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Aerobic Degradation Process in Palm Oil Mill— Issues, Challenges and Upsurging Its Efficiency through Bioremediation

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Abstract

Palm oil mill effluent (POME) is liquid waste produced from palm oil extraction process. Discharging it to the river without treatment is violation according to Malaysia Environment of Quality Act (EQA) 1974. In Malaysia, ponding system is a conventional treatment method for POME due to its economical and simple process. The treatment process mainly involves two main treatment phases; anaerobic and aerobic degradation. Anaerobic degradation has a proven track record in reducing pollutant properties in POME up to 85%. The real challenge is to increase the efficiency of aerobic process as the biological oxygen demand (BOD) discharge limit has been further reduced from 100 mg·L^{-1} to less than 20 mg·L^{-1}. One of economical and feasible approach to increase the efficiency of aerobic phase is via bioremediation. This paper describes the limitation of aerobic degradation in ponding system, besides discussed on the important aspects that need to be optimized for a success implementation of bioremediation and its challenges.

Keywords

Aerobic, Anaerobic, Bioremediation, Biological Oxygen Demand, Palm Oil Mill Effluent

1. Introduction

Palm oil mill effluent (POME) is a high viscous liquid discharge generated from crude palm oil extraction process. It is mainly produced from two major pro-

cesses that use vast amount of water; oil palm fresh fruit bunch (FFB) sterilization and kernel-shell separation processes. Other minor contributors include turbine cooling, boiler blowdown and cleaning activities [1]. These processes generate effluent with high pollution properties containing oil, grease and concentrated solids. These pollution properties are commonly described in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), suspended solid (SS), total solid (TS), oil and grease (O & G) and total nitrogen (TN). Freshly generated POME or known as mixed raw effluent (MRE) is acidic with BOD and SS values may reach up to 25,000 mg·L^{-1} and 50,000 mg·L^{-1} respectively. The BOD and SS values of MRE may vary to different mills according to their daily FFB processing capacity, efficiency of oil extraction process and effluent treatment system. In Malaysia, a palm oil mill can approximately process as high as 20 to 50 metric tonnes of FFB per hour a day, and some may have higher processing capacity. For every metric tonne of the FFB processed, 0.7 to 1.0 m^3 of raw POME are generated [2]. That means, about 5 to 12 metric tonnes of raw POME would be generated by a mill in an hour a day with such FFB processing capacity. In year 2020, the production of crude palm oil (CPO) in Malaysia is 19.14 million tonnes, which increased 77% than 10.84 million tonnes produced in year 2000 [3]. For that reason, the production of POME was undeniably increased during the period corresponding to the increase in CPO production.

2. POME and Pollution

Due to high pollution properties in POME, the waste is considered harmful to the environment. It is not because of its toxicity; POME is non-toxic since no chemical is used during the oil extraction process [4]. POME is considered a harmful pollutant to the aquatic environment since it uses the available oxygen in the river for degradation process. This phenomenon leads to depletion of available oxygen for the existing aquatic lives in the water [5]. Therefore, treatment process is required before discharging to waterways. Department of Environment (DOE) Malaysia has enacted Environment Quality Act (EQA) 1974 that regulates palm oil mills to comply with the effluent discharge standards as shown in Table 1.

Table 1. POME discharge standard by DOE Malaysia.

Parameter	Discharge limit (mg·L^{-1})
Biological oxygen demand (BOD)	100
Suspended solid (SS)	400
Oil & grease (O & G)	50
Ammoniacal nitrogen (AN)	150
Total Nitrogen	200

Source: EQA 1974 (Act 127) and Subsidiary Legislation 2022 [6].

3. Conventional Treatment Method

POME usually goes through a treatment process to reduce its high pollution properties. The conventional treatment method that is implemented by majority of palm oil mills in Malaysia is the ponding system [4]. The ponding system is also conceptually known as waste stabilization pond to reduce the organic content from wastewater. The system in general implements a biological approach in every stage of its treatment process. Figure 1 shows the flow chart of POME treatment process that is commonly implemented in a particular palm oil mill [7]. The treatment process is supported by microbial degradation activities known as biodegradation that occur naturally in the ponds. Native microbes that live in the pond hydrolyzed the organic load in POME and assimilate them to grow. The degradation process leads to the reduction of solids and other pollution properties in POME.

