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Microbial Detoxification of Oilfield Produced Water Using Discontinuous Bio-Unit System

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Abstract: This work investigated the biodetoxification of oilfield produced water (OPW) using indigenous microbial consortium in discontinuous aerobic biological treatment (Bio-Unit) system. The pilot scale Bio-Unit has a single tank that is operated cyclically. The Bio-Unit performance was compared with that of an extant physical treatment unit (PTU) of a crude oil facility. The pilot scale Bio-Unit achieved higher effluent indices at optimal conditions of microbial retention time of 21 days and hydraulic retention time of 24 hours. The percentage removal of Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Total Organic Carbon (TOC), Salinity and Chemical Oxygen Demand (COD) using the Bio-Unit were 98.2%, 96.8%, 98.5%, 96.7%, 97.6%, respectively, while for the physical treatment (PTU) process were 31.5%, 55.3%, 82.2%, 37.1% and 73.8%, respectively. Comparison showed that the Bio-Unit performed better than the extant PTU. The after-treatment concentrations of TOC (83.1 mg/l), Salinity (2290.7 mg/l) and COD (152.6 mg/l) from the existing physical treatment unit (PTU) were above Nigerian DPR inland and nearshore permissible level, while the after-treatment concentrations of TOC (6.81mg/l), Salinity (120.03 mg/l), and COD (14.1 mg/l) from the pilot scale Bio-Unit were below the regulatory limits. Therefore, it is proposed that the extant PTU be upgraded by retrofitting it with the Bio-Unit so as to meet produced water quality requirement for reinjection into oil reservoir or disposal to the environment.

Keywords: Oilfield Produced Water, Physical Treatment, Discontinuous Bio-Unit, Microbial Consortium, Biodecontamination

1. Introduction

Oil and gas industries generate produced water alongside the desired oil and gas product. This produced water contains toxic compounds that pose serious threat to human and environmental health, if not properly detoxified. The treatment of oilfield produced water is often done using physical and chemical methods such as, gravity separation, adsorption, floatation, coagulation, flocculation, membrane separation [1-5]. While these conventional physicochemical treatment methods are expensive, most of them are primarily designed to remove suspended solids, heavy metals, and dispersed oil, while dissolved petroleum hydrocarbons and organic components are ignored, despite the grievous impacts of these compounds on the receiving environment.

The increasing concentration of Polycyclic Aromatic Hydrocarbons (PAHs) in water bodies in recent times has generated concern because these compounds are recalcitrant, carcinogenic and bioaccumulate in marine organisms, toxify fishes, decreases diversity of benthic fauna near the discharge point, disrupts the structure of mangroves habitat and depletes wildlife [6]. The Nigerian Department for Petroleum Resources (DPR), because of these adverse tendencies, has imposed stringent regulation for the disposal of oilfield produced water into the environment [7]. As the regulation on oilfield produced water is getting stiffer, government, industries, scientific and research attentions are focused not only on zero oilfield produced water generation, but also the conversion of this unavoidable toxic waste stream to beneficial reuse through innovative processes within lean space and budget.

Biological treatment methods are considered as cost-effective and eco-friendly for oil/gas PW detoxification [8, 9]. Tellez et al. [10] and Kardena et al. [11] investigated produced water treatment using Continuous Stirred Tank Activated Sludge System. Nie et al. [9] evaluated high salinity and low pH produced water treatment using Biological

Aerated Filter Reactors (BAFRs). Due to inhibitory effect of toxic constituents in certain industrial wastewater, discontinuous biological treatment system is preferred, as it also offers operational flexibility, compactness, low maintenance and useful in upgrades and retrofitting [12, 13]. Fakhru'l-Razi et al. [14] investigated the treatment of oilfield produced water using a Membrane Sequencing Batch Reactor (MSBR) and a combined membrane Sequencing Batch Reactor and Reverse Osmosis (MSBR/RO). Pandashteh et al. [15] investigated the biological pretreatment of synthetic and real produced water in Sequencing Batch Reactor system and reported that the removal rates of the primary pollutants in the real produced water were high.

