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Review Article

Emerging trends in POME treatment and applications: chemical and biotechnological aspects

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Abstract

Globally, environmental challenges are growing more and more significant. Changes in soil have been caused by the years-long discharge and careless disposal of palm oil mill effluent (POME). A systematic review explored emerging trends in POME treatment and applications, with a focus on recent, innovative methods for POME treatment with biological and chemical treatment technologies, chemical and biotechnological approaches. The review highlighted several key findings, including the efficiency and cost-effectiveness of these approaches, their ability to reduce environmental impacts, and their potential to recover resources such as energy and nutrients. Quantitative information on the efficacy of these approaches was also provided. Based on these findings, the review concludes that the aforementioned approaches can significantly improve POME treatment and offer a promising way to reduce environmental impacts and recover resources. However, further research is needed to optimize and scale up these approaches, as well as to assess their long-term sustainability. In addition, it is important to consider the social, economic, and environmental factors that may affect the successful implementation of these approaches.

Keywords: POME, environmental impact, treatment methods, biotechnology, palm oil production

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1. Introduction

Palm oil mill effluent (POME) is a by-product of the palm oil industry, and it is one of the largest sources of wastewater in Nigeria, Malaysia, and Indonesia (Ahmad et al., 2019; Kamyab et al., 2018; Olabode & George, 2020; Liew et al., 2015). But Indonesia and Malaysia are the two biggest oil palm manufacturing nations rich in various endemic and forest-dwelling species. Malaysia has a tropical atmosphere and is prosperous with regular assets. Malaysia produces about 41% of the world's supply of palm oil, Indonesia 44% and Nigeria 2% of global but > 50% of Africa's total palm oil production as shown in **Figure 1** (Anyaoha & Zhang, 2023; Kamyab et al., 2018). POME contains high levels of organic matter, nitrogen, phosphorus, and other pollutants that can cause environmental problems if not adequately treated. Carbon dioxide (CO_2) and methane (CH_4) are released in large amounts and are often kept in open lagoons. There are between 5 to 25 tCO_2 equivalent emissions created for each ton of crude palm oil (CPO), with nine to eighteen percent of those emissions coming from POME (Rajani et al., 2019). However, the current state-of-the-art of POME treatment includes a variety of chemical and biotechnological technologies that have been developed in recent years by several researchers (Ahmad et al., 2019; Cheng et al., 2021; Saputera et al., 2021).

Chemical technologies such as coagulation, flocculation, adsorption, and electrochemical treatment have been effective in removing pollutants such as COD, BOD, nitrogen, phosphorus, and other forms of pollutants from POME (Maluin et al., 2020; Razak et al., 2021).

Biotechnological approaches such as anaerobic digestion and aerobic digestion have also been shown to be effective in treating POME and have the added benefit of producing biogas that can be used as a source of renewable energy (Ahmad et al., 2019; Olabode & George, 2020).

Similarly, POME can be used to produce solvents like actetonebutanol, bio-insecticides, antibiotics, organic acids like citric and acetic acids, and polyhydroxyalkonates. Furthermore, in order to increase soil fertility and address local, national, and international food demands, farmers can utilize POME in both rural and urban settings when it is correctly prepared and packaged (Olabode & George, 2020). Nevertheless, if discharged into the environment untreated, POME is the most significant wastewater pollutant and might have catastrophic effects. Because of the emissions of biogas, POME treatment is crucial for environmental protection (Ahmad et al., 2019).

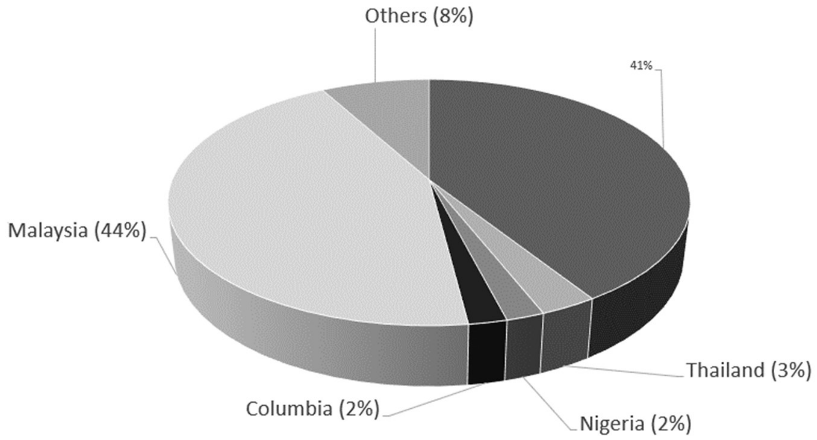

Figure 1. Palm oil production (Kamyab et al., 2018)

The properties of POME are mainly available in the literature, and POME has been reported to have far-reaching effects on the ecosystem (Embrandiri et al., 2012; Mohammad et al., 2021). Given its toxic nature, the growth and development of POME management technologies have intensified from the standpoint of air, soil and water pollution resulting from POME generation.

