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Research Article

Performance Evaluation of Dry Faecal Sludge-Derived Activated Carbon (DFSAC) for Wastewater Pollutant Removal: A Case Study of the Lavender Hill Faecal Treatment Plant

Issahaku Ahmed,[1,2] **Esi Awuah**,[1] **Helen M. K. Essandoh**,[1] **Sampson Oduro-Kwarteng**,[1] **Dennis Ofori-Amanfo**,[1,2] **and Florence Cobbold**[2]

[1]*Department of Civil Engineering, Kwame Nkrumah University of Science & Technology, Kumasi, Ghana*
[2]*Sewerage Systems Ghana Ltd., Accra, Ghana*

Correspondence should be addressed to Issahaku Ahmed; eagleskertoozer@yahoo.co.uk

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This study evaluates the applicability of dry faecal sludge activated carbon (DFSAC) as a wastewater pollutant removal technology by employing both laboratory- and large-scale setups. The setups were monitored using effluent from the Mudor wastewater treatment plant in Accra. The DFSAC was produced from primary sludge obtained from a primary treatment to treat approximately 1000 liters of effluent water per hour to meet the needs of backwashing, cleaning, irrigation, and flushing purposes. The laboratory-scale experiment was monitored for a period of two weeks, while the large-scale experiment was monitored for a period of 16 weeks. Physicochemical, microbial, and metal characteristics were analyzed for the polished effluent. The results obtained from the lab scale showed high removal efficiencies of the wastewater pollutants for the first and second weeks of treatments, respectively, as follows: colour (99.47%, 69.06%), turbidity (99.59%, 42.59%), COD (96.58%, 43.49%), BOD (99.26%, 77.42%), TSS (100%, 62.296%), TDS (92.92, 32.90), ammonia (98.41%, 50.83%), and EC (73.60%, 19.94%). The P value obtained indicated a highly significant difference between the influent and effluents of both weeks. The large-scale application of the DFSAC yielded a percentage reduction of 99.36%, 99.37%, 99.52%, 79.63%, 100%, 48.85%, 90.08%, and 46.72% for colour, turbidity, COD, BOD, TSS, TDS, ammonia, and EC, respectively. The DFSAC showed high removal potential for heavy metals and microbial contaminants over the study period. Pollutant removal in wastewater with DFSAC proved a promising intervention by significantly reducing pollutants in wastewater effluent as a tertiary treatment. The removal efficiencies are indications that physisorption and chemisorption play an important role in the adsorption of pollutants onto the DFSAC. The study has shown that faecal sludge can be used as activated carbon for remediation of wastewater pollutants, especially in treatment facilities, which do not meet EPA effluent discharge guidelines while ensuring a close resource utilization loop.

1. Introduction

Water scarcity has become a major issue in today's world [1–3]. Ironically, large volumes of effluents from wastewater treatment plants (WWTPs) across the country are discharged into receiving water bodies or the surrounding environment because of poor knowledge about recycling treatment technologies and their reuse. Most of these treatment facilities see effluent water as waste from the treatment plant and resort to discharge as the only way. There is little research regarding the reusability potential of treated wastewater effluent in our region of the world, and Ghana is not an exception [2]. Most WWTP managers supervise the use of portable water in wastewater treatment plants for cleaning and other purposes, while effluent water from the treatment plants could be further polished to reduce toxicants as well as pollutants for reuse purposes, serving the same functions.

WWTPs therefore play a crucial role both in the safeguarding of drinking water sources and the production of an

alternative water source, that is, treated wastewater, which, depending on its use, may require an increased level of water treatment [4].

The need for the conservation of water resources in major cities in Africa has been highlighted [5–7]. Development of multifunctional and highly efficient processes that would provide affordable/sustainable, ecofriendly solutions to water/wastewater treatment without relying on large infrastructures or centralized systems is an area of research interest. Regarding the purification and recycling of wastewater, there are several known technologies [8], but most of these come with a lot of startup and operational cost elements. In wastewater treatment, the characteristics of the influent water generally inform the choice of technology [9] to ensure effluent water discharge meets the required regulatory guidelines. Wastewater can be described as water that is not suitable to be used as a result of human influence [7, 8]. This includes waste discharged from commercial properties, home residences, institutions, and industries. This study centers on effluent discharge from wastewater treatment plants. In Ghana, most treatment plant effluent discharges do not meet the required effluent guidelines [9]. With the increasing demand for wastewater treatment plants as a result of population increase and the requisite demand for sanitation improvements, there would be a correspondingly high volume of effluent discharge from these facilities. This will imply that, if alternative methods for recycling are not developed or employed, it has the potential to result in the accumulation of toxicants and pollutants in the environment.

It has therefore become critical and timely to look at supplementary technologies with low-cost options, which deliver excellent results in purifying treatment plant effluents to ensure that resource recovery and utilization are maximized. In the quest to achieve areas of green space, it is essential to ensure a closed resource recovery and utilization loop. Hence, the process of purifying and recycling effluent from WWTP is the need of the present.

The development of economical and stable materials and methods for providing recyclable and fresh water in adequate amounts is the need of the wastewater and water industries. Developing multifunctional and highly efficient processes and providing affordable/sustainable solutions to water/wastewater treatment, which do not rely on large infrastructures or centralized systems remains unfulfilled. The use of activated carbon in wastewater treatment is a widely known and used [4, 7, 10, 11] technology. Activated carbon is one of the most proficient and key adsorbents, which has been examined with excellent accomplishment for the treatment of wastewaters for both small laboratory scales as well as industrial applications [12]. The activated carbon, as it is known over the years, has significant properties, which includes high internal surface area with greatly advanced internal pore structure and the availability of abroad surface functional groups. These features make activated carbon one of the most popular adsorbents [13, 14].