Due to equipment sizing, the use of continuous activated sludge system for oilfield PW treatment is constrained by space availability, especially in offshore operations. Addressing this gap, this work is therefore aimed at decontaminating oilfield PW using a compact aerobic fill-and-draw biological treatment unit (Bio-Unit). The objective of the work includes analyses of the physicochemical properties of oilfield PW from a selected crude oil production facility and comparing its performance, in terms of percentage removal of target contaminants, with the extant Physicochemical Treatment Unit (PTU).

2. Materials and Methods

2.1. Sampling and Characterization of the Oilfield Produced Water

Oilfield Produced Water (OPW) sample was collected from a crude oil flow station located in South-Eastern State of Nigeria. The OPW samples were collected daily for a month to establish the pollutant strength and fluctuation in its quality and composition. The sampling and preservation of the produced water samples were carried out as stipulated in the ASTM [16], APHA [17] and API-45 [18]. While in-situ parameters were done, the collected samples were taken to the laboratory in an iced-box for analysis using standard test methods. The total organic carbon (TOC), chemical oxygen demand (COD), total dissolved solids (TDS), total suspended solids (TSS), and salinity, were determined using ASTM D7573-18, APHA 5220D, APHA 2540C, APHA 2540D, and APHA 4500-Cl- B, respectively. The chemicals used for the analysis were of Analytical Grade (AR).

2.2. Enrichment of Indigenous Microbial Consortium

Indigenous microbial consortium was isolated from a crude oil saver pit located in the crude oil flow station. The isolated Naturally Occurring Microbial Consortia (NOMC) was enriched by inoculating 50 mL of the NOMC in Mineral Salt Medium (MSM) supplemented with raw oilfield produced water 2% (v/v) in 5 L Erlenmeyer flask. The pH of the MSM was adjusted to 7.0 ± 0.2, while raw oilfield produced water was added as a sole carbon and energy source at 2.0% (v/v). The flask was incubated at 30^{o}C and stirred at 150 rpm for 7 days. After 7 days of incubation, 10% of the enriched culture was further inoculated in a fresh MSM supplemented with raw oilfield produced water 2% (v/v). The culture was enriched three consecutive times. The enriched microbial consortium was acclimated in the Bio-Unit by stepwise increase of OPW concentration until minimum target pollutants concentrations and maximum microbial growth were attained.

