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Optimization of a bio adsorbent-integrated multiple barrier technique for palm oil mill effluent treatment

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Abstract: Palm oil mill effluent (POME) is a highly polluting wastewater generated in large volumes in agrarian regions, posing serious environmental and public health concerns if discharged untreated. This study investigates the effectiveness of a bio adsorbent-integrated multiple barrier technique (MBT) for the treatment and quality improvement of POME. The treatment system consisted of sequential physical (sieving and sedimentation), chemical (coagulation and flocculation), and adsorption processes, followed by disinfection. A modified cellulosic bio adsorbent derived from orange mesocarp was incorporated into the adsorption stage to enhance contaminant removal. Operational parameters for each treatment stage were optimized to achieve maximum efficiency. Optimum conditions were obtained at 53 µm sieve size, 3 hours sedimentation time, 5 mg/l alum and 5 mg/l lime for coagulation–flocculation, 0.3 g adsorbent dosage with 20 minutes contact time, and 1.0 mg/l calcium hypochlorite for disinfection. The integrated treatment system achieved substantial reductions in key pollution indicators, including total solids (96.19%), suspended solids (97.57%), dissolved solids (91.19%), biochemical oxygen demand (77.18%), and chemical oxygen demand (60.98%). Significant reductions in microbial load were also observed, alongside improvements in dissolved oxygen and pH towards acceptable limits. The results demonstrate that the synergistic combination of multiple treatment processes with a low-cost, eco-friendly bio adsorbent significantly enhances POME remediation efficiency. This approach offers a sustainable and practical solution for wastewater management and potential reuse in resource-limited settings. Further studies on adsorbent characterization, economic feasibility, and large-scale application are recommended.

Keywords: Palm oil mill effluent (POME), multiple barrier technique (MBT), bio adsorbent, wastewater treatment, sustainable remediation.

1. INTRODUCTION

Water scarcity has emerged as a pressing global concern, driven by increasing demand and limited accessible freshwater resources. Although freshwater constitutes only a small fraction of the Earth's

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total water reserves, its demand for domestic, agricultural, and industrial applications continues to rise. Consequently, the treatment and reuse of wastewater have become essential strategies for sustainable water resource management [1].

This challenge necessitates the exploration of sustainable alternatives such as wastewater treatment and reuse. From about 3% of water resources that compose the freshwater, only one-third are suitable for various industrial, agricultural and domestic purposes [2]. In addition, rapid population growth, industrial sector development and other environmental factors have made global water demand increasingly higher than the available water resource. As stated by the United Nations Development Programme's report, global water usage during 20th century has grown six times and from other literature, the tendency that two-third of the world's population could currently be faced with water stress was predicted [3]. This calls for consideration of alternate and sustainable sources of water. Among these sources is wastewater treatment and recycling. Wastewater composed of water generated from various domestic, agricultural, commercial and industrial activities. In 2020, wastewater global generation was estimated to be 359 billion cubic metres (m^3) with the projection to become 470 billion m^3 in 2030 and 574 billion m^3 in 2050 [4].

An important wastewater commonly released in agrarian community at high volume is palm oil mill effluent (POME). Palm oil mill effluent is a highly concentrated wastewater characterized by its dark coloration and high organic content, resulting from the presence of compounds such as lignin, tannins, oils, and suspended solids. The presence of compounds such as lignin, tannins, oils, and grease contributes to its high pollution potential [5, 6]. POME consist of carotene (8 mg/L), pectin (3400 mg/L), phenolic compounds (5800 mg/L), lignin (4700 mg/L) and tannin. It is made mostly of water with 0.7% oils and 4% suspended particles [7]. Its components also include high organic acid content, minerals, carbohydrate, and proteins that make it a suitable nutrient for microbial growth. Therefore, its disposal without treatment has a detrimental effect on the environment and human life [7, 8].

Conventional methods for treating wastewater include evaporation, sieving, filtration, sedimentation, screening, chemical precipitation, coagulation, oxidation and reduction, electrodeposition, ion exchange filtration, membrane technology, adsorption and biological treatment [7, 9, 10]. However, the complex composition and high pollutant load of POME often limit the effectiveness of single-treatment techniques. In many cases, individual processes are unable to achieve the required discharge standards due to the recalcitrant nature of certain contaminants [11]. This calls for the application of more than one or two treatment methods known as multiple barrier technique (MBT). In the multiple barrier technique, there is synergy in the operation of the treatment methods, called barriers and the weakness of one method is covered by the other methods.