Despite the known great characteristics and uses of activated carbon, they are sometimes limited due to their quite expensive starting raw material and high application cost. Activated carbons have a high potential to become saturated and will require a regeneration step for further application to purify the waste water effluent. A number of techniques, ranging from chemical, electrochemical, oxidation, and thermal [15–18], have been used to regenerate low performing or saturated activated carbons. Research has indicated that regeneration of activated carbon is difficult to achieve without teasing problems. Some of these problems have been attributed to additional operational costs, a decrease in carbon content, and a loss of adsorption capacity in comparison with the parent activated carbon. Researchers have attempted to produce low-cost alternative carbon-based adsorbents from a range of wastes like industrial or agricultural by-products, which may substitute commercial activated carbons in wastewater treatment via adsorption methods [19, 20]. Most of the commercial activated carbons are either coal-based or petroleum pitch-based, which are prone to exhaustion [11] as their applications are immersed. This has resulted in the scarcity of the material in addition to its being expensive. This situation requires the exploration of new sources of carbon materials with desired physical and chemical properties [21]. A lot of research works have previously been done on activated carbon to improve its application. One of the fast-growing areas is in environmental applications such as wastewater treatment, which is used for purification, discoloration, and the removal of toxic organic and heavy metals [11]. Assessment of wastes for the production of low-cost adsorbent has been recommended by research [22], and this particular approach recovers nonrenewable natural resources and allows obtaining value-added products, which may be used in pollution control.

Agricultural wastes and industrial by-products are considered being an essential feedstock for activated carbon preparation since they are renewable sources and low-cost alternative materials. Most research works have been done on the production of activated carbon from agricultural by-products and industrial waste [11, 21, 23–26] since they are renewable sources and are low-cost alternative materials. Several Agricultural feedstock had been used for making activated carbon [27–52], while others had also used sewage sludge in making activated carbon [12, 53]. The production of sewage sludge has increased rapidly and will rise as more municipal wastewater and faecal sludge are treated due to environmental necessity and legal requirements to reach better standards for wastewater treatment along with urbanization and industrial development [9, 51, 54, 55]. Faecal has very complex constituent of biological, organic, and inorganic components as well as water. Research has indicated that the undigested organic components of sludge from faecal sources contain proteins and peptides, lipids, polysaccharides, plant macromolecules, and aliphatic structures [56]. Typically, sewage sludge produced is around 40–60 g dry matter per resident per day for both urban sewage plants and industrial sewage plants, and its generation is expected to reach higher amounts [57–59]. Treatment plants in Ghana generally produce sludge of about 350–900 m^3/day of wet sludge depending on the size of the treatment plant. Considering the large volumes of generated sludge in treatment plants in the present and estimated

situations, and considering the high production amounts, an appropriate handling of sewage sludge is a critical necessity [60, 61].

Sludge from faecal matter contains pollutants and toxicants that are detrimental to the environment and all living organisms. If it is not well treated in a suitable manner, serious pollution problems can occur [62–64]. Several methodologies have been used in handling sludge from faecal matter, either by the utilization of the traditional disposal or through the utilization of reuse and energy applications [62, 65].

Sludge generated from the treatment of wastewater and faecal sludge contains important nutrients that are very vital to plant growth. Some of these essential nutrients include nitrogen and phosphorus, as well as some important trace elements like copper and selenium [64]. The use of sludge generated from wastewater and faecal sludge treatment plants for agricultural purposes is a simpler and ecological alternative. However, the quality of the sludge makes its application, management, appropriate land presence, and tracking practically unfeasible [53, 60, 61, 66]. It is important to highlight that water pollution, odour control, and heavy metals are some of the critical shortcomings for agricultural usage [67, 68].

Research on faecal sludge has identified products that have potential value, including dry sludge as a fuel for combustion, biogas from anaerobic digestion, protein derived from sludge processing used as animal feed, sludge as a component in building materials, and sludge as a soil conditioner [57]. But carbonization (thermal application) is mentioned as an innovative option that allows the utility of sludge from faecal matter for the production of valuable materials. It is also important to note that the heat energy produced in the selection of appropriate thermal solutions must also be put under controlled conditions [69]. Activated carbon from faecal sludge would imply a clear and accurate decision with both a considerable saving in startup material cost, reduction in sludge volume generation in treatment plants, and a plausible pathway of making good use of waste material which is economically valuable [53, 66, 70].

Handling sludge in treatment plants contributes immensely to the total operational cost of these plants. It has been said that about 25%–65% of the total process expense of many treatment plants goes into the handling, treatment, and disposal of sludge generated along the treatment stream. However, the application of sludge generated from treatment plants in the form of activated carbon for the treatment of waste water in the plant itself has the potential to reduce operational costs [60, 66, 71].

Sludge from wastewater and faecal sludge treatment plants has been shown to be a very economically and easily accessible feedstock by many researchers for the production of activated carbon [72]. Recent works in adsorption chemistry for handling toxicants in wastewater had emerged but little is said about that from faecal sludge as base carbon [73–77]. The production of FS activated carbon (biochar) for use in wastewater treatment technologies has not gained much needed attention from researchers, which is what this work seeks to address. The attainment of a circular economy requires a closed-loop utilization of faecal sludge resources, focusing on the whole sanitation value chain, which includes the transformation of FS into sanitation-derived products such as biochar, removing the heckle of sludge treatment and disposal.

The main objective of the study was to evaluate the performance of a novel material; faecal sludge-derived activated carbon for wastewater pollutant removal. The exploration of this objective would provide multifunctional and highly efficient processes that would provide affordable/sustainable solutions to water/wastewater treatment without relying on large infrastructures or centralized systems.

2. Materials and Methods

2.1. Study Area. The study was conducted in two phases. Phase I of the study involves a laboratory-scale setup of the filtration system using dry faecal sludge activated carbon (DFSAC) and phase II involved the large-scale filtration system implementation. Physicochemical, metal, and microbial analyses of effluent samples were conducted at the Lavender Hill laboratory (LH Lab). The dewatered faecal sludge sample used in this work for the carbonization process was obtained from the Lavender Hill faecal treatment plant, which is an urban faecal sludge treatment plant located at James Town in the greater Accra region. The dewatered sludge was obtained right after primary treatment, which involves screening to remove any foreign material load. The polymer is mixed with sewage and dewatered using mechanical dewatering machines (screw press). Effluent water used as feed stock for the filtration system was obtained from the Mudor wastewater treatment plant located in Accra on the same premises as the Lavender Hill faecal treatment plant.

