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Review

Application of semifluidized bed bioreactor as novel bioreactor system for the treatment of palm oil mill effluent (POME)

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Palm oil mill effluent (POME) is a high strength organic wastewater, which adversely affects aquatic life as well as human life directly or indirectly. This has attracted concern due to the rapid expansion of the oil palm industries in countries such as Malaysia and Indonesia, which currently contribute about 80% of the world palm oil. The conventional bioreactors such as pond digester, anaerobic filtration, up-flow anaerobic sludge blanket (UASB), up-flow anaerobic sludge fixed-film (UASFF), continuous stirred tank reactor (CSTR), anaerobic contact digestion and fluidized bed, used over the past decades are largely operated anaerobically. They have been reported to be less effective for the treatment of the increasing volume of POME as well as meeting the new stringent wastewater treatment standards. Therefore, treatment method such as aerobic under a continuous system is anticipated to be effective alternative to the defects observed in the previously employed bioreactors. The use of semifluidized bed bioreactor containing immobilized cells for the biodegradation of various high strength organic wastewater have been reported as highly efficient treatment method. Thus, to address the increasing environmental impact of POME in the producing nations, the application of semifluidized bed bioreactor as a novel technology in the palm oil industry will be of immense benefit, economically and environmentally.

Key words: Bioreactors, palm oil mill effluent (POME), semifluidised bioreactor, wastewater.

INTRODUCTION

Processing of oil palm fresh fruit bunches (FFB) primarily to produce palm oil is often accompanied by liquid, solid and gaseous pollutants, which are ejected into the environment. Most of the palm oil mills in Malaysia were initially considered as less dangerous because of their low numbers and production capacities. However, with the explosive expansion in the palm oil industry, particularly in the late 70's, the pollutants load, mainly in the form of palm oil mill effluent (POME), could not be accommodated by the rivers and the environment in general, perhaps due to the lack of suitable treatment technologies (Industrial Processes and the Environment, 1999; MPOB, 1999). Most of these pollutants have now been identified with various adverse effects on human and the ecology, for instant POME has about 100 times oxygen depletion potential than domestic sewage (Khalid and Wan Mustafa, 1992).

POME is discharged, traditionally from the milling process into open ponds for anaerobic digestion before sending to water bodies, particularly rivers that are usually very close to the mills. The open ponds have attached drying beds used to sundry the sludge settled

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Abbreviations: **POME**, Palm oil mill effluent; **UASB**, up-flow anaerobic sludge blanket; **UASFF**, up-flow anaerobic sludge fixed-film; **CSTR**, continuous stirred tank reactor.

Table 1. Characteristics of wastewater from process industries.

Parameter	Steel Industry	Milk dairy plant	Palm oil mill*	Parameter limits^
pH	8.5 – 9.5	7.3 – 9.5	4 – 5	5 – 9
Total solids (mg/l)	175 – 1300	1690 – 2730	11,500 – 79,000	-
Dissolved solids (mg/l)	125 – 800	920 – 1660	34,000	-
Suspended solids (mg/l)	50 – 500	690 – 1810	5,000 – 54,000	-
Oil and grease (mg/l)	NA	290 – 1390	150 – 18,000	50
Total nitrogen (mg/l)	800 – 1400	62	80 – 14000	200
BOD (mg/l)	160	816 – 3070	10,000 – 44,000	100
COD (mg/l)	790 –2450	1000 – 4510	16,000 – 100,000	-

Adapted from Industrial Processes and the Environment (1999), Jeena et al. (2005) and Ahmad et al. (2005). NA, Not available.

out of the POME, but during the rainy season, the process creates problems such as sludge flooding, insects and bad odour, which characterize a typical palm oil mill. Attempts were made to attend to these wastes, particularly exploiting their reuse potentials as value added raw materials. Such efforts include application of POME as animal feed, fertilizer as well as a source of energy (Khalid and Wan Mustafa, 1992; Igwe and Onyegbado, 2007). Similarly, some solids obtained from different unit operations were exploited for their bioproduct values (Alam et al., 2009).

Large volume of POME generated from the increasing palm oil industries in countries such as Malaysia and the characteristics of wastewater from few processing industries (Table 1) show that the POME contain higher concentrations of various pollutants. Furthermore, the Malaysian Government, under the Department of Environment (DOE), has responded to this environmental menace, thus, parameter limits for effluent discharge (Table 1) has been mandated on the palm oil mills to comply with, in order to make the discharged POME safe to the human and the ecology.