Ponding system which involves anaerobic and aerobic degradation is considered as economical treatment method due to its low capital, maintenance and operation cost [8]. However, some may consider this treatment method to be ineffective and obsolete as it requires vast space, need long hydraulic retention time (HRT) and emits greenhouse gas with unpleasant odour to the environment [4] [9]. Despite the listed drawbacks, ponding system is still a preferred POME treatment method and is widely implemented by palm oil mills in Malaysia.

4. Efficient Anaerobic Phase

Mixed raw effluent (MRE) usually goes through a series of treatment process in an effluent treatment plant (ETP). The treatment process normally involves cooling phase, anaerobic degradation, facultative and aerobic stage. Anaerobic degradation process is beneficial to reduce high concentration of BOD and SS from agricultural wastewater [8]. The process has been proven in significantly plummeting the pollution properties in POME. During this phase, the biodegradation process occurs at the highest peak. Anaerobic process of one of palm oil mill in Malaysia has cause 86% and 90% reduction BOD and SS in the year 2020 (Figure 2). The efficiency of anaerobic process in POME treatment can
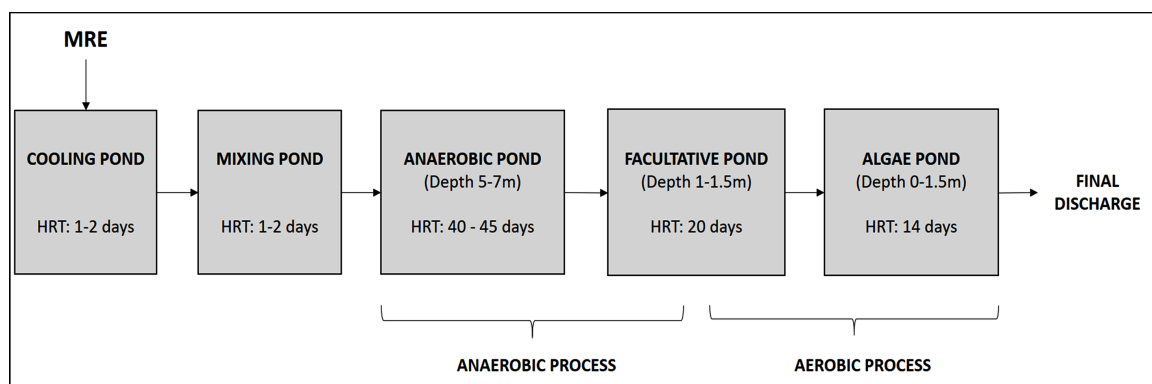
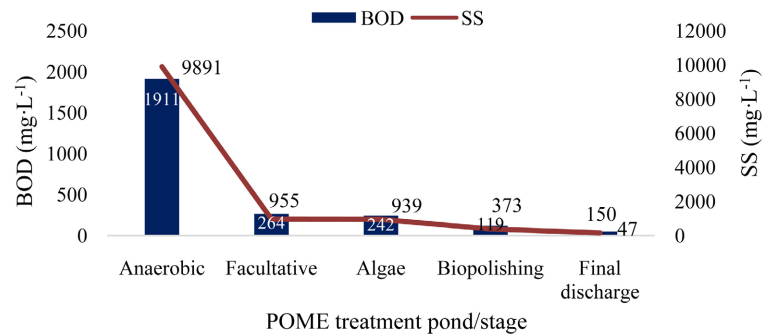Figure 1. The flow of POME treatment process in the palm oil mill.

Figure 2. Reduction of biological oxygen demand (BOD) and suspended solid (SS) recorded throughout different treatment stage of POME.

reach as high 95% [10]. At this stage, POME still contains high load of organic matter rich in carbohydrates, proteins, lipids, fatty acids, nitrogenous compounds and minerals [11]. The digestion involves hydrolysis, acidogenesis and methanogenesis [12] [13]. During hydrolysis and acidogenesis, the BOD is usually sustaining as it only involves the breakdown of complex compounds. The BOD reduced significantly during the final phase of anaerobic process known as methagenesis [7]. Anaerobic pond has the longest HRT (averagely 45 days) than any other pond. Long HRT is required for optimum hydrolysis and acidogenesis of recalcitrant long chain fatty acid (LCFA) like oleic acid, palmitic acid and stearic acid [14]. Olein acid and hexadecenoic acid (palmitic acid) are among LCFA that were not degraded after 14 days. It shows longer time is required for the process and that is why anaerobic pond has the longest HRT compared to other treatment phases. Anaerobic bacteria from *Syntrophomonadaceae* family are commonly reported as LCFA degrading bacteria during anaerobic process in POME [15] [16].