Several strategies have been documented in literature as treatment methods for POME, with a few being adopted at industrial scales. For instance, before environmental discharge, the techniques of aerobic pond systems and/or application on land to treat POME are widespread at the measure industrial scale (Mohammad et al., 2021). However, the inconsistent treatment outcomes across farms over time are significant setbacks, as most studies have examined POME treatment under idyllic laboratory conditions. Among the many and more recent treatment alternative techniques are the biological options of (an)aerobic therapies and chemical techniques. While some of the techniques of choice must, within a reasonable timeframe, offer the best results in terms of waste management – reduction in chemical oxygen demand (COD) and biochemical oxygen demand (BOD), others assist in useful product recovery including but not limited to biofuels, biofertilizers, and bioproducts (Ahmad et al., 2020; Damaraju et al., 2019; Hope & Gideon, 2015; Ndubuisi-Nnaji et al., 2020). Various methodologies have been studied for developing low-priced and active treatment techniques, including the integrated anaerobic-aerobic bioreactor (IAAB) system. Using bacteria, fungi, plants, etc., and other unconventional methods has also been demonstrated as a cost-effective technique for treating POME (Lee et al., 2019; Mohammad et al., 2021).

Due to the ability of POME treatment to protect the environment, this work presents an overview of the characteristics of POME and its environmental impact but mainly reviews and provides up-to-date information on the existing and emerging treatment options for POME treatment for the purpose of combating its daunting environmental impacts. First, it provides an in-depth review of the most recent treatment technologies for POME treatment. Second, it highlights the advantages and disadvantages of these technologies, as well as future research directions and recommendations for their implementation. By doing so, this work will help to guide future research and development efforts in this area. It will also help to improve the efficiency and sustainability of POME treatment in the future.

2. Characteristics of POME

POME, a brown slurry of organic solids (4-5%), residual oil (0.5-1.0%) and water (95%) which is generated by the palm oil mill during the multiple processing steps of crude palm oil production (Onyla et al., 2001). In 2018, Abdulsalam and co-workers surmised that the brownish coloration is due to the high levels of organic matter such as carotene (8 ppm), pectin (3400 ppm), tannin, phenolic (5800 ppm), and lignin (4700 ppm) (Abdulsalam et al., 2018). Also, other reports have established that raw POME contains a considerable amount of carbohydrates, amino acids, and free organic acids with pH ranging from 4.0–5.0, along with organic pollutants, fibres, and some inorganic nutrients such as iron, copper, potassium, magnesium, nitrogen, chromium, and cadmium (Bello & Abdul Raman, 2017; Rana et al., 2017). Abdulsalam et al. (2018) reported that chemical oxygen demand (COD) and biological oxygen demand (BOD) levels in POME ranged from 15,000 to 100,000 mg/L and 10,250–43,730 mg/L, respectively (Abdulsalam et al., 2018). It may also be characterized as low or high-strength wastewater, depending on the amount and concentration of pollutants present. High-strength POME (HSP) contains a considerable amount of COD, total suspended solids (TSS), total solids (TS), NH_3, and inorganics. This means that HSP has a low biodegradability index (BI) as it consists mainly of organic pollutants that are predominantly COD and other toxic nitrogenous compound (Chan et al., 2009). Discharging POME without proper treatment is therefore hazardous to the environment. Information on the physicochemistry and BI of POME reported from recent research is presented in **Table 1**. On the other hand, POME is inhabited by a diverse microbial community important in the degradation of POME (Hassen-Aboushiba et al., 2013). These microorganisms release enzymes such as cellulase, xylanase and lipase to break down the complex polymers in POME (Abdulsalam et al., 2018). Some of the microorganisms bioaccumulate nitrogen and phosphorus and are responsible for their removal from POME.

3. Environmental Impact of POME

Palm oil production is increasing globally, and the resultant pollution from waste materials obtained from POME is quickly becoming a serious environmental issue. Oil palm processing generates three (3) major types of waste streams viz; gaseous, liquid, and solid. POME has been especially problematic environmentally, amongst all others. This is due to high pollution indicators such as oil and grease, and also because it could impact soil and water. The discharge of POME into the soil alters soil pH, which is one of the major factors that mitigates the availability of nutrients to plants (Okwute & Isu, 2007). POME is also believed to be able to change soil appearance and properties relating to vegetation, odour, colour, and composition, leading to a loss of soil's vegetative cover (Eze et al., 2013). During rainy seasons, POME serves as a breeding habitat for mosquitoes, turning rivers, streams, and surrounding lakes brown, smelly, and slimy when discharged directly into these water bodies. Loss of aquatic life and rendering water unavailable for domestic use are other environmental issues attributable to improper disposal of waste streams generated during palm oil processing (Awotoye et al., 2011). The discharge of POME on the soil and surrounding lands can also contaminate the aquatic ecosystem during runoff, leading to acidification and eutrophication (Awotoye et al., 2011).

Table 1. Published data on the Physicochemical and biodegradable indices of POME

BOD	COD	BI	pH	T (°C)	TS	TSS	TVS	TN	Oil/Fat	NH_3-N	TP	Pectin	Lignin	Carotene	Phenolics	Reference
30,000	50,000	0.6	4.5	-	16,495	59,350	-	1820	-	-	-	-	-	-	-	(Ahmad et al., 2005)
34,950	70,500	0.496	4.7	-	51,880	26,547	43,260	1620	-	-	-	-	-	-	-	(Khemkhao et al., 2015)
40,000	65,000	0.615	4.5	56	45,000	20,000	26,300	890	1500	90	950	-	-	-	-	(Ahmad et al., 2011)
25,000	50,000	0.5	4.7	85	40,500	18,000	34,000	750	4000	-	180	-	-	-	-	(Alhaji et al., 2016)
27,000	75,000	0.36	4.3	-	100,000	50,000	80,000	-	-	-	-	-	-	-	-	(Chin et al., 2013)
24,500	49,100	0.499	4.1	-	-	18,000	2600	600	5300	-	-	-	-	-	-	(Zinatizadeh et al., 2006)
32,150	57,500	0.56	4.5	85	-	-	-	-	-	-	-	3,400	4,700	8	5,800	(Abdulsalam et al., 2018)

Units: The units of the parameters are in mg/L except for BI, pH, T (° C), Pectin, Carotene, Lignin and Phenolics (ppm). Both BI and pH are unit-less. TVS is total volatile solid, TN is total nitrogen, NH_3-N is ammonia-nitrogen, and TP is total phosphorous. Information in table is modified, but mostly adapted from Abdulsalam et al. (2018).