The conventional POME treatment method is predominantly anaerobic system, which involves the use of various bioreactors. Some of these bioreactors have been studied for the treatment of POME at laboratory scale, though few have been applied industrially (Ahmad et al, 2005; Hassan et al., 2009). These include up-flow anaerobic sludge blanket (UASB) reactor, up-flow anaerobic filtration; fluidized bed reactor and up-flow anaerobic sludge fixed-film (UASFF) reactor; anaerobic contact digester; continuous stirred tank reactor (CSTR) and membrane technology (Chin, 1981; Ibrahim et al., 1984; Borja and Banks, 1994a, b, 1995a, b; Ahmad et al., 2006; 2007; Najafpour et al., 2007). Few studies on the application of aerobic activated sludge reactor and evaporation method have been reported (Ma, 1997; Vijayaraghavan, 2007).

This mini-review examines the current treatment technologies, involving various bioreactors employed in the treatment of POME and the feasibility of introducing semifluidised bed bioreactor as a novel technology for effective treatment of POME.

TREATMENT TECHNOLOGIES OF POME

Various wastewater treatment technologies employed, independently or jointly in the treatment of POME in most of the local palm oil mills, varies from one mill to the other due to the plant design as well as inclusion of new production and treatment technologies. The pre-treatment of POME is a physical wastewater treatment process, which includes stages such as screening, sedimentation and oil removal in oil traps prior to the secondary treatment in biological treatment systems (Industrial Processes and the Environment, 1999). POME contains a very high organic matter, which is generally biodegradable and this facilitate the application of biological treatments based on anaerobic, aerobic and facultative processes (Chin and Wong, 1983). The biological treatment depends greatly on a consortium of active microorganisms, which utilizes the organic substances present in the POME as nutrients and eventually degrades these organic matters into simple by-products such as methane, carbon dioxide and hydrogen sulphide. Generally, the methane gas (CH_4) is flared, while the digested liquid is discharged into holding ponds before final disposal on land (Igwe and Onyegbado, 2007) (Table 2). This development led to the use of ponds and tanks that characterized most of the palm oil mills (Khalid, and Wan Mustafa, 1992).

Conventional ponding treatment systems

The most common treatment system employed in most palm oil mills to treat POME is the ponding system, which comprises of de-oiling tank, acidification ponds, anaerobic ponds and facultative or aerobic ponds (Chan and Chooi, 2009). Anaerobic ponds produce higher emission of methane with an average methane composition of 54.4% and consistent gaseous mixture as compared to open digester tank (Yacob et al., 2006). However, it takes a longer retention time of about 20 to 200 days (Chan

Table 2. Performance of various anaerobic treatment methods on POME treatment.

Reactor type	Hydraulic retention time (days)	Methane composition (%)	COD removal efficiency (%)	Reference
Anaerobic contact process	4.7	63	93.3	Ibrahim et al., 1984
Upflow Hybrid	N/A	7 L Biogas/day	62	Noor et al., 1989
Single stage immobilized cell	6.2	0.325 L Methane /gCOD	96.2	Borja and Banks, 1994a
Anaerobic filtration	15	63	94	Borja and Banks, 1994b
UASB	4	54.2	98.4	Borja and Banks, 1994c
Anaerobic Filter	3 .5	8.0-20.0 L Biogas/day	88.0-91.0	Borja and Banks, 1995a
Fluidized bed	0.25	N/A	78	Borja and Banks, 1995b
Anaerobic digester	20	36	80.7	Yacob et al., 2006
UASFF	3	71.9	97	Ma et al., 1997
CSTR	18	62.5	80	Tong and Jaafar, 2006
Anaerobic pond	40	54.4	97.8	Yacob et al., 2006

Source: Poh and Chong, 2009.

and Chooi, 2009). Selection of open digesting tanks for the treatment of POME is always an option where there is limited land area for pond system, since a typical pond size, which usually depends on the capacity of the palm oil mill, is approximately equivalent to half the size of a soccer field (Yacob et al., 2006). The generation of methane gas in the open pond digester is often improved through mixing which facilitates effective contact between the bacteria consortia and the organic substrate present in the POME, however, low conversion of methane is reported for the system (Poh and Chong, 2009; Leslie et al., 1999).

Continuous stirred tank reactor (CSTR)

The CSTR is a closed-tank digester equipped with mechanical agitator for effective mixing of the wastewater and this improves the wider surface contact between the microbes and the biomass to generate biogas. Few reports on the application of CSTR for the treatment of POME were those reported by Ugoji (1997) and Yacob et al. (2006) for plant and laboratory scales, industrial and laboratory scales, respectively. The plant scale CSTR adopted for the treatment of POME, situated in Keck Seng palm oil mill, Johor (Malaysia), has COD removal efficiency as high as 83% and biogas generation of 62.5% (Tong and Jaafar, 2006). The laboratory scale application of CSTR for the treatment of POME reported by Ugoji (1997) achieved COD removal efficiency between 93.6 and 97.7%. Poor mixing due to large volume of POME treated in the plant scale may account for the lower removal efficiency. However, biofilm support system (BSS) which serves as a support media for growth of biomass has been incorporated in order to upgrade removal efficiency of CSTR and this eradicated biomass recycling (Ramasamy and Abbasi, 2000).