Previous studies have demonstrated improved pollutant removal when combinations of physical, chemical, and biological processes are employed [12] and application of several methods in treating POME have been established in literatures. Ng et al. (2022) used Membrane Bioreactor (MBR) technology, where membrane filtration method was employed [13]. By integrating MBR with flotation treatment a better performance was achieved with reduction in Chemical Oxygen Demand (COD), Total Suspended Solids (TSS), turbidity, oil/grease content, Mixed Liquor Suspended Solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) [13]. Sajjad et al. (2018) in their work employed biofilm integrated with membrane filtration and produced recyclable and reusable water with COD, turbidity, MLSS, TSS and ammoniacal nitrogen removal above 97.5% [14]. In another study by Irenosen et al. (2014) both the physical, chemical and biological methods were integrated for POME treatment [15]. This technique resulted in better decontamination overcoming the drawbacks of single treatment methods. Despite the growing interest in integrated treatment systems, there remains a gap in the incorporation of modified bio adsorbents into multiple barrier frameworks for POME treatment. Specifically, the use of orange mesocarp-derived cellulosic materials within a structured multi-stage treatment system has not been extensively investigated.

In this study, six different wastewater treatment processes were arranged in succession for POME treatment. These included sieving, sedimentation, coagulation, flocculation, adsorption-using bio adsorbent from orange mesocarp and disinfection. The focus of this research is to examine the optimum conditions at which each of the six methods composing the multiple barrier technique will operate most effectively and thereafter employ these optimum conditions for the clarification of palm oil mill effluent.

2. Materials and methods

2.1. Palm oil mill effluent collection

The effluent sample was collected from a local palm oil mill in Ogwa, Edo State, Nigeria by grab sampling method in clean plastic kegs. At the laboratory, it was analyzed before and after each treatment method.

2.2. Physicochemical and microbial analysis of the raw and treated effluent

All samples were analyzed as described in the standard methods for the examination of water and wastewater. The methods for the physicochemical parameters were as contained in [16] and [17]. The microbial parameters were determined according to [18].

2.3. Methodology

The treatment of palm oil mill effluent (POME) in this study was based on a multiple barrier technique (MBT) involving six sequential unit operations. These included primary treatment (sieving and sedimentation), secondary treatment (coagulation and flocculation), and tertiary treatment (adsorption and disinfection). Each stage was optimized individually prior to integration into the full treatment system. Figure 1 below captures the serial arrangement of the treatment procedure leading to an assemblage of six different unit processes from sieving to disinfection.

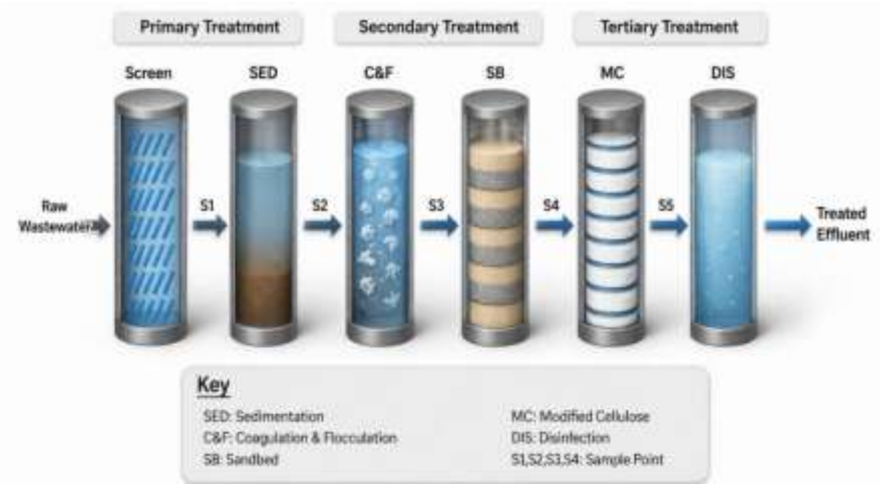


Figure 1: Multiple Barrier Technique Setup

2.4. Process Optimization

Primary treatment

It comprises of sieving and sedimentation. The sample was sieved using three different standard sieves of sizes (53, 150 and 250micron), after physicochemical parameters of the raw effluent sample have been determined. TS, SS, DS, and pH for each sieve were determined using the filtrates obtained. Sedimentation was then carried out using the sieve with optimum result obtained during sieving. The sieved sample was poured into six one-litre sized flask and the flasks left to settle for 1hr, 2hrs, 3hrs, 6hrs, 12hrs and 24hrs respectively. After which, the TS, DS, SS, and pH respectively was analyzed for the supernatant in each of the flask which had been carefully separated.

Secondary treatment

It comprises of coagulation treatment using potash alum and flocculation with lime. 1.837g of hydrated alum was dissolved in 1000ml distilled water for the preparation of stock solution of 1g/L. About 10L supernatant (using optimum time interval) from each of the effluent samples was collected and 1000ml of each was put in seven flat bottom flasks containing varied concentration of potash alum solution. The mixtures were stirred for five minutes and allowed to settle for another fifteen minutes. The resulting supernatant was filtered and pH, TS, SS, DS and COD determined respectively using the filtrate obtained.

Then, effluent gotten after coagulation was treated at different lime concentrations using a stock solution of calcium oxide (lime) prepared by dissolving 0.5g lime in 500ml distilled water. The mixtures were stirred for five minutes and left to settle for fifteen minutes. Sand filtration bed was employed in filtering the resulting supernatant and pH, TS, SS, DS and COD determined respectively using the filtrate obtained.