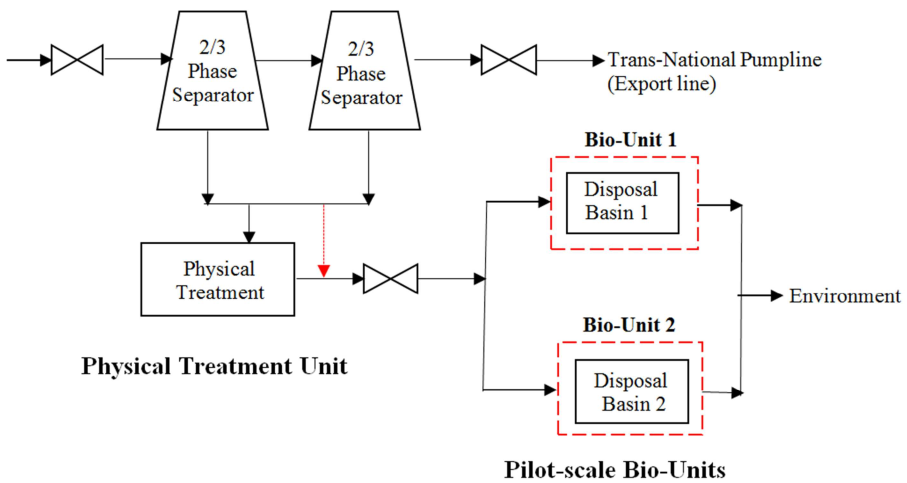

Figure 1. *Schematic of the Treatment Units.*

2.3. Configuration and Operation of the Pilot-Scale Bio-Unit

The produced water disposal pit (PWDP) was modified into a compact pilot-scale Bio-Unit. The PWDP is a rectangular concrete tank with a length of 3.30 m, width of 2.70 m, depth of 1.80 m, a total volume of 16.04 m^3 (16040.0 L) and a working volume of 15.00 m^3 (15000.0 L). The outlet of the Bio-Unit used for decanting has a height of 1.50 m from the bottom. This is to prevent loss of biomass in the reactor after settling is completed. Aeration, to ensure a Dissolved Oxygen (DO) concentration of not less than 3.0 mg/L and complete mixing was provided by uniformly arranged PVC piping and fine bubble diffuser. Feeding, decanting and biomass wastage were enabled by consolidated pneumatic pumps. The produced water flows to the Bio-Unit system from a skimming basin of downstream crude oil/water phase separator. Each Bio-Unit operational cycle lasted for 24 hours as follows: Filling period - 4 hours, Reacting period - 19 hours, Settling period - 0.5 hours (30 min), Decanting period - 0.5 hours (30 min), and Idle period - 0.25 hours (15 min). A simplified scheme of the OPW gathering, and treatment facility using Bio-Unit systems is shown in Figure 1. [19].

3. Results and Discussion

3.1. Performance Evaluation of the Treatment Methods

The physicochemical properties of before and after treatment of Oilfield Produced Water (OPW) by the extant Physical Treatment Unit (PTU) and the proposed Biological Treatment Unit (Bio-Unit) were compared to the DPR standard. Table 1 elucidates the treatment performance of the two treatment methods in comparison to DPR specification. The quality of the oilfield produced water from the skimming basin outlet, as displayed in Table 1, shows that the concentrations of Chemical Oxygen Demand (152.6 mg/l), Total Organic Carbon (83.1 mg/l), Total Dissolved Solids (3940.3 mg/l), Total Suspended Solids (125.2 mg/l) and Salinity (2290.7 mg/l) are above DPR permissible limits. Similar results of oilfield produced water effluent having concentrations above permissible level have been reported [20, 21]. High concentrations of target pollutants after being treated by the extant PTU could be due to high volume of produced water generated from aged oil reservoirs which has overstretched the physical treatment unit beyond its design specification. Also, PTU may be incapable of removing dissolved hydrocarbons in produced water.

Table 1. *Comparison of the Treatment Methods with DPR [7] Standard.*

Produced Water Characteristics	Compliance Limits		Before Treatment	After Treatment	
	Inland	Nearshore		PTU	Proposed Bio-Unit
Temperature	Ambient ±2	Ambient ±2	30.5	26.5	29.8
pH	6.5 – 8.5	6.5 – 8.5	7.90	7.80	7.75
TOC, mg/l	10.0	20.0	466.1	83.1	6.81
Salinity (Cl^-) mg/l	600.0	2000.0	3645.8	2290.7	120.03
TDS, mg/l	2000.0	5000.0	5754.6	3940.3	103.9
TSS, mg/l	<30% (of the receiving medium)	<50% (of the receiving medium)	280.3	125.2	9.10
COD, mg/l	40.0	125.0	582.5	152.6	14.1

Comparing the effluent quality of the two treatment methods revealed that, though reduction in concentrations of the target pollutants occurred by the physical treatment process, the Aerobic Biological Treatment (Bio-Unit) system demonstrated drastic reduction in concentrations of the target contaminants. The physicochemical properties of treated OPW from the Bio-Unit met the DPR standard [7], while the extant PTU did not. The results also showed that the effluent quality from the physical treatment process is unsuitable for reinjection into oil reservoir, because of high concentration of TSS and TDS. Such concentrations cause precipitation and depositions of suspended solids and scales. Solids and scales deposit results in impairment of pumps and piping system [22]. The comparison of the extant PTU and the Bio-Unit in terms of percentage removal of target pollutants is given in Figure 2.