Anaerobic filter bioreactor (AFB)

The anaerobic filter bioreactor (AFB) applied for the treatment of POME is fitted with packing, which allows biomass to be attached on the surface. The raw POME feed is introduced from the bottom of the bioreactor and in the process the treated effluent, as well as the usually gene-rated biogas, leaves through the top of the bioreactor (Borja and Banks, 1994a, 1995a). The construction and operation of anaerobic filter is relatively less expensive and removes suspended solids in the effluent eliminates from the standard, which requires no further solid separation or recycle (Russo et al., 1985).

Other advantages include the use of smaller reactor volume, shorter hydraulic retention times (HRTs), high substrate removal efficiency, maintenance of high concentration of biomass and tolerance to shock loadings (Borja and Banks, 1994b; Reyes et al, 1999; Wang and Banks, 2007; Van Der Merwe and Britz, 1993). Moreover, the efficiency of the anaerobic filters is usually affected by filter clogging, particularly in continuous operation (Bodkhe, 2008; Jawed and Tare, 2000; Parawira et al., 2006), though this is less pronounced for wastewater containing lower content of suspended solid as compared to POME. Borja and Banks (1995a) reported clogging of anaerobic filter in the treatment of POME at organic loading rate (OLR) of 20 g COD/l/day and COD removal efficiency as high as 94% which was recorded in another study (Borja and Banks,1995a).

Up-flow anaerobic sludge blanket (UASB) reactor

The UASB reactor was primarily designed to improve anaerobic sludge that will give good settling properties (Lettinga, 1995). Thus, in its operation, sludge from organic matter degradation and biomass settles in the reactor, leading to effective digestion by the biomass granules (Poh and Chong, 2009). The application of UASB for the treatment of POME has attracted interest, particularly, with high COD removal efficiency (≈98.4%) with the highest operating OLR of 10.63 kg COD/m^{3}day (Borja and Banks, 1994c). Similarly, its ability to treat wastewater with high suspended solid content, which are susceptible to clog reactors containing packing materials and generation of higher methane production, have made the use of UASB more attractive (Stronach, 1987; Fang and Chui, 1994; Kalyuzhnyi et al., 1996, 1998). The current challenges facing this reactor include long start-up periods, particularly, if seeded sludge is not granulated and operation of treatment system at higher OLR is due to large volume of POME discharge daily from palm oil processing mills (Poh and Chong, 1984).

Fluidized bed reactor

Fluidized bed reactor is an advanced packed bed system, which allows expansion of the bed during operation. This has various advantages such as large surface areas for biomass attachment, enabling high OLR and short HRTs during operation, minimization of channelling, plugging or gas hold-up problems (Toldrá et al., 1987; Garcia-Calderon et al., 1998; Borja, 2001; Sowmeyan and Swaminathan, 2008). The fluidized bed bioreactor may be operated at higher up-flow or inverse flow; however, the inverse flow anaerobic fluidized bed is capable of tolerating higher OLRs than the up-flow system. Borja and Banks (1995b) have studied the treatment of POME in higher up-flow fluidized bed reactor, where velocity of raw POME is maintained at high velocity for effective expansion of the support material bed as well as biomass attachment and growth on the support material. Similarly, Poh and Chong (2009) reported a better treatment of POME, using fluidized bed as compared to anaerobic filter and this is due to fluidized bed's tolerance for higher OLRs, better methane gas generation and shorter HRT (6h). Moreover, this system usually requires recycling or further filtration retain the bed's support materials.

Anaerobic contact digestion

Contact process is an important wastewater treatment technology, which involves the application of digester and sedimentation tank (Vlissidis and Zouboulis, 1993). Generally, the digester effluent containing sludge transferred to the sedimentation tank is allowed to settle for a period of time and the effluent is later recycled into the digester. Ibrahim (1984) reported the application of contact process technology for POME treatment pilot plant but indicated that formation of scum affects the efficiency of the system. Moreover, Vlissidis and Zouboulis (1993) reported 80% COD removal efficiency by the system, despite the challenges of the scum formation (Table 3).