Tertiary treatment

Adsorption studies and flocculation were carried out in this stage. Batch adsorption experiments were done using mechanical agitation at room temperature. Acrylamide grafted copolymer of orange mesocarp (AGCOM) which was obtained from previous work [19] was used as the adsorbent. The adsorbent was mixed with 100ml of the secondary palm oil mill effluent (POME) for each round. Different amount of AGCOM were agitated at the optimum condition of time (30mins) on the effluents ranging from 0.1 to 0.5g (0.1, 0.2, 0.3, 0.4, 0.5) to determine the optimum amount of adsorbent. Meanwhile for optimum adsorption time determination, 0.2g of each adsorbent (AGCOM) was agitated with100ml of the effluent for a given time (10, 20, 30, 40, 50 and 60mins). A stock solution of 0.5g/L of calcium hypochlorite was prepared by dissolving 0.5g of $Ca(OCl)_2$ in 1000ml distilled water for the disinfection of the effluent. Disinfection was done at different concentration of the calcium hypochlorite from the filtrate gotten from adsorption treatment.

3. Results and discussion

3.1. Physicochemical and microbial properties of raw POME

Table 1: Analysis of the physicochemical and microbial parameters of raw Palm oil mill effluent (POME) against 0Federal Ministry of Environment (FME) standard

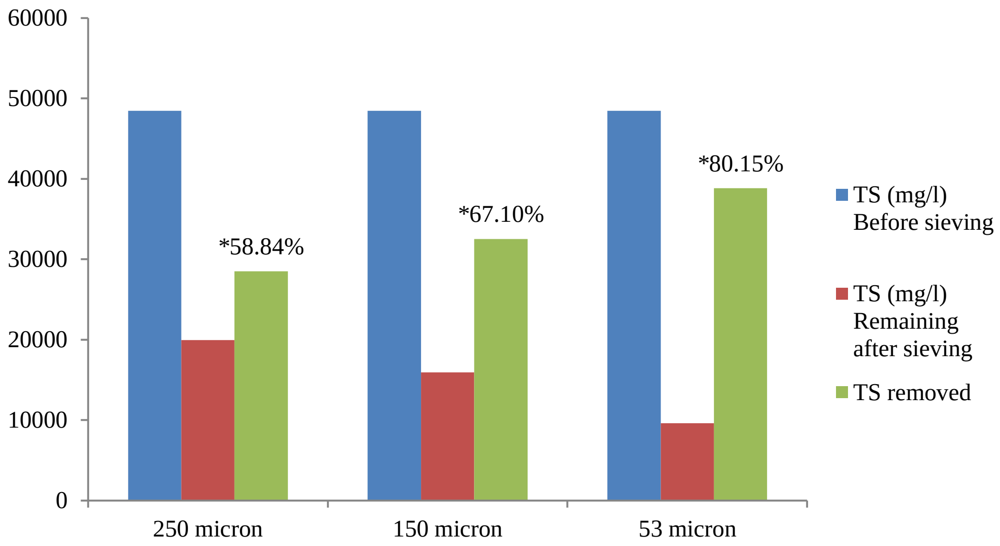
Parameters	Mean	FME limit	WHO Guideline / Target
Total Solid (TS) (mg/l)	48460	2000	-
Dissolved Solid (DS) (mg/l)	10466	2000	~1,500 mg/L
Suspended Solid (SS) (mg/l)	37994	30	-
Potential Hydrogen (pH)	3.32	6-9	6.5 – 9.5
Dissolved Oxygen (DO) (mg/l)	0.08	-	> 2 mg/L
Biochemical Oxygen Demand (BOD_5) (mg/l)	563.54	30	< 30 mg/L
Chemical Oxygen Demand (COD) (mg/l)	4100	50	< 55 mg/L
Nitrate (mg/l)	21.46	20	-
Phosphate (mg/l)	254.75	5.0	≤ 30 mg/L
Total Bacteria Count (10^4cfu/ml)	8.56	-	-
Total Fungi Count (10^4cfu/ml)	3.85	-	-

The physicochemical and microbial properties of the raw effluent before any of the treatment procedure captured in the data presented in Table 1 show that the effluent poses a great threat to the environment if discharged without any treatment as the solids, Total Solid with 48460 mg/l (comprising the Dissolved Solid and Suspended Solid), the effluent organic matter oxygen demand expressed by the Biochemical Oxygen Demand with 563.5 mg/l and Chemical Oxygen Demand with 4100 mg/l, and the nutrients available in the wastewater as revealed by the nitrate and phosphate with 21.46 mg/l and 254.75 mg/l respectively were all above the Federal Ministry of Environment (FME) standards and World Health Organization (WHO) . The pH of 3.32 shows that the effluent is acidic which may be due to partial decomposition of organic matter present during the palm oil extraction process [15] and does not meet the expectation of effluent near neutral or slightly basic as revealed in the standards. The pH value for the raw effluent is close to the pH range of 4.1 to 4.8 [20, 21]. The wastewater is equally loaded with microorganism.