2.2. Materials. The materials used included faecal sludge, barrels, water, sieve, mortar and pestle, storage tanks (polytank), stainless steel pipes and plates, PVC pipes and fittings, pumps, 5-micron filter, and hypochlorite.

2.3. Methods

2.3.1. Preparation of the DFS. Before the carbonization and activation experiments, the dewatered faecal sludge was dried on a sand drying bed with an average moisture content of 62% for a period of three months. The average temperature reading was 32°C while blocking all other variables. Dry faecal sludge (DFS) obtained from the sand drying bed recorded a moisture content of 2% and was resized by breaking them into an average minimum and maximum size range of 3–20 cm (Figure 1(a)).

2.3.2. Carbonization of Dried Faecal Sludge. DFS was loaded in a metal barrel with one side fully opened and the other side perforated (2 mm diameter), Figure 1(b). The perforated side of the barrel was put on three sited stones to raise the base and allow little air for combustion. The top of the barrel was covered with a halved barrel having cut into two cross-

(a) (b) (c)

Figure 1: (a) 3–10 cm of DFS. (b) Carbonization of DFS. (c) Produced biochar.

sectional areas on the top and raised. This was with direct smoke to the top serving as a chimney. DFS sample sizing is critical in the carbonization process, as fine DFS would burn completely and too big DFS would not be able to carbonize wholly. The carbonization of the DFS was done for 30 mins with maximum temperature reading of 400°C, which was measured with 400°C oven thermometer to obtain the biochar (Figure 1(c)). Wet fine sand (approximately 70–80% moisture) was manually used to end the carbonization process to prevent complete burning into ash. The carbonized samples were harvested after air drying and were kept in buckets to further cool to ambient temperature.

2.3.3. Activation Process. The carbonized sample was grounded using a designed metal mortar and pistil (Figure 2(a)). The powdered biochar was sieved using 0.2–2 mm net mesh to obtain a uniform size (Figure 2(b)). Activation of the charred DFS was achieved with water at 100°C and allowed to drain.

2.4. Pilot Scale Implementation. A laboratory-scale filtration system using DFSAC was setup at the Lavender Hill laboratory (Figures 3(a) and 3(b)), which was done using a separator funnel with a plastic stopper (SFT3-1k0-002) and monitored for a period of two weeks (14 days). The separator funnel was filled with DFSAC to an approximate column height of 18 cm with a corresponding weight of 56.13 g. Cotton wool was used at the base to prevent the escape of the DFSAC when filtering. Effluent sample from the Mudor wastewater treatment plant was used as feedstock for the filtration setup. A series of filtrations was done over a two-week period to determine the extent to which the DFSAC could lose efficiency. Tables 1–4 present averages of physicochemical, microbial, and metal concentrations of laboratory-scale filtration system effluent over the period. A total of 42 samples were analyzed, with three grabs sampled each day for a period of 14 days from 3 liters of filtrate each day. A total of 42 liters of Mudor WWTP effluent were filtered using the DFSAC lab setup. This laboratory experimental setup was monitored using the quality of tap water as a reference or control for monitoring the possible fouling of the activated carbon media.

2.5. Design of the Large-Scale DFSAC Filtration System. The implementation of the large-scale filtration system was based on the data obtained from the laboratory-scale setup of the filtration system. Four (4) pieces of 9 m long stainless steel pipes (3 inches) were used as stands (2.8 × 2 m interval) and firmly wielded with three divisions of stainless plates. The structure was erected and firmly concretized at the base to prevent falling. The overhead plate carried two 700 liter polytanks ($D = 1035$ mm, $H = 1083$ mm), which receive influent water delivered by a pump (2 hp, 0.6–7 m^3/hr) from the effluent chamber of the treatment plant. The second division plate carried a 700 liter polytank packed with powdered DFSAC with a weight of about 95.00 kg (866.5 mm depth). A 3 inch PVC pipes were used for the piping system. The base plate carried a 1000 liter capacity polytank to store purified water (Figure 4(a)). The influent water (Figure 4(b)) flows by gravity through the packed powdered DFSAC and recycled water (Figure 4(c)) stored before disinfection. The setup was run for five hours continuously each day, five days in a week, for 16 consecutive weeks. Hourly grab samples were taken to make a single composite sample for each day to be analyzed for the quality parameters. The average polished water (Figure 4(c)) obtained from the setup was measured to be about 1000 liters per hour, which is quite substantial to meet the operational water needs of many wastewater treatment plants.

2.6. Analytical Methods. The method outlined in the standard methods for the examination of water and wastewater [78] was used to analyze both physicochemical and microbial concentrations as well as metal concentrations. For COD and pH, the Lovibond XD 7500 UV-Vis Spectrophotometer and a Hanna multiparameter water proof meter (HI 98195) procedure manuals were followed, respectively. The data were subjected to descriptive statistics and analysis

(a) (b)

Figure 2: (a) Grounding of biochar. (b) Sieved biochar.

(a) (b)

Figure 3: (a) Filtrate from DFSAC lab setup. (b) Mudor WWTP effluent.

Table 1: Physicochemical and microbial characteristics of effluent from wk 1 of laboratory-scale filtration setup.