As depicted in Figure 2 showed that the Bio-Unit performed better than the extant PTU. The percentage removal of TDS, TSS, TOC, salinity and COD using the Bio-Unit were 98.2%, 96.8%, 98.5%, 96.7%, 97.6%, respectively, while for the PTU were 31.5%, 55.3%, 82.2%, 37.1% and 73.8%, respectively. The effectual decontamination of the produced water hydrocarbons could also be attributed to the diverse indigenous microbial found in the consortium having the appropriate metabolic pathways to degrade the target pollutants in OPW. It is reported that mixed microbial consortium had superior biodegrading capabilities resulting from synergetic interactions amid the consortium [9, 10, 23-25].

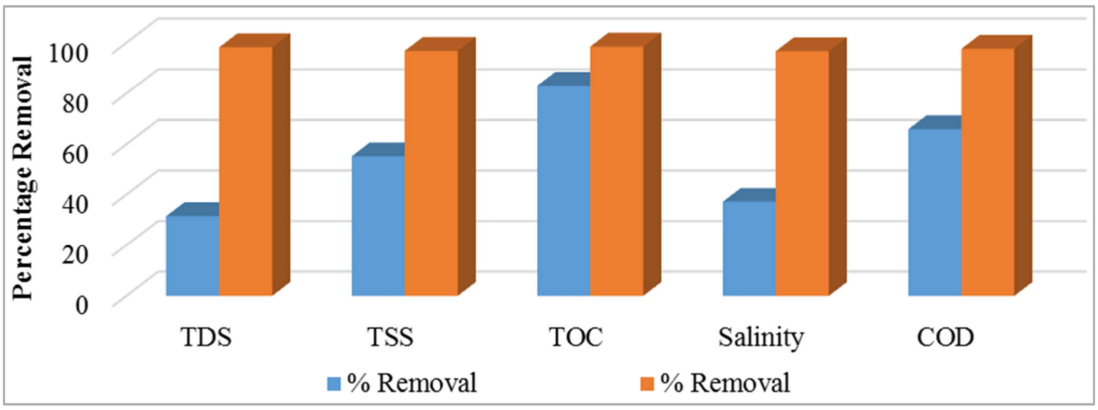

Figure 2. *Comparison of Removal Performance of PTU to Bio-Unit.*

3.2. Performance of the Bio-Unit at Different Biosolids Retention Time

The biosolids retention time (BRT) being a key experimental variable in this study, especially in determining biokinetic coefficients, the performance of the Bio-Unit was carried out at various BRT. The concentrations of the target pollutants in the treated oilfield produced water and percentage removal result depict that the concentrations decreased, and percentage performance increased with biosolids retention time (BRT). This could be attributed to microbial adaptability to targeted pollutants, which was enhanced when resident for a longer time, thereby resulting in improved bioenergetic activities and bioreactor performance. The result also divulges that the percentage removal of these targeted pollutants increased considerably till above BRT of 21 days, after which, the increase was insignificant for both target pollutants and microbials. It implied that for overall process performance and economic incentive, the BRT value of approximately 21 days suffice as minimum microbial residence time for optimal degradation of target pollutants. This assertion consonant with reports that BRT of 20 days was the minimum biosolids retention time required for biodegrading target organo-pollutants found in oilfield produced water [10, 11].