The enduring negative aftermath from the industrial production or milling of crude palm oil through the standard and typical wet method is its large waste yield. It is especially troubling when wastes are disposed of improperly. Amongst them, the two most abundant are palm oil mill effluent (POME) —a brown liquid extremely rich in organic contents and palm press fibre (PPF —solid biomass. It is estimated that about 30 million tonnes of POME and 26.7 million tonnes of PFF are generated annually, aside from the volume, they are quite difficult to manage (Rupani et al., 2013). A large proportion of the effluent volume, which is estimated to be at the ratio of

1:3 crude palm oil to POME (Cheng et al., 2021; Liew et al., 2015; Wu et al., 2009), is thought to be released into natural, non-standard discharge environment, and possess very gross negative consequences to the environment. Their impact ranges from eliciting greenhouse gas (GHGs) emissions to endangering aquatic and terrestrial fauna and flora. POME contains very high concentrations of chemical oxygen demand (COD); biochemical oxygen demand (BOD); turbidity and microbial contaminant (Al-Amshawee et al., 2020; Hosseini & Abdul Wahid, 2015; Mohammed & Chong, 2014; Poh & Chong, 2009; Rupani et al., 2010).

The use of machines to squeeze digested mashes to produces crude palm oil does not yield concomitant POME, but it is less popular (Liew et al., 2015; Wu et al., 2010). According to Liew et al. (2015), fifty (50%) per cent of the total water used in wet milling processes turn out to be wastewater. For every tonne of fresh fruit bunch (FFB) processed, sterilizer condensate (36%); clarification wastewater (60%) and hydrocyclone wastewater (4%) are noted to be the three major source points for POME (Liew et al., 2015). Other sources are unpredictable, negligible and unreported: cooling turbines, boilers and floor washing. The characteristics of POME are mainly influenced by first, the quality of the fresh fruit bunch, the extraction techniques adopted, the effluent discharge limit of the milling plant, processing conditions, cropping seasons and concurrent climatic factors. The variation in the quantities and quality of POME suggests the method to be adopted for the treatment of POME (Kamyab et al., 2018; Wu et al., 2010).

Government agencies, industrial quality assurance units and environmental researchers battle to curb potential negative impacts of POME in a non-standard discharge environment. Many projections have been made to utilize the rich non-toxic colloidal suspensions of carbohydrate, protein, fatty acid, minor organic and mineral constituents as bioenergies sources (thereby reducing waste impact, protecting the environment while forming useful by-products) (Foo & Hameed, 2010; Igwe & Onyegbado, 2007; Kamyab et al., 2018; Lam & Lee, 2011; Osman et al., 2020; Yoochatchaval et al., 2011). Malaysia and Indonesia are the leading producers of crude palm oil and are pioneering most of the environmentally sustainable methods and technologies for both up-and down-streams treatment of POME. Some of these techniques have reportedly achieved a 95.5% level for effluent discharge limits in 2011 (Liew et al., 2015). About 85% of Malaysian oil milling plants adopt the ponding system for POME treatment (Lam & Lee, 2011; Wu et al., 2010), with some downside of (a) needing long retention periods, (b) large land area for treatment, (c) yielding unsatisfactory levels of BOD, (d) smell and (e) nitrogen, they need low maintenance cost and low operating energy (Al-Amshawee et al., 2020; Chou et al., 2016; Lam & Lee, 2011).

4. Environmental Impact of POME

4.1 Biological treatments of POME

Like other liquid wastes, POME goes through the primary and secondary stages for treatment. The primary or mechanical stage involves the removal of suspended solids particles with the use of sieves, sedimentation beds and filters. Other processes include coagulation of fine suspended particles, adsorption of dissolved heavy metals, selective crystallization, and ion exchange (Igwe & Onyegbado, 2007). The secondary or biological stage involves activated sludge, trickling filters, contact stabilization, etc. (Igwe & Onyegbado, 2007). Biological treatment consists of the use of suitable biological agents (living organisms capable of metabolic processes) for the digestion or degradation of POME because POME contents are largely biodegradable.

Protozoans, marshland plants, aquatic plants, and plant seeds have been used in the treatment of POME, but microorganisms (bacteria and fungi) are most preferred (Al-Amshawee et al., 2020; Rupani et al., 2013). Predominantly, the crude oil milling industry favours the aerobic-anaerobic open pond system for the treatment of POME (Chou et al., 2016). Microbes capable of self-perpetuation in POME ponds are the ones that can utilize organic and inorganic constituents of POME as a nutrient source to increase their population and size (Al-Amshawee et al., 2020). Suitable microbes can grow and remove these suspended matters depending on environmental conditions, either aerobically (with oxygen) or anaerobically (without oxygen).