3.2. Optimization of multiple barrier technique

The multiple barriers used in the effluent treatment were of six different treatment methods. There is the need to obtain first the optimization of each method as this enables getting the best results for the treatment methods. The results of the optimization process for each of the treatment procedure from sieving to disinfection are shown in Tables and Figures below.

Sieving process optimization

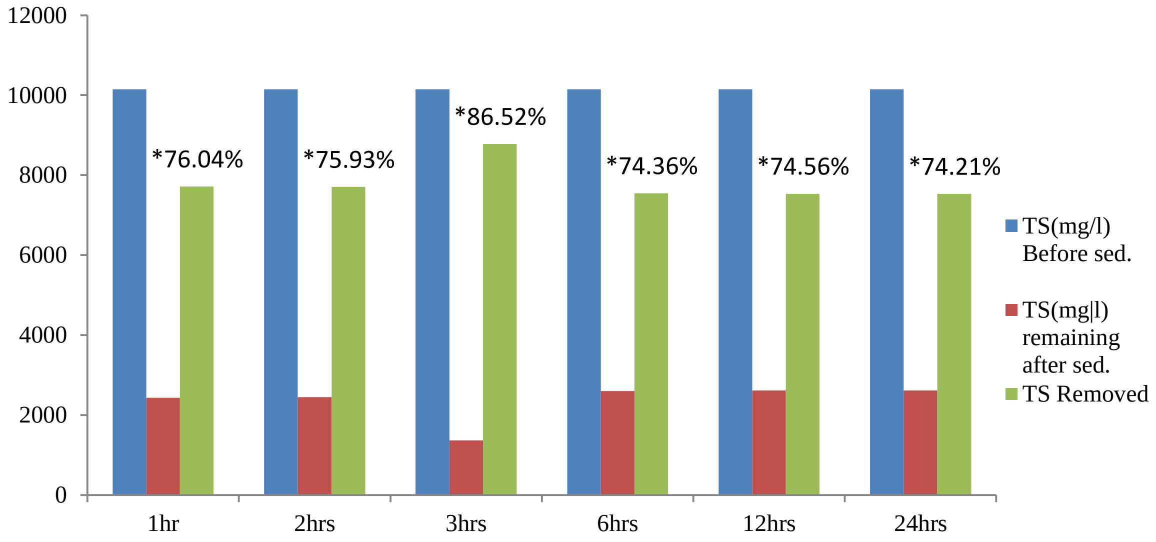


Note: * signify TS percentage removal

Figure 2: Total solid (TS) after sieving with standard sieves of different mesh sizes

Sieving was the first barrier utilized. It is one of the physical methods for wastewater treatment, which employs the principle of size exclusion for the removal of coarse particle like rags, leaves, sticks and other floatable objects [22]. In this study three different standard sieves with mesh sizes 250, 150 and 53microns were used. From Figure 2, it was observed that the 53 micron sieve had the highest total solid (TS) removal of 38841 mg/l giving a % TS removal of 80.15 while 150 micron and 250 micron had TS removal of 32517 mg/l and 28514 mg/l constituting %TS removal of 67.10 and 58.84 respectively. Finer meshes enhance the retention of suspended particulates as indicated by the observed increase in % TS removal with decreasing sieve size. The highest removal efficiency was exhibited by the 53-µm sieve, confirming its suitability for subsequent treatment stages.

Sedimentation process optimization



Note: * signify TS percentage removal

Figure 3: Total solid (TS) parameters with different sedimentation time

Sedimentation which is also a physical and primary treatment process and which utilizes principle of gravity separation of solid from suspension [23] was the second barrier used. Figure 3 shows the results of the optimization process using sedimentation at various time conditions with 53 micron sieve. The detention time (1, 2, 3, 6, 12, 24 hrs) was related with the TS of the effluent. TS removed varied significantly and % TS removed was seen to be highest at 3hrs (86.52) making it the optimum for sedimentation. This result is comparable to 1.5hrs detention time from the study of [24]. The rate of sedimentation is related to the type of suspension, particle settling velocity and detention time.

Coagulation process optimization

Table 2: Physicochemical parameters of different alum concentration for POME coagulation

Alum Conc. (mg/l)	pH	TS (mg/l) rem. after coag.	TS (mg/l) removal	%TS Removal	TS removal /mg Alum
5	6.16	3506	6640	65.44	1328.0
10	5.70	3360	6786	66.92	678.6
15	5.35	4360	5786	57.03	385.7
20	4.89	4280	5866	57.82	293.3
25	4.54	5940	4206	41.45	168.24
30	5.27	3180	6966	68.59	232.2
35	5.04	7600	2546	25.09	72.74

Coagulation which is the third barrier is a chemical treatment process which utilizes the use of coagulants, with their charges effecting a characteristic property of destabilizing stabilized contaminants in suspension, colloidal or dissolved state that has evaded removal during the primary treatment [25]. Coagulation process is important in the treatment of Palm mill oil effluent because most of the organic matter in this effluent occur in the form of dissolved or colloidal suspension which are difficult to be removed by simple or natural decantation method [21]. The results of the optimization process using coagulation at different concentration of alum are captured in Table 2. As the concentration of Alum increases from 5mg/l to 35 mg/l, the percentage Total Solid removal increased from 65.44 % (5mg/l) to 66.92% (10mg/l) after which a decrease to 41.45% (25mg/l) was noticed. However an optimum value of TS removal of 1328 TS/mg was obtained at 5mg/l Alum.