5. Inefficient Aerobic Phase

Effluent from anaerobic ponds is fed into facultative ponds, mainly constructed from 1 to 1.5 m depth. In facultative pond, both anaerobic and aerobic digestion occurs at different depth ranges of the pond [8]. After 20 days, output from facultative pond with BOD approximately less than 500 mg·L^{-1} will be fed into algae ponds to be aerobically treated. Algae ponds are categorized as aerobic pond usually have lower depth structures between 0.5 to 1 m deep with shorter HRT (14 days) than previous ponds [11]. With lower incoming BOD and shorter HRT, the efficiency of the ponds in terms of reduction in BOD and solids has gradually reduced towards the end of treatment process. This is where the real challenge begins. It started after the enforcement of new POME discharge limit from 100 mg·L^{-1} to less than 20 mg·L^{-1} [17]. Further reduction of BOD and solids through aerobic process is critically challenging as the organic load in the respective ponds is already low. The BOD values of the ponds indirectly described the available biodegradable organic matter in the ponds. Therefore, various approaches are explored to meet the discharged limit. One of economical

and feasible treatment method is through the implementation of bioremediation. Bioremediation is including bioaugmentation and bioflocculation via microbial application and phycoremediation by using microalgae. Important variables also need to be optimized to establish a success aerobic degradation.

6. Bioremediation

6.1. Bioaugmentation

POME comprises both organic and inorganic substances. These substances degrade through biodegradation that occurs throughout the treatment process. The use of microbes with the potential ability to degrade organic substances in POME is an alternative approach that has been widely explored and reported. *Pseudomonas*, *Acinetobacter*, *Sphingomonas*, *Nocardia*, *Flayobacterium*, *Rhodococcus* and *Mycobacterium* are among aerobic bacteria with degradative capabilities to degrade compounds like alkanes, polyaromatic and hydrocarbons which are commonly found in many pollutants including POME [18].

The use of indigenous and introduced microbes for POME treatment was found to be promising in various studies [19] [20] [21] [22]. Indigenous microbes are believed to be more tolerant to withstand extreme conditions as they have already used to the condition. Coexisting of the microbes makes them physiologically compatible and complements the surrounding environment [23]. The use of indigenous microbes for bioremediation of various effluent has been widely reported. *Pseudomonas* and *Bacillus sp.* were among indigenous bacteria that were isolated and reapplied onto oil contaminated soil [24]. *Bacillus cereus* 103 PB which was isolated from POME has been reported to induce the reduction of solid, oil and grease in the pollutant [19]. *Lysinibacillus* and *Salinibacterium* were indigenous species with polymer and hydrocarbon degrading ability to degrade naturally weathered polyethylene film in plastic [25]. Other indigenous microbes have been reported and their effectiveness to treat different types of wastewater is shown in Table 2. The use of indigenous microbes for POME treatment would create least issue to establish their population in the contaminated site.

Introduced microbes are believed to have better degradation ability to degrade the remaining substances compared to native microbes. Some compounds in POME may not be able to be degraded by the native microbes resulting in consistently high BOD and solids. The use of introduced microbes may increase the efficiency of POME treatment process. For example, the introduction of *Pseudomonas aeruginosa* that was not originally isolated from POME, but was able to remove COD and colour of final discharge POME [32]. *Bacillus cereus* is also an introduced isolate that has successfully reduced the COD and BOD of tested POME [33]. The population of introduced isolates *Aspergillus niger*, *Bacillus subtilis* and *Pseudomonas aeruginosa* increased in POME throughout fermentation time [34]. The reported studies prove that introduced microbes have no adaptability issue to grow and survive in POME.

Table 2. Indigenous microbes and their effectiveness to treat different type of effluent.