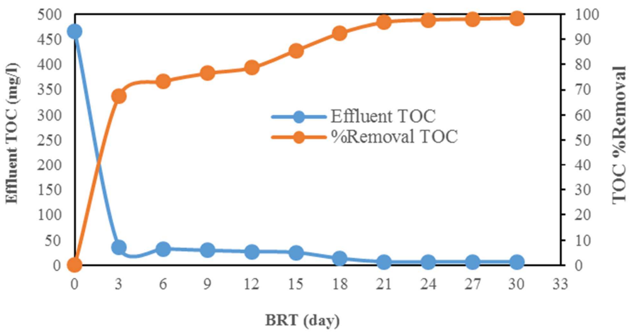

Figure 3. *Effluent TOC and % Removal vs BRT.*

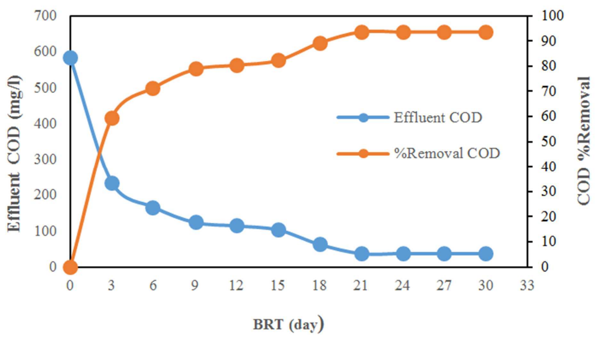

Figure 4. *Effluent COD and %Removal vs BRT.*

Figure 3 relates the effluent total organic carbon (TOC) concentration and the percentage removal with biosolids retention time (BRT). The TOC decreased from initial mean value of 466.1 mg/l to 6.81 mg/l. It illustrates that percentage TOC removal increased to 98.5%, as BRT increased to 30 days. These imply that, the TOC decreases, while percentage removal increases with increase in BRT. Pandashteh et al. [15] had reported 85% removal of oil and grease from real produced water. Sharghi et al. [26] had reported oil and grease removal efficiency from 89.2% to 95.5%, as the loading rate increased in a submerged membrane bioreactor treating synthetic oilfield produced using halophilic bacterial consortium. In this work, the TOC percentage removal was 98.5%. The TOC of the treated oilfield produced water (6.81 mg/l) and the percentage removal of 98.5% divulge the enzymatic competence of the indigenous microbial consortium identified as strains of *Bacillus species*, *Pseudomonas species* and *Chryseobacterium Species* by Nwokoma et al. [19]. Also, it indicated that the Bio-Unit discontinuous configuration favoured the detoxification of oilfield produced water for disposal or re-injection into oil reservoirs.

Figure 4 relates the effluent Chemical Oxygen Demand (COD) concentration and percentage COD removal with BRT. Figure 4 indicated that the effluent COD concentration was decreasing, while COD percentage removal was increasing with increase in BRT. It showed that for overall process performance and economic incentive, the BRT value of approximately 21 days suffice as optimal BRT for effective degradation of targeted pollutant. This assertion consonant with reports that BRT of 20 days was the minimum retention time required for biodegrading target organo-pollutants found in oilfield produced water [10, 11].

It was also reported that the concentration of organic compounds and TDS in OPW could affect the microbial detoxification ability [15]. In this study, the indigenous microbial consortia inoculated from the oilfield saver pit seem to adapt effectively in the oilfield produced water, as the percentage removals showed non inhibitory effects. Pandashteh et al. [15] disclosed that the removal rates of COD for the real produced water was 81%. Sharghi et al. [26] reported COD removal of 83% from synthetic oilfield produced water in a submerged membrane bioreactor using a halophilic bacterial consortium. However, in this work, the percentage removal of 97.6% was obtained from the aerobic Bio-Unit. The low COD concentration (14.1 mg/l) of the treated oilfield produced water and the percentage removal of 97.6% elicit the enzymatic competence of the indigenous microbial consortium and the discontinuous disposition of the Bio-Unit [19]. Also, longer BRT enhanced the microbial adaptability to targeted pollutants. Another reason for the high performance could be the use of long Fill period of 8 hours, instead of short Fill period. Long Fill period ensured that substrate concentration did not vary significantly over the cycle time, thus beneficial to avoiding substrate inhibition due to highly concentrated influent wastewater.

Figure 5 relates the effluent salinity concentration and salinity percentage removal with BRT. It indicates that the salinity concentration decreased from initial value of 3645.8 mg/l to 120.03 mg/l for 21 days BRT, after which it increased to 356.3 mg/l, as BRT increased to 30 days. The salinity percentage removal increased to 96.7% for 21 days BRT, thereafter, decreased to 90.2% as BRT increased to 30 days.