Flocculation process optimization

Table 3: **Physicochemical parameters of different lime concentration for POME flocculation**

Al^{3+}(mg/l)	CaO (mg/l)	pH	TS (mg/l) rem. after floc.	%TS Removal	TS removal /mg CaO
5	5	3.90	8160	21.1	4.22
5	10	3.92	7940	23.21	2.32
5	15	3.95	7920	23.40	1.56
5	20	3.96	7926	23.35	1.17
5	25	3.84	8113	21.54	0.86
5	30	3.79	8113	21.54	0.72
5	35	3.78	7920	23.40	0.67

Flocculation was the fourth barrier. Just like coagulation, flocculation is a chemical treatment used with the aim of precipitating stabilized suspended particles in the wastewater. The process initiated with the coagulant is enhanced by increasing the floc formation and aggregation using flocculants. From literature slaked lime has been used to serve as floc conditioner, alkalinity adjuster and water softener when mixed with iron (III) chloride or alum during wastewater treatment [16, 26]. In this study at 5mg/l Alum, the concentration of lime was varied from 5 mg/l to 35 mg/l. As shown in Table 3, the %TS removal increased from 21.10 (at 5 mg/l) to 23.40 (at 15 mg/l) and decreased to 21.54 (at both 25 and 30 mg/l) but increased to 23.40 (at 35 mg/l). However, TS removal per unit Alum concentration gave an optimum value of 4.22 at 5mg/l calcium oxide.

Adsorption process optimization

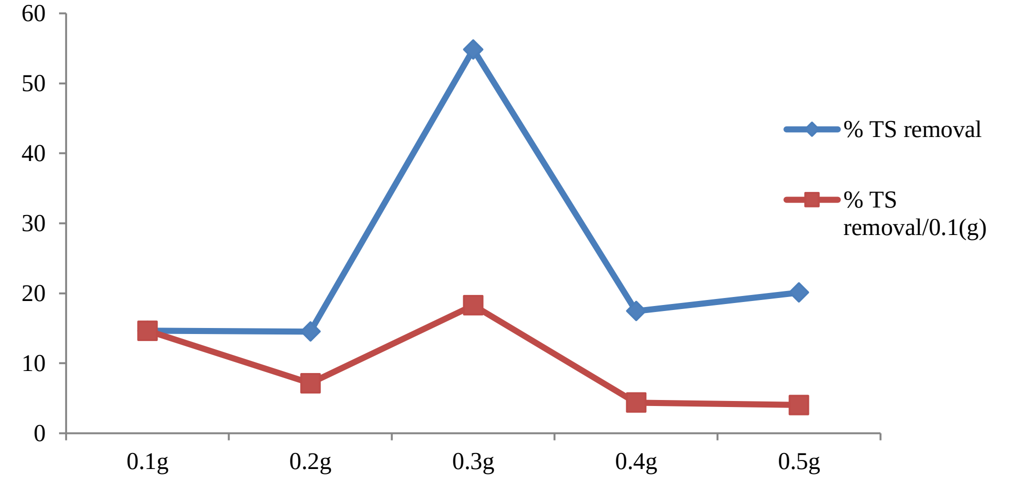


Fig. 4: Total solid (TS) percentage removal at different adsorbent dosage

The fifth barrier was adsorption. Adsorption involves the accumulation of substances at the interface of a solid material, where pollutants adhere to the surface of an adsorbent through physical or chemical interactions. This method is widely used for wastewater treatment due to its low cost, simple design and having specific affinity [10]. In this study, the pH and TS were used as the physicochemical parameter to ascertain the effectiveness of orange mesocarp used as the adsorbent. Figure 4 shows the variations at different adsorbent dosage (0.1 to 0.5g). The percentage total solid removal decreased from 14.65 for 0.1g to 14.53 for 0.2g. The value increased to 54.85 with 0.3g and decreased to 17.46g with 0.4g while increasing to 20.11 for 0.5g adsorbent. The percentage total solid removal per gram of adsorbent was seen to be optimum at 0.3g of the adsorbent.