However, some authors have reported reasonable amounts of organic matter in treated POME, making them still unsuitable for discharge into natural environments (Ibrahim et al., 2017; Madaki & Seng, 2013). Phytoremediation has been suggested as a good bioprocess capable of removing more of these remaining organic substances from already treated POME (Klomjek, 2016; Truu et al., 2015; Ujang et al., 2018). Finally, the measure of the efficacy of any adopted biological process is the rate at which the organic matter is converted, and it is measured by the ratio of BOD: COD, figures greater than 0.6 are noted to be ideal treatment (Igwe & Onyegbado, 2007; Ujang et al., 2018). **Table 2** enlists discharge limits for POME.

Table 2. POME discharge limits according to Malaysian standards*

Parameters	Limits
BOD (mg/L)	100
COD (mg/L)	-
Total solids (mg/L)	-
Suspended solids (mg/L)	400
Oil and grease (mg/L)	50
Ammoniacal nitrogen (mg/L)	150
Total nitrogen (mg/L)	200
pH	5.0-9.0
Temperature (°C)	45

*Source: (Latif Ahmad et al., 2003; Poh et al., 2010)

4.1.1. Aerobic treatment of POME

Aerobic treatment of POME, after anaerobic digestion gives very significant reductions of organic matter (Chou et al., 2016). Microbes utilized in the aerobic treatment of POME use oxygen as their electron exchange when degrading the suspended organic and inorganic matters. Aerobic treatment of POME is more efficient, have shorter hydraulic retention time and are reputed to removing high amounts of these suspended matters at low costs (Bhatia et al., 2007). The 24 days retention time is usually done in a shallow pond of about 0.5-1m depth (Lam & Lee, 2011). The three stages in aerobic treatments of POME are the acidic, methanogenic and finally the aerobic phases.

Acidic phase: Microorganisms involved in this phase convert large amounts of suspended organic components into volatile fatty acids. The effects of environmental conditions on performance is negligible. Previous anaerobic liquid is mixed with the clarification waste. This provides the starter microbial culture for the digestion of organic matter in the waste to acids and lowers the temperature of the liquid and, subsequently the pH (due to fatty acid formation) (Igwe & Onyegbado, 2007).

Methanogenic phase: this is done in a closed tank to reduce rain water dilution and acidification that would harm the microorganisms involved in this phase. The tank system should make it easy for the sludge to be dislodged, to curtail build-up and system failure. This phase yields a high volume of CH_4/CO_2 gases which are collected in a floating roof storage compartment and can be used as a source of clean energy. The settled solids are recycled to the acidification ponds while the supernatant is discharged to the aerobic lagoon, after a holding time of 20 days (Igwe & Onyegbado, 2007). Due to possible accumulations, the digester tanks have to be dislodged often; the sludge could be used as a source of fertilizer (Igwe & Onyegbado, 2007). At this point, the discharge liquid is still high with BOD and need extended aeration in the aerated lagoon.

Aerobic phase: The liquid discharged from the digestion tank is pumped into the sedimentation tank. The settling of suspended sludge is either used as fertilizer or sent to the decanter, for dewatering. The sedimentation tank's supernatant is made to flow into the aeration lagoon. The aeration of the lagoon is very important and mostly done by twin aerators to provide continuous, evenly mixed liquid with high oxygen transfer. The digested liquid from the aerated lagoon can be recycled back to the acidification pond (Igwe & Onyegbado, 2007). Meanwhile, the sludge cake is mixed with fibre to attain a moisture level of 60%, after which this set-up is placed in the composting tank.

4.1.2 Anaerobic treatment of POME

Unlike the aerobic treatment, anaerobic treatment requires much less power input; the occasional mixing is done by emitted gas bubbling (Hassan et al., 2004). The success of any anaerobic system set up for the treatment of POME will primarily depend on the growth, structure and matter utilization abilities of the microbial community present in the waste stabilization pond. The fate and performance of the microbes is in turn dependent on the environmental conditions in the pond: pH, temperature and absence of oxygen (Lam & Lee, 2011). Also, a well-controlled and closed pond system increases the recovery and use of methane (Chou et al., 2016). This multi-stage complex biochemical process progresses through four stages in the presence of suitable anaerobic microorganisms in suitable environmental conditions. These processes are collectively termed the anaerobic food chain and comprise: (a) hydrolytic microbes carry out the hydrolysis process, (b) the acidogenesis process is carried out by fermentative acidogenic microbes, (c) acetogenesis by acetogenic microbes, and (d) methanogenesis by methanogenic microbes (Demirel & Scherer, 2008).

Hydrolysis: This process ensures the breakdown of polymeric organic matters into their component monomer units like sugar and alcohol sourced from carbohydrates, amino acids or peptides sourced from proteins, and fatty acids sourced from lipids. Suitable microbes elicit an array of enzymes like amylase, cellulase, cellobiase, lipase, protease and xylanase in hydrolyzing these large organic matters (Lam & Lee, 2011; Weiland, 2010).

Acidogenesis: The fermentation process or acidogenesis ensures the yield of simpler organic products like acetate, alcohols, aldehydes, ketones, hydrogen, water, ammonia volatile fatty acids and carbon dioxide from previously hydrolyzed products (Lam & Lee, 2011).

Acetogenesis: Obligatory hydrogen-producing microbes in this phase oxidize the fatty acids: propionate, butyrate, lactate and ethanol which are complex intermediary products to produce more acetate, hydrogen and carbon dioxide (Lam & Lee, 2011).