		N	Mudor WWTP effluent				Lab-scale setup effluent				% Reduction	EPA std.
			Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.		
COD	mg/L	21	82.822	175.550	117.268	28.805	2.340	6.350	4.009	0.939	96.58**	250
BOD	mg/L	21	6.980	89.450	46.147	25.749	0.200	0.510	0.341	0.089	99.26**	50
TSS	mg/L	21	14.234	46.012	34.103	9.203	000	000	000	000	100**	50
TDS	mg/L	21	1002	1462.590	1230.27	153.317	500	734.800	615.200	87.000	58.11**	1000
EC	μS/cm	21	1346	2621.00	1608.65	266.336	301.450	501.783	424.652	61.953	73.60**	1500
pH		21	6.959	8.858	7.599	0.512	7.220	8.451	7.849	0.389	—	6–9
Turbidity	NTU	21	12.780	85.090	43.523	32.799	0.107	0.264	0.181	0.041	99.59**	75
Color	TCU	21	91.223	289.56	152.681	59.203	0.323	1.433	0.827	0.402	99.47**	200
ORP	mg/L	21	5.032	36.000	18.769	10.441	9.000	32.000	19.430	6.947	—	
DO	mg/L	21	0.573	2.890	1.620	0.677	2.120	5.860	3.762	1.188	-**	
NH_3	mg/L	21	10.000	125.000	51.352	33.842	0.320	1.550	0.817	0.436	98.41**	1
TC	CFU/100 ml	21	18×10^5	72×10^5	41×10^5	16.01	10×10^2	43×10^2	24×10^2	11.138	99.94**	400
E. coli	CFU/100 ml	21	9×10^5	44×10^5	26×10^5	13.866	6×10^2	10×10^2	7.82×10^2	1.28	99.97**	

N: number of samples; **Significant at 95% confidence level; total of 21 L of Mudor effluent water was filtered at week 1.

Table 2: Wk 1 mean results for analyzed heavy metal concentration of Mudor and lab-scale setup effluent.

Metal		N	Mudor WWTP effluent				Recycled effluent				% Removal	EPA std.
			Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.		
Cu	mg/L	21	0.018	0.092	0.060	0.029	0.001	0.019	0.013	0.005	78.33**	0
Cd	mg/L	21	0.017	0.056	0.031	0.013	0.00	0.002	0.001	0.001	96.77**	0.1
Zn	mg/L	21	0.018	0.026	0.022	0.002	0.001	0.006	0.004	0.001	81.82**	0.5
Fe	mg/L	21	0.003	0.015	0.008	0.004	0.001	0.003	0.002	0.001	75.00**	0.3
Pb	mg/L	21	$6E-05$	0.003	0.001	0.001	0.00	0.00	0.00	0.00	100**	0.1
As	mg/L	21	0.001	0.005	0.006	0.004	0.002	0.00	0.00	0.00	100**	0.1

Wk: week; **Significance at 95% confidence level.

Table 3: Mean results for analyzed physicochemical and microbial characteristics of effluent samples for wk 2 of laboratory-scale filtration setup.

		N	Mudor WWTP effluent				Lab-scale setup effluent				% Removal	EPA std.
			Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.		
COD	mg/L	21	84.675	183.125	127.232	33.333	51.000	102.453	71.901	18.684	43.49**	250
BOD	mg/L	21	8.670	91.256	43.126	30.226	8.265	12.158	9.736	1.127	77.42**	50
TSS	mg/L	21	15.564	46.012	33.381	10.134	9.560	20.300	12.586	3.177	62.296**	50
TDS	mg/L	21	160.56	1821.78	1269.90	461.105	760.000	999.158	852.158	61.994	32.90**	1000
EC	μS/cm	21	1442.364	1715.368	1590.03	92.660	1066.330	1452.385	1273.00	126.600	19.94**	1500
pH		21	6.00	8.50	7.414	0.798	7.00	8.20	7.67	0.432	—	6–9
Turbidity	NTU	21	18.235	94.368	58.143	26.161	10.652	55.870	33.380	12.544	42.59**	75
Color	TCU	21	102.587	298.368	187.706	52.316	40.000	100.110	58.082	15.923	69.06**	200
ORP	mg/L	21	7.00	28.00	17.029	7.587	12.00	38.00	24.540	8.528	—	
DO	mg/L	21	0.882	4.587	2.446	1.126	1.335	2.705	1.847	0.553	—	
NH_3	mg/L	21	11.689	126.857	69.940	42.912	8.890	100.00	34.392	22.646	50.83**	1
TC	MPN/100 ml	21	22×10^5	70×10^5	43.07×10^5	16.455	15×10^4	81×10^4	60×10^4	12.385	86.07**	400
E. coli	MPN/100 ml	21	12×10^5	48×10^5	30×10^5	12.255	23×10^4	52×10^4	30×10^4	4.028	90.00**	

N: Number of samples; Wk: week; **Significant; *Nonsignificant at 95% confidence level; a total of 21 L of Mudor effluent water was filtered at week 2.

Table 4: Wk 2 mean results for analyzed heavy metal concentration of Mudor and lab-scale setup effluent.

Metal		N	Mudor WWTP effluent				Recycled effluent				% Removal	EPA STD.
			Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.		
Cu	mg/L	21	0.017	0.092	0.057	0.0265	0.002	0.021	0.015	0.005	73.68**	0
Cd	mg/L	21	0.014	0.055	0.028	0.010	0.001	0.027	0.008	0.001	71.43**	0.1
Zn	mg/L	21	0.018	0.026	0.022	0.002	0.004	0.015	0.010	0.003	54.55**	0.5
Fe	mg/L	21	0.004	0.019	0.010	0.006	0.001	0.009	0.003	0.002	70.00**	0.3
Pb	mg/L	21	0.000	0.004	0.002	0.001	0.00	0.00	0.00	0.00	100**	0.1
As	mg/L	21	0.000	0.008	0.003	0.002	0.00	0.001	0.0002	0.000	93.33**	0.1

Wk: week; **Significance at 95% confidence level.

(a) (b) (c)

Figure 4: (a) DFSAC filtration setup. (b) Effluent from Mudor WWTP. (c) Effluent from DFSAC filtration setup.

of variance (ANOVA). The LSD and Levene's homogeneity of variance were also investigated using IBM SPSS Windows version 22 package (IBM Corp., USA), and the significance of the treatment means were tested at $p \leq 0.05$.

3. Results and Discussion

3.1. Laboratory-Scale Setup. Tables 1 and 2 show the mean values obtained from the laboratory-scale setup. The Physicochemical and microbial concentrations of the effluents from both the Mudor wastewater treatment and those after the application of the DFSAC treatment were monitored over a two-week period. The mean values recorded for the physicochemical parameters of effluent from the Mudor wastewater treatment plant were found to be consistent with previous research work conducted [55]. The overall performance of the plant has seen increased removal efficiency in terms of colour, TSS, and DO. BOD, turbidity, and EC values reordered indicates a decrease in plant efficiency of the above listed parameters; however, the final effluent of the Mudor WWTP effluent quality is very much desirable as most parameters falls within the EPA's required regulations except for microbial characteristics. Total coliforms and *Escherichia coli* (*E. coli*) recorded high values in Mudor effluent water. The effluent obtained from the laboratory-scale filtration setup in the first week showed significant differences relative to the effluent from the Mudor treatment plant for COD, BOD, TSS, TDS, EC, turbidity, DO, ammonia, total coliforms, and *E. coli*.