Type of effluent	Microbial isolates	Incubation time	Removal efficiency (%)*								References
			BOD	COD	TSS	TS	TDS	TN	P	AN	
Brewery effluent	*Aeromonas* sp. *Pseudomonas* sp. *Bacillus* sp	12 days	74 to 95	77 to 93	67 to 90	55 to 85	53 to 88	54 to 77	42 to 78		Oljira *et al.*, 2018 [26]
Shrimp aquaculture wastewater	*Bacillus vietnamensis*	5 days								72	Sarmila *et al.*, 2015 [27]
Municipal waste	*Bacillus Anthracis*	72 hours	42	84	68		71		59		Singh *et al.*, 2018 [28]
	Serratia Marcescens		29	21	80		69		59		
	Listeria Monocytogenes		22	60	44		14		48		
	Klebsiella Pneumonia		29	23	0		0		19		
	Streptococcus Pneumonia		25	21	0		77		42		
	Enterococcus Faecalis		14	83	54		81		55		
	Staphylococcus Aureus		42	55	0		0		72		
	Control		9	15	0		12		0		
Maize processing wastewater	*Saccharomyces cerevisiae, Bacillus subtilis, Bacillus amyloliquefaciens, and Bacillus licheniformis*	30 days	98	97							Ewida, 2020 [29]
Tannery wastewaters	*Citrobacter freundii*	5 days	86	80							Vijayaraj *et al.*, 2018 [30]
POME	*Meyerozyma guilliermondii*	7 days		72				49	61		Ganapathy *et al.*, 2019 [31]

*BOD—Biological Oxygen Demand, COD—Chemical Oxygen Demand, TSS—Total Suspended Solid, TS—Total Solid, TDS—Total Dissolved Solid, TN—Total Nitrogen, P—Phosphate and AN—Ammoniacal Nitrogen.

The use of microbial consortia consisting a mixture of microbial isolates is another promising approach in bioremediation. The microbes may have different abilities to degrade different pollutant compounds in waste based on their enzymatic functions capability [35] [36] [37]. The consortium of potential microbes has been widely reported capable to further reduce the BOD and COD level in POME. The inoculation of multi-microorganisms constitutes *Pseudomonas* sp., *Bacillus* sp., *Aspergillus* sp., *Fusarium* sp. has decreased BOD of tested POME [19]. Other studies have reported that microbial consortia comprise *Pseudomonas* spp., *Actinomycetes* spp., *Bacillus* spp., *Streptomyces* spp. and *Staphylococcus* spp. demonstrated high BOD reduction up to 94% compared to individual isolate which only ranges from 59% to 77% [38]. The use of bacteria combination *Bacillus cereus* 103 PB and *Bacillus subtilis* 106 PB reduced 91% COD in POME compared to 14% recorded in control [39]. While consortium bacteria *Bacillus cereus*, *Pseudomonas azotoformans* and *Burkholderia cepacia* have successfully caused BOD, COD and TSS reduction as high 92%, 82% and 74%, respectively [22].

Dissolve oxygen is a crucial parameter to determine BOD in a particular effluent. Microbes use oxygen for degradation of organic matter and eventually reduce dissolve oxygen in the effluent. This will rise the BOD level in the effluent right after microbial application. The BOD will sustain high during the degradation process, as the microbial population is increased. Finally, the microbial population will drop once the degradation process of organic matter is completed. This phenomenon shows that time is the killer factor for a successful biodegradation. The higher organic matter in a particular effluent, the longer period for biodegradation is required. The use of microbes in the effluent treatment would not immediately reduce BOD of the sample as proven by chemical treatment or filtration method. However, bioaugmentation would be sustainable approach for environment and offer cheaper solution for the effluent treatment process. Types of microbes, sufficient dose and suitable inoculation point need to further studied for better implementation of bioaugmentation in the contaminated field.

6.2. Bioflocculation

Flocculation is another methodology adopted in wastewater treatment where colloids or particulates floc and settle to be removed from water (as shown in Figure 3). Bioflocculation for wastewater treatment has been explored as a substitute to the chemical flocculating agent which primarily gives disadvantages to the environment and human health. Bioflocculants produce by microorganisms through the secretion of flocculating substances such as polysaccharides, proteins and glycoproteins [40]. Various studies have reported the significant effect of bioflocculants in reducing turbidity, COD and solids in industrial wastewater [41] [42] [43] [44]. However, the potential use of bioflocculants for POME treatment has not yet been reported. POME has been recently reported for its potential use as substrate for bioflocculant production [45] [46] indicating the potential use of bioflocculants for POME treatment.