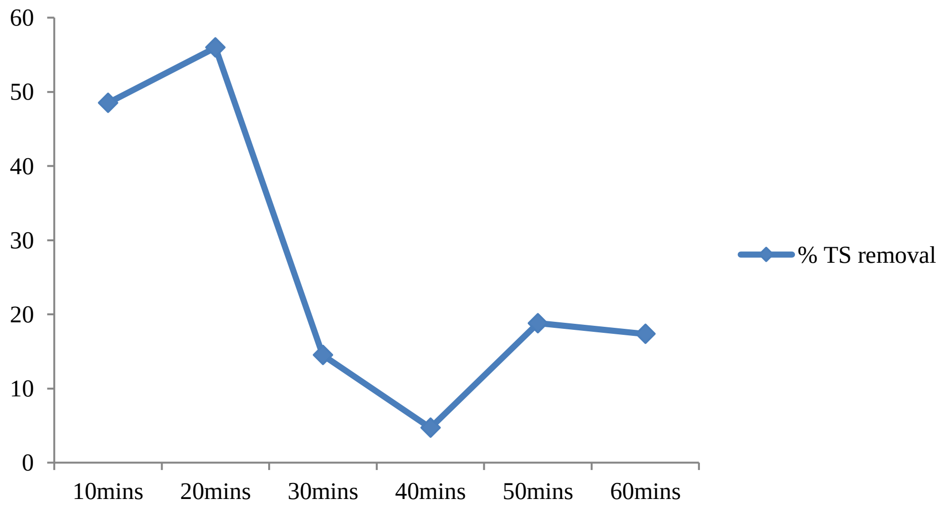


Fig. 5: Total solid (TS) percentage removal at different sorption time

Figure 5 captures the adsorption results at different time interval, from 10 to 60 minutes. The percentage total solid removal shows an increase from 48.51% at 10 mins to 55.98% at 20 mins while a decrease to 14.53% and 4.72% at 30 mins and 40 mins respectively. Thereafter, an increase to 18.82% was noticed at 50mins and a decrease to 17.38% at 60 mins. For all the time intervals applied, adsorption at 20 minutes gave the optimum result.

Disinfection process optimization

Table 4: Total Bacteria Count (TBC) and pH after POME disinfection

$Ca(OCl)_2$ Conc. (mg/l)	pH	TBC (10^4cfu/ml)
0.5	5.95	6.8
1.0	5.93	1.1
1.5	5.96	1.7
2.0	5.90	6.2
2.5	5.87	7.4
3.0	5.92	6.8
3.5	5.97	6.8

Disinfection was the sixth and last barrier employed in the MBT setup. Disinfection is a wastewater treatment process intended to kill all harmful organisms present in the wastewater. Studies have revealed that substantial amount of harmful organisms is removed during coagulation and flocculation processes [16]. However, a sizeable amount is still present in the processed effluent and must be removed by disinfection. Table 4 captures the results of the optimization of the effluent disinfection using calcium hypochlorite. The variation of calcium hypochlorite concentration from 0.5 mg/l to 3.5mg/l gave TBC from 6.8 (0.5mg/l), 1.1(1.0mg/l), 1.7(1.5mg/l), 6.2(2.0mg/l), 7.4(2.5mg/l) to 6.8(3.0 and 3.5mg/l). The lowest total bacteria count and the optimum value was found to be at 1.0mg/l of calcium hypochlorite.

3.3. Optimum condition for each method in the MBT

Table 5: Optimum conditions for the treatment of POME using MBT

Conditions	Optimum values
Sieve mesh size (micron)	53
Sedimentation Time (hrs.)	3.0
Al^{3+} Conc. (mg/l)	5.0

CaO Conc. (mg/l)	5.0
Amount of adsorbent (g)	0.3
Contact time with adsorbent (mins)	20
Amount of disinfectant (mg/l)	1.0

The optimization of the six methods composing the multiple barrier technique used in this study gave optimum values captured in Table 5 above. For sieving 53-micron sieve and for sedimentation time, 3 hours were the optimum values. For coagulation and flocculation, 5.0 mg/l was found to be optimum. In adsorption, 0.3 g adsorbent weight and 20 minutes contact time was found to be optimum. While in the disinfection process, 1.0 mg/l calcium hypochlorite gave the optimum value.

3.4. Comparative study of the parameters of the raw and treated effluent

Table 6: Physicochemical and microbial parameters of the raw and MBT treated POME

Parameter	Raw POME	Treated POME	% Removal
TS(mg/l)	48460	1845.77	96.19
DS(mg/l)	10466	922.00	91.19
SS(mg/l)	37994	923.77	97.57
pH	3.32	6.65	Δ pH = + 3.33
DO(mg/l)	0.08	0.91	Δ DO = +0.83
BOD_5(mg/l)	563.54	128.61	77.18
COD (mg/l)	4100	1600	60.98
Phosphate(mg/l)	21.46	11.79	45.06
Nitrate(mg/l)	254.75	132.68	47.92
TBC(x10^4cfu/ml)	8.56	3.15	63.20
TFC(x10^4 cfu/ml)	3.85	1.42	63.12

***= % increase; + =adjusted TBC=Total bacteria count; TFC=Total fungal count**

Table 6 shows the results of the treatment of POME using multiple barrier technique. The comparison of the physicochemical and microbial properties of the raw effluent with the treated effluent shows a good clarification of the effluent. The percentage removal of the solids; TS, DS and SS are 96.19%, 91.19% and 97.57% respectively. The TS reduction is comparable with 91.7% gotten in the work of [15] while integrating physical, chemical and biological approaches for POME decontamination.