Methanogenesis: Two groups of methanogens produce resultant methane and carbon dioxide during this phase. While acetate is converted by the acetotrophic methanogens to biomethane and carbon dioxide, the hydrogenotrophic methanogens produce biomethane by either (i) using H_2 as an electron donor and carbon dioxide as an electron acceptor or (ii) by using formate as an electron donor for the reduction of CO_2 (Demirel & Scherer, 2008; Yoochatchaval et al., 2011).

As the bubbles keep rising, it carries suspended solids with it forming scums, comprising grease and oil which were not fully removed during pretreatment. Another setback with the anaerobic system is the settling of sludges at the bottom of the pond. When the scum and sludge clump together, they lower the effectiveness of the pond (Hassan et al., 2004). An excavator is used to remove the sludge which could easily be dried or composted.

Predominant methanogens in biogas reactors are limited to *Methanobacterium*, *Methanothermobacter*, *Methanobrevibacter, Methanosarcina and Methanosaeta* (formerly Methanothrix) mostly due to the thermophilic conditions in the reactors (Sekiguchi, Kamagata, et al., 2001; Sekiguchi, Takahashi, et al., 2001). The disadvantages of anaerobic treatments of POME are time consumption- due to its need for low organic loading, difficulty in yielding complete biodegradation of organic contents (lipid and low chain fatty acids), large anaerobic ponds-taking up large spaces and uneven distribution of waste liquor, but they are known to produce less waste sludge, no unpleasant odour, volumes of biogas and can easily be restarted after extended shutdown periods (Lam & Lee, 2011; Rupani et al., 2010; Yoochatchaval et al., 2011). Their depth is usually 5 to 7m hydraulic retention time-HRT for 30-45 days or 1-1.5m depth for hydraulic retention time-HRT of 15 to 20 days (Lam & Lee, 2011).

4.1.3 Composting of POME

Asides from the POME which is liquid, the sludge that results from the treatment of POME is also a major issue. Improper disposal of palm oil mill sludge (POMS) or dewatered POME sludge can also pose a problem to the environment, especially, when disposed of in a non-standard, natural environment (Rupani et al., 2010). Mere drying of the resultant sludge, in open pond settings, can yield high nutrient soil-like fertilizer, proper dryings during wet seasons is a major setback to this simple process (Hassan et al., 2004; Liew et al., 2015; Rupani et al., 2010).

During composting, aerobic microorganisms help degrade or break down remainder organic or contents or substrates in the sludge, reducing its volume/weight. The biodegradable portions are broken down while the other part is turned into humic acid-like substances, which is the result of a chemically stabilized substance (Rupani et al., 2010). As the decomposition progresses, with a reduction in oxygen content in the composite sludge, the aerobic microbes renege their self-perpetuated action, and this results in the production of ammonia, ethylene oxide and organic acids and partially decomposed or unstable portions of the sludge (Rupani et al., 2010).

4.1.3.1 Co-compositing of POME

The collective compositing of POME, POME anaerobic sludge, and oil palm empty fruit bunch (OPEFB) is becoming an avenue for the sourcing of organic fertilizer and soil amendment components. Co-composting is thought to be faster and yields more nutrient-filled humus than mere composting, which has higher productivity as the microorganisms are more mature and accelerate the composting process. Others have also used sawdust and kitchen waste (Kuczynski et al., 2012; Zainudin et al., 2017).

4.1.3.2 Vermicomposting of POME

The use of earthworms has also been applied as agents in the biodegradation of POMS and PPF; it is referred to as vermicomposting or earthworm composting (Rupani et al., 2010; Rupani et al., 2013). Earthworms that can decompose POMS or even PPF are also able to survive in temperatures in the range of 0-40 °C, neutral or near-neutral pH. They reduce the bulk sludge (high organic content) or PPF (high lignin) via several biological, physicochemical reactions to a much more fragmented, fine, homogenous, porous, microbially active and highly nutritive humus-like, a low toxic, odour-free product called vermicompost or casting, within shortened time (Rupani et al., 2010; Rupani et al., 2013). The advantage of using vermicomposting in the agro sector are: waste reduction- operators reported waste degradation efficiency even at a mixture of 3:1 waste volume to earthworm population, soil fertilization with vermicompost and resultant earthworm biomass that could be used for livestock or fishery feeds (Rupani et al., 2010). A few examples of earthworms used in composting are the *Lumbricus rubellus*, *Eisenia anderi* and *Lumbricus terrestris.*

4.1.4 Phytoremediation of POME

Plant and plant parts can be used to remove organic pollutants from the natural environment. An example of a capable plant is the Napier grass- *P. purpureum* (Klomjek, 2016; Ujang et al., 2018). Phytoremediation is a green technology that uses green plants and their associated microorganisms to reduce pollutants in water and wastewater (Okereke & Ginikanwa, 2020). The phyto-micro-associated remediation method is used mainly in constructed or artificial wetlands, which can either be free water surface flow (FWS), sub-surface flow (SSF), or hybrid constructed wetland (Okereke & Ginikanwa, 2020).