Figure 5 showed that the effluent salinity concentration decreases with increase in BRT, while salinity percentage removal increased with increase in certain BRT.

The exit salinity concentrations (120.03 mg/l) of the treated oilfield produced water and the percentage removal (96.7%) for BRT of 21 days demonstrated that the Bio-Unit system was effective in reducing high salinity in oilfield produced water to permissible levels. It has been reported that wastewater with high salinity adversely affects the enzymatic degradation of hydrocarbons [27] and that high salinity inhibit conventional biological treatment processes [28, 29]. However, this is not so with the fill-and-draw aerobic biological treatment unit (Bio-Unit) as observed from this investigation. The Bio-Unit withstood high salinity wastewater, due to its discontinuous disposition. This agrees with previous report that a discontinuous activated sludge system enhances the biodegradation of high saline wastewater [28, 29]. Also, the synergetic effects of halophilic microbial consortium caused better detoxification of the produced water, when compared to individual strains. This agrees with related studies [30].

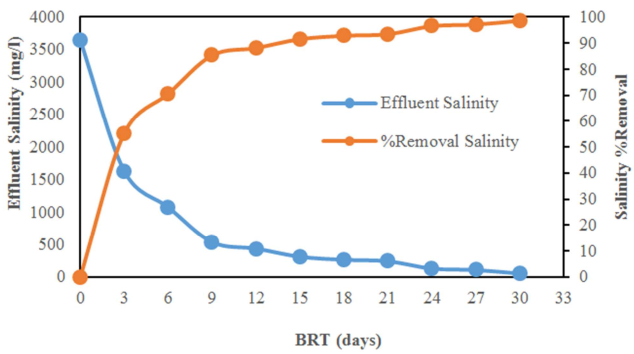

Figure 5. *Effluent Salinity and %Removal vs BRT.*

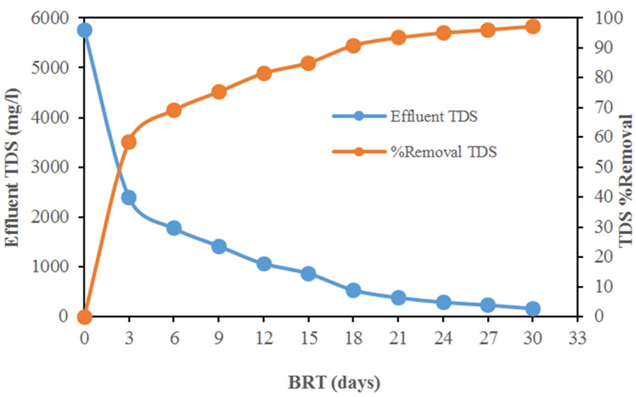

Figure 6. *Effluent TDS and %Removal vs BRT.*

Figure 6 is a plot of Effluent TDS concentration and TDS removal percentage against BRT. It illustrates that the TDS reduced from the initial average concentration of 5754.6 mg/l to effluent concentration of 103.9 mg/, as BRT increased from 3 days to 21 days, thereafter the effluent TDS increased sparingly to 214.3 mg/l, as BRT increased to 30 days. Figure 6 indicates that the percentage removal of TDS increased to 98.2%, as BRT increased to 21 days, after which it decreased to 96.3 as BRT increases to 30 days, which implies that BRT of 21 days is optimal for TDS removal from oilfield produced water using the Bio-Unit system. This result indicates that the aerobic Bio-Unit reactor system could effectively handle and detoxify TDS oilfield produced water to permissible levels.