Low concentrations of metals were observed in the effluent samples from the treatment plant; however, further treatment in the DFSAC laboratory setup gave a much reduced concentration, which was observed to be significantly different from the concentrations of the effluent sample from the treatment plant.

The boxplot presented above (Figure 5) showed that the physicochemical parameters of the effluents from both the treatment plant and lab-scale treatment with the DFSAC were statistically significant at 95 percent confidence interval at least for COD, BOD, EC, TSS, color, and ammonia. However, no significant difference was observed for pH and ORP at the same confidence interval. The laboratory pilot scale filtration setup using the DFSAC demonstrated the potential characteristics of wastewater pollutants removal efficacy. Attributed removal capacity of the DFSAC could be due to properties like high internal surface area, advanced internal pore structure, and the availability of broad rage surface functional groups as reported in earlier works [79]. These supposed properties could make the DFSAC to have a good potential in adsorption chemistry.

Tables 3 and 4 show the effluent quality parameters for the second week of filtration. The results indicated good removal efficiencies for the monitored physicochemical (COD, TSS, BOD, TDS, turbidity, ammonia), microbial (total coliform, *E. coli*), and heavy metal concentrations (Cu, Cd, Zn, Fe, Pb, As). Some of the concentrations, however, showed a decline in percentage reduction compared to the first week of the laboratory setup. The trend in the decrease of efficiency could be linked to a potential decrease in adsorption capacity with an increment in the amount of influent treated by the setup. Even though there was a slight decline in the percentage efficiency of some of the parameters from week 1 to week 2, the result for week 2 was still statistically significant relative to the effluent from the wastewater treatment at 95% CI (Tables 5 and 6). Moreover, just as it was observed in week 1, parameters like pH, ORP, and DO showed no significant difference in terms of treatment in week 2.

Considering the decline in the percentage reduction in some of the monitored parameters from week 1 to week 2, it was noted that the effluent from the wastewater treatment plant was showing variations in almost all monitored parameters (Table 5). The variations were seen to be significant at 95% CI and contributed to the decline in the percentage reduction in some of the parameters, like COD, in the second week of the experiment. Again, accounting for the slight reduction in some of the pollutant load removal in week 2, it was observed that the extremely high removal of the suspended solids in the influent of the laboratory-setup (thus effluent from the wastewater treatment plant) contributed to the trend as the surface activity of DFSAC could potentially decline due to blockage by the adsorbed solids in the water. This trend presupposes that to have the DFSAC perform continuously for a reasonable period of time to achieve its consistent efficacy on a large scale, there is a need to trap some of the suspended solids before they enter the DFSAC media column. This observation was taken into consideration during the setup of the large-scale setup for optimum operation.

Municipal tap water flowing in the laboratory where the experiment occurred was used as a control for the experiment. The intent or motivation for the use of tap water was not to compare the effluent of the setup with drinking water but to serve as a guide for a possible determination of fouling of the media (DFSAC). Table 6 shows the mean results obtained from the analysis of monitored parameters of the control and the effluents obtained at weeks 1 and 2 of the lab-scale setup.

The mean comparison from Table 6 showed that the lab-scale setup effluent at week 1 recorded a much better COD level in this study than the control samples. A similar trend was also noted for turbidity, colour, ORP, and DO. The BOD recorded in week 1 was high compared to the control sample. The same trend was also seen in other parameters like TDS, EC, ORP, NH_3, TC, and *E. coli*. The TSS recorded in Week 1 was found to be the same as the one recorded for the control sample. As highlighted in the aforementioned discussions, the performance of the DFSAC declined in week 2. Again, in the comparison of the monitored quality parameters to the control sample, the results were, however, higher. It is important to highlight that, after the application of hypochlorite at a concentration of about 4–6 ppm to the effluent obtained from the laboratory setup for both weeks, no microbial load (total coliforms and *E. coli*) was measured in the final effluent.