Plants capable of phytoremediation of POME can take up the organic pollutant and suspended solids, bioaccumulate, degrade, or volatilize, without affecting their growth rate (Klomjek, 2016; Negawo et al., 2017; Rezania et al., 2015; Truu et al., 2015). Plants that accumulate pollutants from soil or water in their plant parts are called hyperaccumulators (Okereke & Ginikanwa, 2020). This is more cost-effective, low-energy consumption, eco-friendly, and produces no toxic by-products (Stefanakis, 2020). *P. purpureum* is commonly used in the phytoremediation-treated POME (Islam et al., 2017; Klomjek, 2016), because it can grow likewise in low or high water/nutrient source from the soil (Islam et al., 2017; Osman et al., 2020). Other plants used in the clean-up of POME are the water hyacinth (*Eichhornia crassipes*), water lily (*Nymphaea sp*.), alga (*Spriulina sp*.) (Hadiyanto et al., 2013), duckweed (*Lemna minor*), water fern (*Azolla filiculoides*), water spinach (*Ipomoea aquatica*), water lettuce (*Pistia stratiotes*), *Cyperus alternifolius*, vetiver grass (*Chrysopogon zizanioides*) and bulrush (*Typha latifolia* and *Scirpus maritimus*) (Okereke & Ginikanwa, 2020).

4.2 Chemical treatments of POME

4.2.1 Advanced oxidation processes for POME treatment

An area of research with promising and tested potentials for water treatment due to its efficiency over time is advanced oxidation processes (AOPs) and a lot of reports abound that substantiate this assertion (Akpan & Hameed, 2009; Fujishima et al., 2008; Rajeshwar et al., 2008). In light of this, AOP is x-rayed for the treatment of POME. There has been a cumulative interest in developing alternative methods for improving potable water production from POME and reducing environmental hazards. A combination of using a photocatalyst (majorly titanium dioxide) and UV or visible light is often used to treat wastewater and gaseous pollutants. Importantly, proximity and lack of impediment on the path of the illumination source are highly critical to the efficiency of the process. Photodegradation is comparatively employed over other AOPs like UV/peroxide/ ozone, UV/ozone, and UV/peroxide systems due to the speed of the process, minimal sludge generation, simple reaction conditions, and high mineralization rate (Akpan & Hameed, 2009; Rajeshwar et al., 2008). However, it is expensive, and the significant hazards associated with handling photo-oxidation byproducts seriously hamper the widespread application of photodegradation technology. Ng and Cheng (2015) reported band energy reduction after introducing platinum into titanium dioxide while successfully evaluating the photodegradion capacity against POME. Treatment of waste water and by extension POME via photocatalytic degradation is highly dependent of several experimental parameters or conditions. These factors affect the overall performance of the photocatalyst during the POME treatment. One very important consideration is the optimum dosage of the photocatalyst in relation to the quantity of POME, while others are the degree of acidity /alkalinity of the solution, morphology and size of the catalyst, levels and nature of the contaminant, metal ions and reaction temperature (Alhaji et al., 2016). Photocatalysis, as one of the most important advanced oxidation processe,s can be used not only for oxidative treatment of wastewater containing various organic and inorganic compounds as shown in **Table 3**, but also for reductive treatment such as reductive deposition of metals from wastewater. The implementation of photocatalytic technology in palm oil mill industry indicates the significant potential for future wide-scale adoption (Ng & Cheng, 2015).

4.2.2 Coagulation/flocculation

Due to the high contents of organic, oil, and suspended solids, POME is regarded as a highly contaminant-ridden wastewater if not treated to the required standards before being discharged to waterways. The natural biological degradation of the organic matter in POME depletes the dissolved oxygen in the rivers though the degradation process is considered as non-toxic as no harmful chemicals are added throughout the process; however, the pH is low due to organic acids in complex forms (Loh et al., 2013). Coagulation and flocculation entail the separation of suspended solids in aqueous media on the basis of size, composition, source, mass and charge-related properties (Hassan & Puteh, 2007; Rivas et al., 2001). These processes have received significant attention owing to their simplicity, ease of operation as well as efficiency (Hassan & Puteh, 2007). They have played a remarkable role in water treatment for centuries, as illustrated in **Figure 2**. Still, sludge generation remains a major drawback (Kweinor Tetteh & Rathilal, 2020). Treatments of POME using coagulants (natural and synthetic) have been adequately documented (Choong Lek et al., 2018; Jagaba et al., 2016), often targeted at colloidal particles (Borchate et al., 2012) mostly as preliminary steps in the overall treatment process (Jami et al., 2012; Oyakhilome et al., 2014). As a pre-treatment intervention procedure in the treatment of POME, coagulation, and flocculation employ aluminium sulphate (the most commonly used coagulant) due to its performance, availability, reliability and cost efficiency (Hassan & Puteh, 2007; Rivas et al., 2001) to reduce the contaminant load as absence of this critical step hampers efficiency of the entire advanced POME treatment process. Consequent upon this, coagulation and flocculation have remained a backbone in the sector of POME treatment.

4.2.3 Adsorption

Adsorption is a surface process where molecules are transferred from a phase to the surface of an adsorbent via physical or chemical means, depending on the mechanism of the process (Choksi & Joshi, 2007). The mechanisms of action are often elucidated using adsorption isotherms to gain insight into the process (Weng et al., 2007). The composition of POME is highly diverse, ranging from oil, heavy metals, and debris to suspended solids making it a unique waste stream to treat (Mohammed, 2013; Silva et al., 2013; Zinatizadeh et al., 2007) In a bid to rid POME of some of these recalcitrant contaminants, Shavandi et al. (2012) applied natural adsorbent (zeolites) to sequestrate zinc, manganese and iron ions from POME at predefined experimental conditions however, the removal process was highly dependent on hydrogen ion concentration of the POME. Activated carbon has become the most commonly used adsorbent for POME treatment, but sustainable use is encumbered by cost, poor regeneration potentials, and comparative low adsorption capacities, consequently necessitating a search for a viable alternative (ATIA, 2008; Boonamnuayvitaya et al., 2004; Choksi & Joshi, 2007; Rivagli et al., 2014; Weng et al., 2007). Given the effective, inexpensive, versatile, and simplistic nature of adsorption, it is highly embraced by researchers and applied on many waste streams, particularly on POME, to ameliorate its environmental footprint (Choksi & Joshi, 2007; Weng et al., 2007).