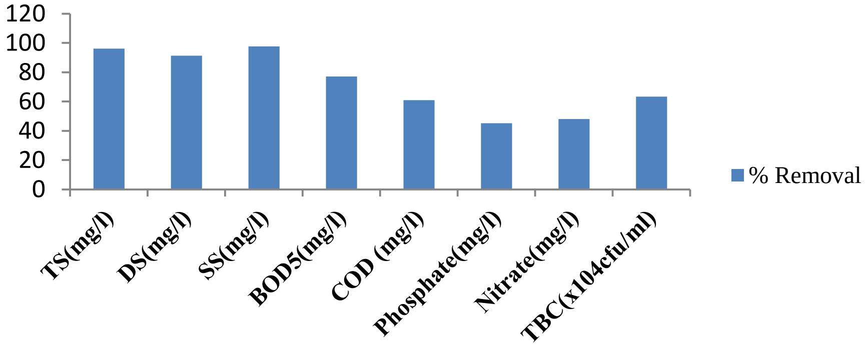


Figure 6: Percentage removal of the physicochemical and microbial parameters of the raw and MBT treated POME

The DO of the effluent improved from 0.08 to 0.91 with a change of 0.83. The Oxygen Demands; BOD and COD have percentage removal of 77.18% and 60.98% respectively. The COD value of this work could be compared with 69.72% COD gotten by [20] while using a combination of treatment methods including sedimentation, bio filtration, aeration and sand filtration. The phosphate and nitrate have a percentage removal of 45.06% and 47.92% respectively. Also the microbial loads represented by TBC and TFC have significant percentage reduction of 63.20% and 63.12% respectively. In the overall analysis, the treatment employed show high level of effectiveness as revealed in the properties of the treated effluent.

4. Conclusion

This study demonstrated the effectiveness of a bio adsorbent-integrated multiple barrier technique (MBT) for the treatment of palm oil mill effluent. The sequential application of physical (sieving and sedimentation), chemical (coagulation and flocculation), and adsorption processes, followed by disinfection, resulted in significant improvement in the physicochemical and microbial quality of the effluent. The optimization of operational parameters for each treatment stage played a critical role in achieving high removal efficiencies. The integrated system successfully reduced total solids, suspended solids, dissolved solids, biochemical oxygen demand, chemical oxygen demand, and microbial load to levels approaching or meeting recommended standards. The observed increase in dissolved oxygen and adjustment of pH towards neutrality further confirm the effectiveness of the treatment process.

The incorporation of a low-cost, environmentally friendly bio adsorbent derived from agricultural waste (orange mesocarp) enhances the sustainability and economic feasibility of the treatment system. This highlights the potential of combining conventional treatment methods with green materials for efficient wastewater remediation. However, for broader application and scale-up, further studies are recommended to include detailed adsorbent characterization, cost analysis, and evaluation of additional pollutants such as heavy metals and oil residues. Future research should also incorporate statistical validation and pilot-scale studies to assess real-world applicability. However, bio adsorbent-integrated multiple barrier technique presents a promising, efficient, and sustainable approach for the treatment and potential reuse of palm oil mill effluent.

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Onigbinde, M.O. together with Osuide, M.O. conceived and designed the research idea. Onigbinde, M.O. and Ogunbiyi, A. conducted the experiments and collected crucial data. Onigbinde, M.O. and

Osuide, M.O. interpreted and evaluated the results. Onigbinde, M.O. and Isola,O.B. wrote the paper. And the work was submitted with the consent of Osuide, M.O., Isola, O.B. and Ogunbiyi, A.

References

[1] United Nations World Water Assessment Programme. (2017). The United Nations world water development report. UNESCO.

[2] Ivbanikaro, A. E., Okonkwo, J. O., Sadiku, E. R., & Maepa, C. E. (2023). Recent development in the formation and surface modification of cellulose-bead nanocomposites as adsorbents for water purification: A comprehensive review. *J. Polym. Eng*., 43(8), 680–714. https://doi.org/10.1515/polyeng-2023-0056

[3] Fatoye, E. O., & Onigbinde, M. O. (2020). Dye adsorption with sugarcane bagasse and corn cob. *SAU Sci.-Tech. J*., 5(1), 182–193.

[4] Awogbemi, O., & Kallon, D. V. V. (2023). Progress in agricultural waste derived biochar as adsorbents for wastewater treatment. *Appl. Surf. Adv.*, 18, Article 100518. https://doi.org/10.1016/j.apsadv.2023.100518

[5] Ahmad, A. L., Ismail, S., & Bhatia, S. (2003). Water recycling from palm oil mill effluent (POME) using membrane technology. *Desalination*, 157(1–3), 87–95.

[6] Wu, T. Y., Mohammad, A. W., Jahim, J. M., & Anuar, N. (2010). Pollution control technologies for the treatment of palm oil mill effluent. *J. Environ. Manage*., 91(7), 1467–1490.