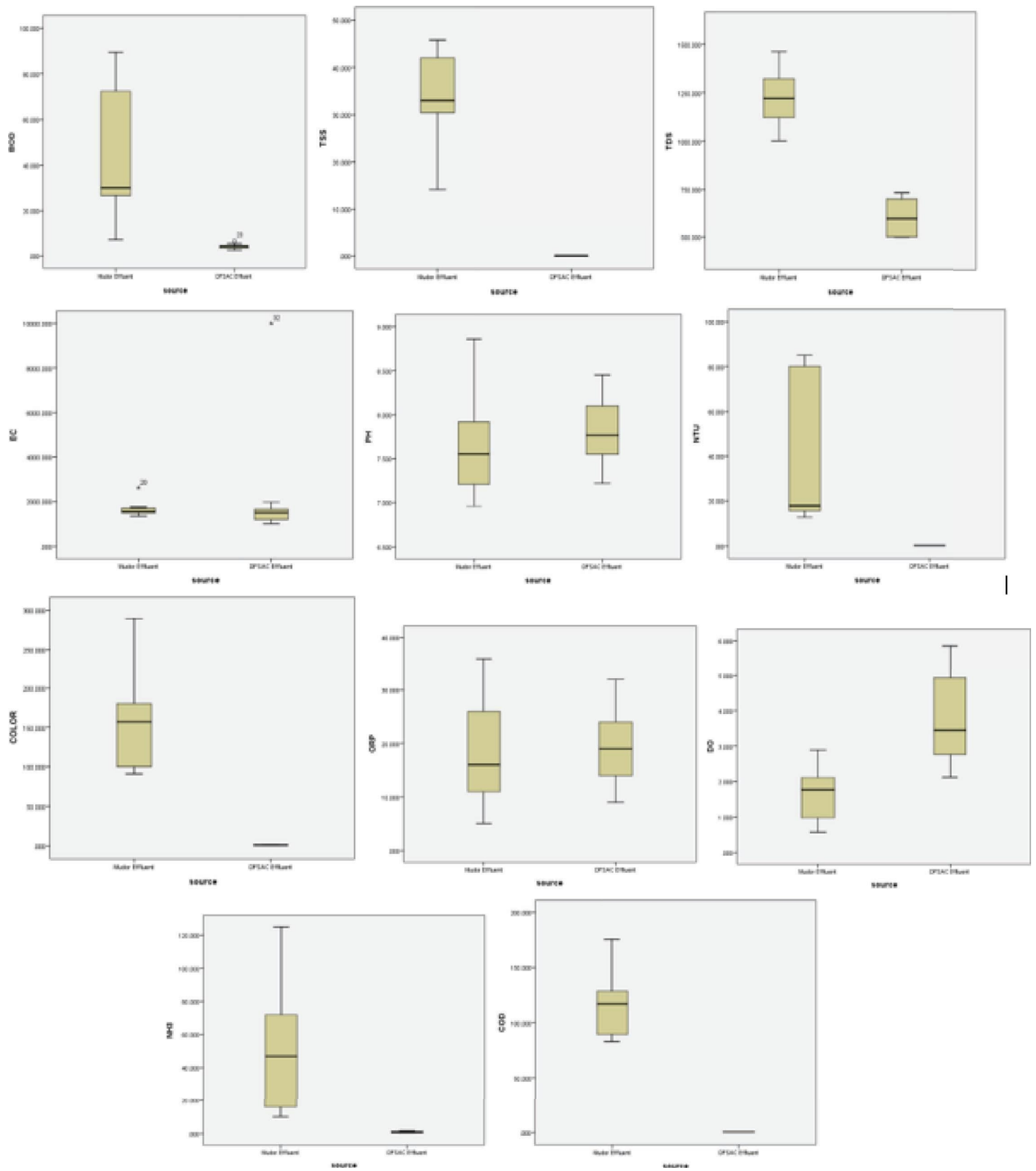

Figure 5: Boxplot of effluents from the treatment plant and the lab-scale setup.

3.2. Large-Scale DFSAC Filtration System. Data obtained after the laboratory-scale setup was used to scale up the implementation of a large-scale DFSAC filtration system at the Mudor WWTP site. The lessons and results observed were used in the upscale stage for improved efficiency and optimum operation.

Table 7 shows the mean values obtained for the monitored physiochemical and microbial parameters for both the effluents from the Mudor wastewater treatment plant and the large-scale filtration system setup over sixteen weeks. The overall removal efficiency of contaminants using the DFSAC on the large-scale application recorded significant differences relative to the feed. The pollutants found in the Mudor WWTP effluent water were significantly reduced (Figure 6), and the same trend was recorded for the laboratory-scale experimental setup for the first week. The fouling potential observed during the second week of the lab-scale experiments, which is attributed to the variations in the feed and

Table 5: P values for analyzed Mudor and lab-scale setup effluent for weeks 1 and 2.

		P values	
		Mudor effluent (W1 and 2)	Lab-scale setup effluent (W1 and 2)
COD	mg/L	0.306	0.0001
BOD	mg/L	0.729	0.0001
TSS	mg/L	0.617	0.0001
TDS	mg/L	7.11	0.0001
EC	μS/cm	0.764	0.0001
pH		0.377	0.132
Turbidity	NTU	0.118	0.0001
Color	TCU	0.59	0.0001
ORP	mg/L	0.540	0.039
DO	mg/L	0.448	0.0001
NH_3	mg/L	0.127	0.0001
TC	MPN/100 ml	0.132	0.0001
E. coli	MPN/100 ml	0.122	0.0001

Significance at 95% confidence level.

Table 6: Mean results for analyzed lab-scale setup effluent characteristics of tap water for weeks 1 and 2.

		Mean		
		Week 1	Week 2	Tap water
COD	mg/L	4.009	71.901	3.20
BOD	mg/L	0.341	9.736	0.00
TSS	mg/L	000	12.586	0.00
TDS	mg/L	615.200	852.158	100.23
EC	μS/cm	424.652	1273.00	209.70
pH		7.849	7.67	7.62
Turbidity	NTU	0.181	33.380	0.85
Color	TCU	0.827	58.082	<10
ORP	mg/L	19.430	24.540	47.57
DO	mg/L	3.762	1.847	5.148
NH_3	mg/L	0.817	34.392	0.044
TC	MPN/100 ml	24×10^2	60×10^4	16.52
E. coli	MPN/100 ml	7.82×10^2	30×10^4	2.00

the high retention of the suspended solids on the surface of the DFSAC media, was controlled using a 5-micron filter cartridge. The cartridge filter was placed between the pump discharging the effluent from the treatment plant and the 2 receiving tanks in the setup.

The results obtained showed high removal efficiency of pollutants and a reduction in parameters such as BOD, turbidity, TDS, TSS, COD, EC, ammonia, and colour. At 95% CI, the recorded results over the period were statistically significant (Figure 6), as the recorded P values were all less than 0.05 ($P < 0.05$). The obtained result is an affirmation of the potential of the DFSAC effectiveness in the removal of wastewater pollutants on a large-scale level, as was seen in the previously discussed laboratory-scale setup results. DFS-activated carbon reduced the colour of the influent (183 PtCo) significantly to 1.18 PtCo, and the same trend was observed in turbidity, which decreased from 35 NTU to 0.22 NTU. The level of turbidity recorded after treatment was lower than the controlled sample used for the tap water in the lab-scale setup experiment (Table 6). The performance of the DFSAC on large-scale applications was seen to give results for turbidity far better than earlier works reported [7]. The removal efficiency of pollutants using DFSAC was observed to be more effective compared with the values obtained using activated carbon from agricultural materials [7, 11, 23–26]. Adsorption capacity could be attributed to the large surface area of the DFSAC as well as the high internal surface area, the advanced internal pore structure, and the availability of a broad range of surface functional groups.