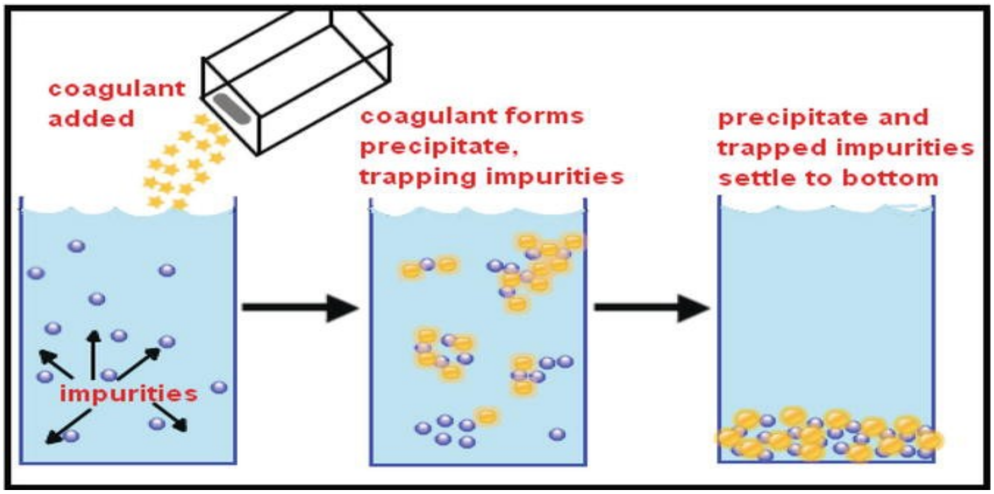

Figure 2. Process of coagulation, flocculation, and sedimentation (Kweinor Tetteh & Rathilal, 2020)

4.2.4 Membrane separation/filtration

Membrane separation technologies (microfiltration, ultrafiltration, nanofiltration, reverse osmosis) are a fast-rising choice of waste water treatment for the removal of nutrients, microorganisms, organic matter, particulate matter, organic compounds and inorganic ions (Ahmad et al., 2006; Hau et al., 2020; Abdulsalam et al., 2018).

Table 3. Utilization of photocatalysis for the treatment of POME

Parameters	Degradation results	References
COD	After 20h under UV irradiation, POME degradation attained 78% and the final COD level dropped to 37 ppm, which indicates that the effluent is safe to be discharged	(Ng & Cheng, 2015)
Colour	Reduction of fluorescence excitation-emission matrix FEEM intensity was 98.61% which is related to the decolorization	(Kongnoo et al., 2012)
	10 wt% of TiO_2 can remove more than 70% of the colour pigment in AT-POME	(Tan et al., 2014)

Table 3 (continued)

Degradation rate	The POME degradation efficiency jumps to 300% by photoreaction over 1.0g/l of 0.25wt Ag/TiO_2 compared to the bare TiO_2	(Cheng et al., 2016)
	0.5 wt% Pt/TiO_2 photocatalyst offered the most effective degradation of pre-treated POME under the irradiation of 100 W UV light (10%) and visible light (11%), respectively	(Cheng et al., 2015)
Degradation rate	Compared to the bare TiO_2, the photoreaction over 1.0 g/L of 0.25 wt% Ag/TiO_2 increased the POME degradation efficiency by 300%.	(Alhaji et al., 2016)
pH	Establish the type of charge on the photocatalyst's surface, the size of the aggregate, the location of the conduction band, and the valence	(Saputera et al., 2021)
COD	The reduction efficiency went from 7% to 74%, and power density output went from 1.73 to 35.85 $\mu W/cm^2$.	(Alhaji et al., 2016)
DO, COD, and BOD	The study showed that the use of ZnO-PEG nanoparticles in the photocatalysis process led to significant degradation of the organic matter in the POMSE.	(Zainuri et al., 2018)
Turbidity, color and DO,	The research indicates that ZnO-PEG has superior efficacy compared to ZnO-PVP in terms of lowering turbidity, enhancing color, and elevating dissolved oxygen (DO).	(Zainuri et al., 2018)
COD	The addition of isopropyl alcohol (IPA) to the reaction mixture in an attempt to remove hydroxyl radicals caused the removal of COD to decrease from 56% to 7%, indicating that hydroxyl radicals are the main reactive species that cause POME to photodegrade.	(Charles & Cheng, 2019)
Color, COD, BOD and turbidity	The smaller ZnO-CC 3:1 (6.6–42.9 nm) particles, which encourage more degrading activity and reduce membrane flux decline during the process, are correlated with improved performance efficiency for POMSE treatment utilizing MPR.	(Sidik et al., 2020)