Bioflocculation process would be an ideal approach to be implemented at the final treatment stage. Solids in POME that usually contains very small particulates of lignocellulose materials are hard to be degraded. Further degrading the particulates at final treatment stage is not feasible and therefore, bioflocculation
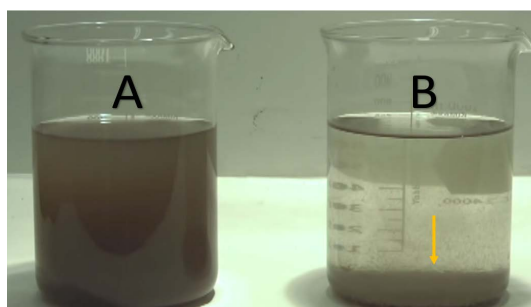

Figure 3. (A) Polluted water containing suspended colloids and (B) Flocculated colloids settled to the bottom of beaker.

could be used to remove the remaining contaminants. The flocculated particulates are also easier to be removed as they are already binded together. Therefore, economical solid remover can be used instead of installing expensive filter that could increase the operational cost of the mill.

6.3. Phycoremediation

The use of microalgae in wastewater treatment has gained much attention nowadays. Microalgae is photosynthetic microorganisms that live in either freshwater or marine. It has an outstanding ability to absorb carbon sources in wastewater as nutrients and for lipids production [47]. This ability makes microalgae a potential biofuel producer. Microalgae uses light water and carbon dioxide to grow and produce oxygen to the environment. Therefore, the use of microalgae would be another approach to further reduce contaminants in wastewater especially in POME.

Microalgae have been reported to treat various pollutants including domestic sewage ([48], industrial and agro industrial [49] including POME [50]. Despite listed advantages, the growth of microalgae is prone to high nitrogen concentration compounds in wastewater such as ammonia [51]. Due to this condition, microalgae is usually implemented as a downstream wastewater treatment process.

6.4. Sufficient Inoculum for Optimum Aerobic Process

Most of the reported findings on optimizing the right inoculum size are based on laboratory studies which may not utterly simulate the real condition in the effluent treatment pond. The establishment of sufficient microbial inoculum at treatment site becomes more challenging due to the inconsistent BOD of incoming POME, resulting in inconsistency to meet the effluent discharge standard. Optimizing the growth of selected microbes on the selected treatment site is also important to prevent the development of excess final biomass [52]. Aerobic biodegradation normally produced solid matter or sludge as a by-product [53] [54]. The solid matter comprises suspended and dissolved solids which are mainly generated from microbial cells, microbial waste products, cell fragments, macromolecules and miscellaneous debris [55]. The use of excess starter seed of microbial inoculum would produce excess final biomass in the form of sludge. The growth of inoculated microbes was increased through time in diluted POME [33] [34]. Aerobic degradation would suddenly rise the oxygen demand in treated POME due to the increase of microbial activity, population and environmental conditions [54].

At the same time, sufficient inoculum is needed to prevent microbial elimination due to nutrient deficiency [56]. No field study on optimum microbial inoculum for POME treatment has been reported so far. Most laboratory scale studies reported using more than 5% starter inoculum [22] [34] [57] [58]. Therefore, the growth of the used microbes should be optimized for an efficient de-

gradation of the remaining contaminants with a very minimal development of biomass. At the same time, the size should be practical to be applied in the real contaminated field.

6.5. Optimum Aeration

The crucial part is to provide a conducive environment to propagate and sustain their population in the intended treatment site. The use of aeration mechanization like surface aerator and air diffuser would support an optimum biodegradation process in POME. Mechanical surface aerators are mainly introduced at aerobic ponds to supply sufficient aeration and have effectively reduced BOD through aerobic process [7]. Diffuse aeration is usually installed in an activated sludge system or bio polishing plant to supply sufficient oxygen and improve the effluent properties before finally discharge [54]. However, it is crucial to increase the concentration of oxygen supply into the aerobic pond. Purified oxygen with higher concentration would increase the biodegradation process in the pond.