Table 8 shows the mean results obtained for heavy metals monitored over the same 16 weeks' period of the setup. From Figures 6 and 7, it can be seen that the output of the influent-effluent results gave a significant difference between the heavy metal parameters studied (Figure 7).

Removal efficiencies for Cu, Cd, and Zn recorded $P < 0.05$ at 95% confidence interval, hence were statistically significant and this is evident in the observed percentage removal recorded. However, Fe, Pb, and As recorded P values greater than 0.05 ($P > 0.05$), and their respective reductions by the setup were not significant. Even though

Table 7: Mean results for analyzed physicochemical parameters of influent and effluent water samples collected for sixteen weeks: large-scale filtration system.

		N	Mudor WWTP effluent				Large-scale filtration system				% Removal	EPA std.
			Minimum	Maximum	Mean	Std. dev.	Minimum	Maximum	Mean	Std. dev.		
pH		80	6.9587	8.8554	7.91	0.21	7.3587	8.4509	7.88	0.12	n/a	6.0–9.0
EC	μS/cm	80	1,656.19	3,557.61	2,634.07	197.51	1,034.75	1,772.03	1,403.47	85.36	46.72	1,500.00
TDS	mg/L	80	1,286.54	1,462.59	1,374.30	19.26	671.288	734.77	703	7.38	48.85**	1500
ORP	mg/L	80	−38.408	2.496	−19.41	4.43	11.916	35.935	24.05	2.76	n/a	
DO	mg/L	80	0.4799	1.578	0.55	0.24	2.462	4.9303	3.76	0.27	n/a	1000
TSS	mg/L	80	11.198	39.721	25.22	2.98	0.00	0.00	0.00	0.00	100**	50
BOD	mg/L	80	31.28	85.90	26.12	13.14	4.2392	6.3842	5.32	0.24	79.63**	50
COD	mg/L	80	82.822	127.775	105.3	5.17	0.42277	0.59607	0.51	0.02	99.52**	250
Turbidity	NTU	80	14.417	80.148	35.05	9.86	0.177034	0.263894	0.22	0.01	99.37**	75
Color	TCU	80	106.82	260.2	183.12	17.69	0.82371	1.53672	1.18	0.08	99.36**	200
NH_3	mg/L	80	9.606	100.6	55.45	10.5	−6.373	18.205	5.5	2.75	90.08**	1
TC	MPN/100 ml	80	23×10^5	80×10^5	45×10^5	106.25	18×10^4	89×10^4	73×10^4	142.342	88.23**	
E. coli	MPN/100 ml	80	15×10^5	45×10^5	26×10^5	122.034	20×10^4	49×10^4	27×10^4	55.025	92.00**	

**Significance at 95% confidence level.

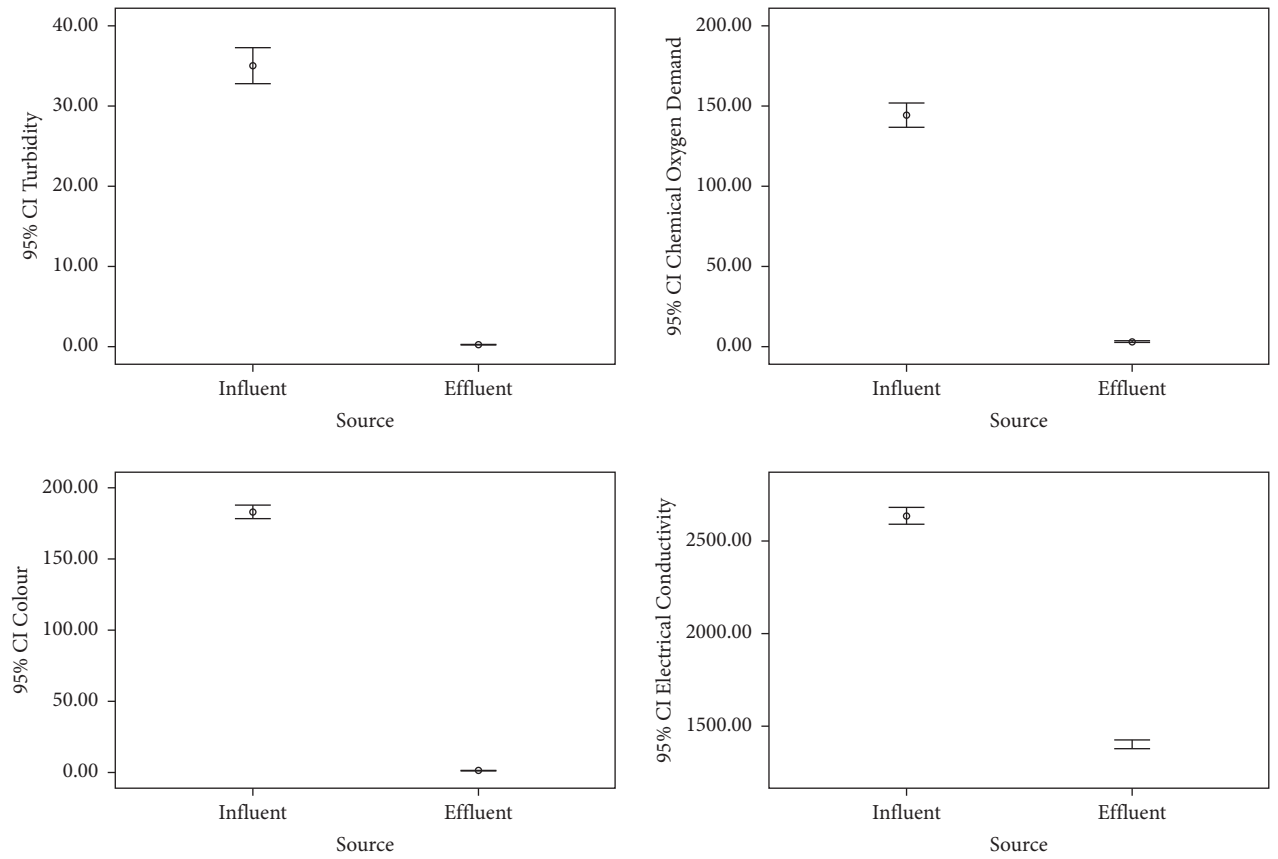

Figure 6: Output of influent-effluent values showed significant difference for some physicochemical parameters.