APPLICATION OF SEMI-FLUIDIZED BED BIOREACTOR FOR WASTEWATER TREATMENT

Semifluidized bed bioreactor is characterized by simultaneous formation of packed bed and fluidized bed, as well as an adjustable top screen that allows the fluid to pass through, thus, preventing the free expansion commonly found in fluidized bed. While in operations, the bottom portion of the bed is in fluidized condition while the top portion of the bed assumes a packed bed state. Unlike fluidized bed, higher velocity of fluid in semi-fluidized bed is possible and this lessens the external mass transfer resistance (Jeena, 2005). Furthermore, improved mass transfer in semi-fluidized bed at the cost of higher-pressure drop is compensated by lower operation cost through efficient use of oxygen. The top packed bed portion complement the fluidized bed portion by acting as a polishing section and this lowers the level of contaminants as compared to fluidized bed bioreactor. Semifluidized bed bioreactors do not exhibit elutriation of the particles coated with microorganisms, and unstable bed expansion commonly associated with fluidized bed bioreactors. Similarly, technical challenges such as plug-ing of the bed by solids found in fixed-bed operations are eliminated in semifluidized bed. A new semifluidized bed is usually seeded by introducing microorganisms and nutrients to the bed under flow rates slightly higher than the minimum fluidization velocity as part of the start-up operation processes. However, the use of immobilized particles is currently considered as economical and effective option, though the previous method may be employed particularly to stimulate the column wall. Meikap and Roy (1997) compared the performance of different bioreactors with respect to degradation of phenol in wastewater (Table 4). As a result of the superiority of this bioreactor, this study was conducted to treat POME, which is equally a high strength wastewater.

DEVELOPMENT OF SEMIFLUIDIZED BED BIOREACTOR

The novel semifluidised bed bioreactors are preferred to be packed as solid support containing immobilized cells,

Table 3. Some advantages and disadvantages of various bioreactors used for the treatment of POME.

Reactor	Advantages	Disadvantages	Reference
Conventional anaerobic digestion (pond and digester)	Low capital, operating and maintenance cost Tolerate large range of OLR (peculiar to POME) Produced sludge cake (bio-fertilizer)	Large volume for digestion Long retention times No facilities to capture biogas Lower methane emission	Chan and Chooi, 1984
Anaerobic filtration	Small reactor volume required Production of high quality effluent Short hydraulic retention times Tolerate shock loadings High biomass concentration retention in the packing	Clogging at high OLRs High media and support cost Unsuitable for high suspended solid wastewater	Borja and Banks, 1994b, 1995b
Fluidized bed	Most compact of all high-rate processes Effective mixed conditions in the reactor Large surface area for biomass attachment No channelling, plugging or gas hold-up Faster start-up	Require high power for bed fluidization High cost of carrier media Unsuitable for high suspended solid wastewater Generate biogas not capture	Leslie Grady, 1999
UASB	Highly effective for treatment of high suspended solid wastewater Produce high quality effluent No media required (less cost) High concentration of biomass retained in the reactor High methane production	Performance dependent on sludge settleability Foaming and sludge floatation at high OLRs Long start-up period if granulated seed sludge is not used Granulation inhibition at high volatile fatty acid concentration	Lettinga, 1995; Kalyuzhnyi, 1996; Goodwin, 1992
UASFF	Higher OLR achievable No clogging Higher biomass retention More stable operation Tolerate shock loadings Suitable for diluted wastewater	Lower OLR when treating suspended solid wastewaters	Ayati and Ganjidoust, 2006
CSTR	Large surface area for wastewater and biomass contact through mixing Higher gas production as compared to conventional method	Less efficient gas production at high treatment volume Less biomass retention	

Table 3. Contd.

Anaerobic contact process	Reaches steady state quickly Short hydraulic retention time Produces relatively high effluent quality	Less stable due to oxygen transfer in digesting tank Settleability of biomass influences effective performance	Hamdi and Garcia, 1991

Source: Poh and Chong, 2009

Table 4. Comparison of performance of bioreactors used for the degradation of phenolic wastewater.

Condition of feed/ effluent	CSTR Bioreactor	Packed bed bioreactor	Fluidized bed bioreactor	Semi-fluidized bed bioreactor
500 mg/L of phenol	1.0 kg of phenol/day/m^3	4.7 kg of phenol/day/m^3	8.5 kg of phenol/day/ m^3	9.1 kg of phenol/day/ m^3
Treated effluent	0.25-1.0 mg/L	0.21-1.0 mg/L	0.01-0.5 mg/L	0.008-0.45 mg/L

Jeena et al. (2005).

as a result, the design of semifluidized bed would include the development of the immobilized cell support as well as other essential parameters for the bioreactor configurations. Parameters governing the performance of a semi-fluidized bioreactor include properties of particle: size, shape and density; properties of fluid: density, viscosity and velocity; initial static bed height; height of top restraint; dimensions of column and its configuretion (Meikap and Roy, 1997).

CONCLUSION

The current facilities and methods adapted for the treatment of POME in most of the palm oil mills are not highly effective in treating the pollutants in the POME to the stringent standards required. Similarly, they have challenges by ecological factors such as large land requirements, thus introduction of semifluidised bed bioreactor, containing immobilized cells, as a novel unit operation for biodegradation of POME will facilitate improvement on environmental impact of POME and related issues in the rapid expanding palm oil mill industry.

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