6.6. Sustaining Sufficient Inoculum via Establishment of Microbial Biofilm

Short HRT of the treatment pond may cause a repetitive replenishment of the microbes in order to sustain the BOD level. The establishment of microbial fixed biofilm is believed able to reduce the BOD as well preventing the microbial cells from being drained from the treatment system [59]. Biofilm is a complex structure community if bacterial cells are densely packed together in a self-enclosed slimy polymeric matrix that adheres to surface or interface [60]. Extracellular polymeric substances (EPS) secreted by the microbes establish protective surface area to support the growth of their cells and protect them from a harsh environment (as shown in **Figure 4**). Hydrolysis activity of biofilm-containing suspensions was higher than cell free suspensions [61]. This makes the fixed biofilm system which is mainly established as downstream treatment a better approach to further degrade the leftover contaminants in POME [59]. Some of fixed biofilm that has been used in POME treatment are rotating biological contractors (RBC), trickling filters [54] and moving bed fiofilm reactor (MBBR) [62].
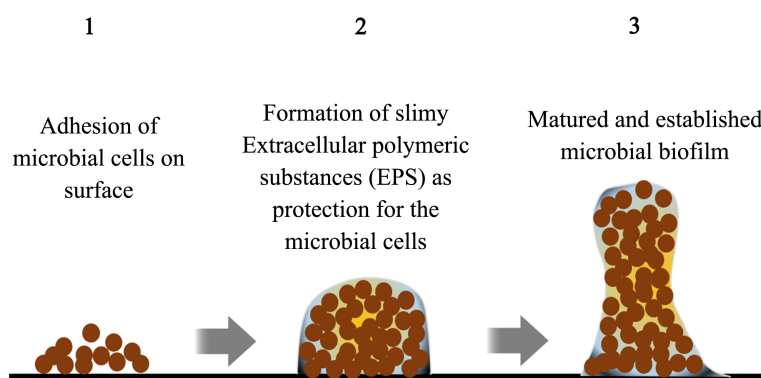

Figure 4. Formation of microbial biofilm.

6.7. Available Extended Treatment System for POME

Bio-polishing plant and filtration via membrane bioreactor (MBR) are among the extended treatment process that has been employed by some palm oil mills. In order to meet with the new discharge standard limits, these systems were established as downstream treatment processes to further degrade and remove the remaining contaminants. In bio-polishing, the incoming POME goes through biodegradation process with support of supplied oxygen via vigorous agitation [7]. Separation of suspended solid from POME happened in clarifier tanks. The sediment of produced biomass discharge from the system can be used as organic fertilizer while the supernatant is finally discharged into the watercourse. However, sometimes the separation process is not efficiently occurred leads to the presence of solids particulates in the final discharge effluent.

The MBR filtration process has a successful track record to remove the remaining contaminants that were not completely degraded in earlier treatment stages. The advantage of using this system is that it can remove inorganic matter from the effluent that is impossible to be degraded by microbes. It requires a shorter treatment period, smaller coverage area and produces high quality water with less odour [63]. Despite the listed advantages, MBR technology is reported to be prone to fouling membrane due to the gradual accumulation of particulates on the membrane surface and pores [64]. **Figure 5** shows one of MBR systems that is used to filter POME in palm oil mill. The installation and maintenance cost of the technology is also extortionate [65]. Therefore, optimizing the biodegradation activity of POME during aerobic phase would be an alternative approach to compensate any drawbacks that existed from the implementation of high technology treatment method.

Figure 5. MBR system for POME treatment in palm oil mill.

7. Conclusions

It is a regulation to treat POME before discharging into waterways. The conventional treatment method usually is able to reduce BOD of final discharge to less than 100 mg·L^{-1}. The treatment process becomes more challenging as the discharge standard limit in Malaysia for BOD has been further decreased to 20 mg·L^{-1}. Currently, anaerobic degradation phase has managed to reduce more than 80% BOD of POME. The critical part is to further increase the efficiency of aerobic degradation phase to meet the new discharge limit. Different to anaerobic phase, POME in aerobic phase is no longer feasible for renewable energy as the nutrient content is already low. Establishing a costly treatment method such as MBR would significantly increase the operational cost of the mill.

Increasing the efficiency of aerobic degradation phase through bioaugmentation would be economical and practical to be implemented. The use of microbes would degrade the remaining organic compounds that contribute to the BOD level of the effluent. Optimizing the related variables to reach a successful aerobic degradation should be done. The important variables are including determining compounds related to BOD, prospecting the potential and workable isolates, optimizing the inoculum size, optimizing the optimum requirement of dissolve oxygen, aeration and determine the suitable inoculation point. These important variables need to be properly optimized so that the remaining contaminants would be completely degraded and finally achieve BOD lower than 20 mg·L^{-1}.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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