Table 8: Mean results for the analyzed heavy metal concentrations of Mudor and recycled effluent.

Metal		N	Mudor WWTP effluent				Recycled effluent				% Removal	EPA STD
			Min	Max	Mean	Std. dev.	Min	Max	Mean	Std. dev.		
Cu	mg/L	80	0.015	0.077	0.031	0.01	0.001	0.019	0.01	0.002	67.74	0
Cd	mg/L	80	0.017	0.046	0.014	0.007	0.00	0.00	0.00	0.00	100**	0.1
Zn	mg/L	80	0.019	0.023	0.021	0.0005	0.005	0.013	0.009	0.001	57.14**	0.5
Fe	mg/L	80	0.004	0.010	0.007	0.0007	0.001	0.003	0.002	0.0002	71.43	0.3
Pb	mg/L	80	$7.99E-05$	0.003	0.0014	0.0003	0.00	0.00	0.00	0.00	100**	0.1
As	mg/L	80	0.0019	0.005	0.0018	0.0008	0.00	0.00	0.00	0.00	100	0.1

**Significance at 95% confidence level.

the results obtained in the polished water for Fe, Pb, and As with respective removal efficiencies of 71.4%, 100%, and 100% look satisfactory in percentage terms, they were still not statistically different from the feed. And this was due to the originally low concentrations of these trace metals in the effluent water of the treatment plant. The observed effluent heavy metal concentrations from the treatment plant were already in compliance with the recommended EPA guidelines, but it is critical to know that treatment of this effluent from the treatment plant with DFSAC can further reduce heavy metals to ensure the safe use of recycled water. Even in trace amounts, heavy metals pose threats to the human body if exposed to the body continuously [7]. This implies that there may be no safe level of exposure to some metals like lead [80]. For instance, cadmium exposure, even in lower amounts, could cause detrimental health problems [81, 82]. Beyond the recommended limits, zinc exposure could result in significant bioaccumulation with possible toxic effects for aquatic organisms.

The large surface area of the activated FS charcoal was able to remove all the arsenic in the wastewater, although the arsenic composition may be insignificant in the wastewater influent. The ability of the DFSAC to effectively and

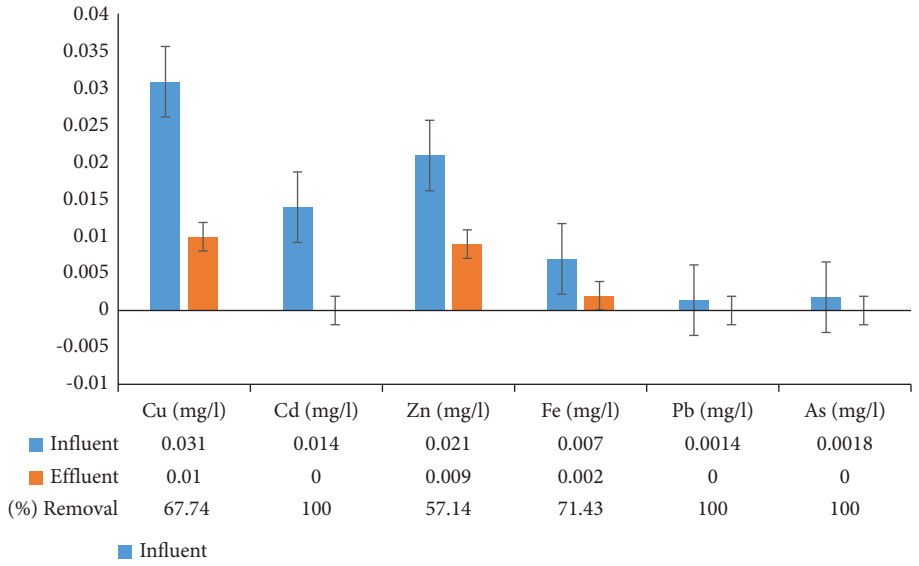

Figure 7: Output of influent-effluent values showing significant difference for some of the heavy metals studied.

efficiently remove pollutants and toxicants from the Mudor wastewater effluent is consistent with earlier works studied [7, 11, 23–26, 60, 83–87].

4. Conclusion

A novel material (DFSAC) and purification method plausible for polishing wastewater in large-scale management of faecal sludge and wastewater have been developed. In effect, the DFSAC filtration system, with both laboratory-scale setup implementation and the large-scale results presented in this research, has proven beyond a reasonable doubt to be very effective and could be adopted as an innovative purification treatment system in treating effluent water for recycling in treatment plants. This in effect is a considerable saving in starting material costs, reducing the sludge volume generated in wastewater treatment plants, and a way of making use of waste material in an economically valuable and sustainable way of cost reduction where plant effluent can be recycled for reuse.

It also produces effluent that is substantially pure due to the high toxicity removal efficiency, making the effluent water free from impurities, dissolved solids, and turbidity. Polished recycled water obtained from the system can be used for purposes such as cleaning, irrigation, chemical dissolution in wastewater treatment, washing of cars, and flushing of WC when disinfected. This method of treatment using DFS-activated charcoal may require replacement after several treatments are done, but dry faecal sludge is always readily available from the WWTP; hence, DFS-activated charcoal can easily be available, is cheap, and has a high degree of purification potential. This process has so many advantages and aims to meet all the needs of the present situation. Using the DFSAC for filtration has a good prospect, and WWTP operators should consider closing the resource loop by ensuring effluent water from treatment facilities undergoes a cheap but more effective means of purification for reuse. However, it can be said that an economical and stable material and method, which are a novelty in providing recyclable and fresh water in adequate amounts, have been developed by this work. The exploration of the DFSAC surface activity and improvement would provide multifunctional and highly efficient processes that would provide affordable/sustainable, ecofriendly solutions to water/wastewater treatment without relying on large infrastructures or centralized systems.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request. However, substantial data information on the research is provided in the manuscript.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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