Figure 7 describes effluent TSS concentration and the percentage removal with BRT. It showed that the effluent TSS concentration in the oilfield produced water decreased from its initial concentration of 280.3 mg/l to 9.2 mg/l for BRT of 21 days. Increasing the BRT to 30 days caused the effluent TSS to increase gradually to 12.02 mg/l. The TSS percentage removal increased to 96.7%, as BRT increased to 21 days, and after that there was little decline as BRT proceeds to 30 days. The high reduction of TSS concentration portrays the efficacy of aerobic Bio-Unit reactor system to detox oilfield produced water. He et al. [31] reported 90.9% reduction of TSS in oilfield produced water by high oil-degrading microbes. Moreover, the low TSS concentration indicated that the treated oilfield produced water can be re-injected into oil reservoir for enhanced oil production or reused for agricultural and recreational activities.

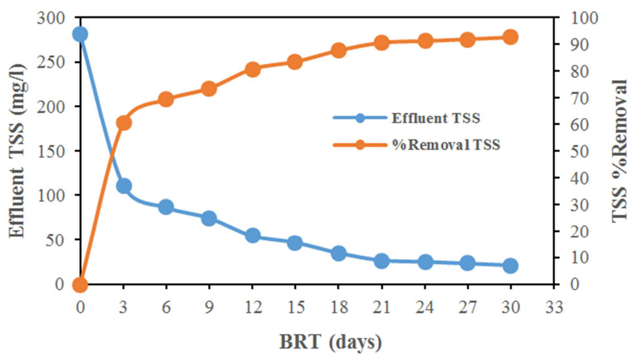

Figure 7. *Plot of Effluent TSS and %Removal vs BRT.*

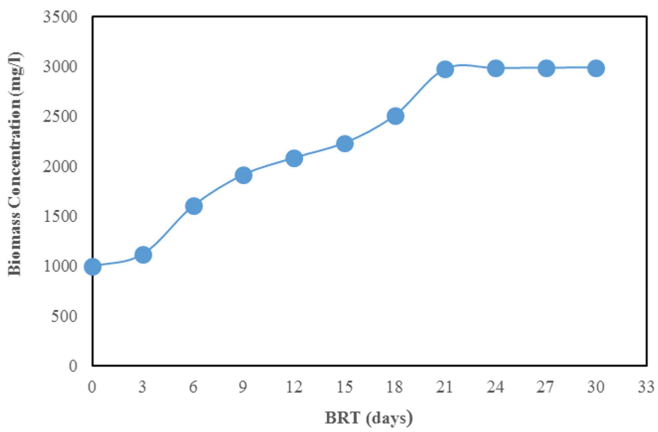

Figure 8. *Biomass Concentration vs BRT.*

Figure 8 relates the biomass concentration BRT. It showed that the biomass concentration increases with increase in BRT. The increase in biomass concentration showed the active phase of the biological system, which flattened from 21 days, indicating limited or stationary growth. This trend denotes traditional microbial growth rate. The microbial growth curve indicates that the indigenous microbial consortia could grow significantly in the oilfield produced water. This is consistent with the reports that higher microbial concentration in the bioreactor heightens the efficacy of biocatalytic process [32, 33].

4. Conclusion

This study analysed the physicochemical properties of an oilfield produced water. The raw oilfield produced water elicits high concentrations of total organic carbon, TOC (466.1 mg/l), chemical oxygen demand, COD (582.5 mg/l), total suspended solid, TSS (280.3 mg/l), total dissolved solid, TDS (5754.6 mg/l), Salinity as Cl^- (3645.8 mg/l), which are above permissibility by the Nigerian Department of Petroleum Resources, DPR standards. Evaluation of the efficiency of the extant produced water Physical Treatment Unit (PTU) showed that concentrations of TOC, COD, TDS, TSS and Salinity of treated produced water were above permissible limits. The aerobic biological treatment (Bio-Unit) proposed in this work is compact and offered a better effluent quality as the Bio-Unit, at optimal condition of 21 days biosolid retention time (BRT), demonstrated robust and high (≥ 98%) effectiveness in removing TOC, TDS, TSS, salinity and COD from oilfield produced water to permissible and re-injectable levels. It therefore implies that BRT can be used to control the biotreatment operation, since the extent of treatment efficiency basically depends on the BRT.

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Conflicts of Interest

The authors declare no conflicts of interest.

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