable hydrophobic bio-based adsorbent from modified sphagnum moss for efficient oil-water separation. *Scientific Reports*, *15*(1), 11792. https://doi.org/10.1038/s41598-025-96059-7

[25] Somasundaran, P. (Ed.). (2014). *Encyclopedia of Surface and Colloid Science, 2004 Update Supplement* (0 ed.). CRC Press. https://doi.org/10.1201/9781482299625

[26] Srinivasan, A., & Viraraghavan, T. (2008a). Removal of oil by walnut shell media. *Bioresource Technology*, *99*(17), 8217–8220. https://doi.org/10.1016/j.biortech.2008.03.072

[27] Srinivasan, A., & Viraraghavan, T. (2008b). Removal of oil by walnut shell media. *Bioresource Technology*, *99*(17), 8217–8220. https://doi.org/10.1016/j.biortech.2008.03.072

[28] Teli, M. D., & Valia, S. P. (2013). Acetylation of Jute fiber to improve oil absorbency. *Fibers and Polymers*, *14*(6), 915–919. https://doi.org/10.1007/s12221-013-0915-8

[29] Wolok, E., Barafi, J., Joshi, N., Girimonte, R., & Chakraborty, S. (2020). Study of bio-materials for removal of the oil spill. *Arabian Journal of Geosciences*, *13*(23), 1244. https://doi.org/10.1007/s12517-020-06244-3

[30] Zamparas, M., Tzivras, D., Dracopoulos, V., & Ioannides, T. (2020a). Application of Sorbents for Oil Spill Cleanup Focusing on Natural-Based Modified Materials: A Review. *Molecules*, *25*(19), 4522. https://doi.org/10.3390/molecules25194522

[31] Zamparas, M., Tzivras, D., Dracopoulos, V., & Ioannides, T. (2020b). Application of Sorbents for Oil Spill Cleanup Focusing on Natural-Based Modified Materials: A Review. *Molecules*, *25*(19), 4522. https://doi.org/10.3390/molecules25194522