[7] Khan, I. U., Rahman, M. A., Othman, M. H. D., Iftikhar, M., Jilani, A., Mehmood, S., Shakoor, M. B., Rizwan, M., & Yong, J. W. H. (2025). Innovative solutions for palm oil mill effluent treatment: A membrane technology perspective. *ACS EST Water*, 5, 3538–3562. https://doi.org/10.1021/acsestwater/4c00432

[8] Akhbari, A., Kutty, P. K., Chuen, O. C., & Ibrahim, S. (2020). A study of palm oil mill processing and environmental assessment of palm oil mill effluent treatment. *Environ. Eng. Res*., 25(2), 212–221. https://doi.org/10.4491/eer.2018.452

[9] Naser, H., Czinkota, I., Dorkota, A., & Horvath, M. (2023). A review of advancements of potential toxic element adsorption by various cellulose-based materials and the used adsorbents' fate. *Prog. Agric. Eng. Sci*., 19(1), 1–13. https://doi.org/10.1556/446.2023.00068

[10] Onigbinde, M. O., & Okeke, S. R. (2021). Heavy metals adsorption on cellulosic materials from agricultural waste. *J. Appl. Sci. Environ. Manage*., 25(5), 783–786. https://doi.org/10.4314/jasem.v25i5.14

[11] World Health Organization. (2022). Guidelines for drinking-water quality (4th ed.). WHO.

[12] Crittenden, J. C., Trussell, R. R., Hand, D. W., Howe, K. J., & Tchobanoglous, G. (2012). MWH's water treatment: Principles and design (3rd ed.). John Wiley & Sons. https://doi.org/10.1002/9781118131473

[13] Ng, L. Y., Ng, E. C., Ng, C. Y., Hasyimah, I. N., & Said, M. (2022). Performance of membrane bioreactor in palm oil mill effluent treatment: An overview. *J. Appl. Membr. Sci. Technol*., 26(2), 11–16. https://doi.org/10.11113/amst.v26n2.232

[14] Sajjad, A. A., Yeit, H. T., & Hussain, A. W. M. (2018). Sustainable approach of recycling palm oil mill effluent (POME) using integrated biofilm/membrane filtration system for internal plant usage. *J. Teknol*., 80(4), 165–172.

[15] Irenosen, O. G., Oluyemi, A. S., Korede, A. O., & Samuel, A. S. (2014). Integration of physical, chemical and biological methods for the treatment of palm oil mill effluent. *Sci. J. Anal. Chem*., 2(2), 7–10. https://doi.org/10.11648/j.sjac.20140202.11

[16] Ademoroti, C. M. A. (1996). Standard methods for water and effluents analysis. Foludex Press Ltd.

[17] APHA. (2017). Standard methods for the examination of water and wastewater (23rd ed.). American Public Health Association.

[18] Cheesbrough, M. (2006). District laboratory practice in tropical countries. Cambridge University Press.

[19] Onigbinde, M.O., & Osuide, M.O. (2024). Green adsorbent synthesis from orange mesocarp cellulose using graft copolymerization. *Nig. J. of Sci. & Environ.*, 22 (1) 17 – 31. Https://doi.org/10.61448/njse221242

[20] Lawal, N. S., Ogedengbe, K., & Oamen, E. C. (2019). Cassava mill wastewater treatment by a combination of physical and natural-based processes: A pilot study. *Appl. J. Environ. Eng. Sci*., 5(4), 349–356. https://doi.org/10.15243/jdmlm.2019.063.1737

[21] Trevisan, A. P., Lied, E. B., Fronza, F. L., Devens, K. U., & Gomes, S. D. (2019). Cassava wastewater treatment by coagulation/flocculation using Moringa oleifera seeds. *Chem. Eng. Trans*., 74, 367–372. https://doi.org/10.3303/CET1974062

[22] Ward, B. J., Nguyen, M. T., Sam, S. B., Korir, N., Niwagaba, C. B., Morgenroth, E., & Strande, L. (2023). Particle size as a driver of dewatering performance and its relationship to stabilization in fecal sludge. *J. Environ. Manage*., 326, 116801. https://doi.org/10.1016/j.jenvman.2022.116801

[23] De, A. K. (2017). Sedimentation process. In Environmental chemistry (pp. 115–134). *Springer*. https://doi.org/10.1007/978-81-322-3634-4_4

[24] Bhatia, A. L., Ibrahim, N., Ismail, S., & Ahmad, A. L. (2003). Coagulation–sedimentation–extraction pretreatment methods for the removal of suspended solids and residual oil from palm oil mill effluent (POME). *IIUM Eng. J*., 4(1), 25–33. https://doi.org/10.31436/iiumej.v3i1.351

[25] Sillanpää, M., Ncibi, M. C., Matilainen, A., & Vepsäläinen, M. (2018). Removal of natural organic matter in drinking water treatment by coagulation: A comprehensive review. *Chemosphere*, 190, 54–71. https://doi.org/10.1016/j.chemosphere.2017.09.113

[26] Quintero, J. D., Gómez-García, M. A., & Dobrosz-Gómez, I. (2024). The scope of alum coagulation–flocculation assisted by slaked lime for industrial wastewater treatment. *Renew. Sustain. Energy Rev*. https://doi.org/10.1016/j.rser.2024.114567