The pore size, nature of the membrane, and waste composition are factors considered when applying membrane treatment for waste streams of diverse compositions. The different membrane separation processes are primarily based on the pore size of the semi-permeable material, which determines the compounds that can pass through it under a driving force applied (Ahmad et al., 2011; Azmi & Yunos, 2014). Conventional treatment of POME is bedeviled by several challenges (cost, poor sensitivity, and sludge generation). Still, introducing membrane separation processes is anticipated to tackle these drawbacks (Alkarimiah & Rahman, 2014). Coupled with the inherent merits (versatility, efficiency, and automation) associated with membrane treatment of POME, fouling remains a major weakness of this method of treatment that many researchers are brainstorming on improvement options (Cheryan & Rajagopalan, 1998; Azmi & Yunos, 2014). Even with the widespread acceptance of membrane technology, its application for POME treatment without pretreatment significantly impacts the cost of treatment and subsequently damages the membrane (Latif Ahmad et al., 2003; Poh et al., 2010).

4.2.5 Electrocoagulation

The effluent from the palm oil mills is complex, with a high polycyclic aromatic hydrocarbons (PAHs) from natural and anthropogenic sources. This anthropogenic source contributes immensely to the adverse effects of wastewater pollutants encountered in the environment. Electrocoagulation (EC), which can potentially eliminate the characteristic drawbacks of classical treatment techniques extensively, is a complicated process involving many chemical and physical phenomena that employ consumable electrodes to supply ions into the wastewater stream (Moussavi et al., 2011). Electrocoagulation has been an ideal technology to upgrade water quality and has been successfully applied to a wide range of pollutants in an even more comprehensive range of reactor designs (Kobya et al., 2003; Şengil & Özacar, 2006). Research has shown that EC of POME can be used in industry to facilitate wastewater treatment and hydrogen production. It is also assumed that hydrogen production from POME may contribute to the cost-effectiveness of the treatment process by producing extra revenue.

5. Chemical Applications of POME

POME has been used as raw material for derivation of or valorised into many useful chemical products as well as material inputs in several chemical processes. Most of the chemical applications of POME are closely related with the technologies developed for its treatment. While a lot of studies have been targeted towards energy and environmental applications using integrated biotechnological/chemical approaches (Yashni et al., 2020), a significant number of studies on other useful products have been reported (**Table 4**).

5.1 POME feedstock for biochar and other ashed biomass products

Biochar materials are products of pyrolysis of biomass in the absence of oxygen. Related materials include activated carbon and other substrates produced via ashing. These materials have been widely applied in sorption of pollutants in various environmental matrices, especially contaminated or waste waters. Feedstock for production of biochar and ashed substrates can be sourced from a wide range of sources such as wood, leaves, grasses, animal wastes and bones. POME sludge-derived biochar materials have been used to treat POME and other wastewater matrices contaminated with both trace metals and organic pollutants (Thangalazhy-Gopakumar et al., 2015; Zaini et al., 2014; Zaini, et al., 2013).

5.2 Recovery of useful chemicals and nutrients

POME is known to be loaded with varieties of useful chemicals (Ahmad et al., 2006; Hau et al., 2020; Junpadit et al., 2017; Kareem et al., 2021; Tang et al., 2021; Teh et al., 2017). However, the recovery or extracting procedures for commercial quantities of these chemicals are limited. Therefore, this area of research has remained active and increasing yearly. Chemical processes such as ashing, pyrolysis, acidification, ethanolysis, hydrolysis, precipitation, redox reactions, and transesterification, amongst others, have found extensive use in valorisation or transformation of POME into chemicals such as fatty acids, carboxylic acids, lipid/lipase, citric acid, biopesticide, biosurfactants, syngas ($H_2 + CO$), bioethanol, carotenes, etc (Ahmad et al., 2010; Ahmad et al., 2020; Mumtaz et al., 2008; Rakkan et al., 2017). In **Table** 4, a summary of some selected useful chemicals derived from POME and their associated processes and applications are presented. Preparation of nano-size materials such as nano-lignin and gold nanoparticles (AuNPs) have now emerged. In many of the previously reported studies, utilisation of nanomaterials has been limited to treatment of POME. However, in a recent study, synthesis of vanillin (a common flavouring agent in foods and pharmaceutical industry) through photocatalytic degradation of POME-derived lignin using TiO_2 nanoparticles has been proposed (Arutanti et al., 2020).

POME, even after pre-treatment, is rich in nutrient parameters such as nitrogenous and phosphorus compounds (Yashni et al., 2020). A recent study has reported the recovery of phosphorus from POME through combustion of the sludge, followed by acid leaching and extraction using sulphuric and oxalic acids (Damaraju et al., 2019).

Table 4. Some useful chemicals/materials derived from POME with associated processes and applications

Chemical product(s)	Process(es)	Product application	References
3, 4, 5-trihydroxycinnamic acid (THCA)	Extraction of *p*-coumaric and caffeic acids, followed by biocatalysis	NR	(Pinthong et al., 2017)
Carotenes	Column chromatography using silica-based resins and solvent extraction	NR	(Ahmad et al., 2008, 2009, 2010)
Polyhydroxyalkonoates (PHAs)	Biocatalysis/biosynthesis	Tissue engineering	(Zubairi et al., 2016)
Fatty acid ethyl ester (FAEE)	Lipase-catalyzed ethanolysis	Biodiesel production	(Rachmadona et al., 2020)
Lignin	Acid precipitation, followed by centrifugation	NR	(Ibrahim et al., 2018)
Nano-lignin	Acid precipitation, followed by centrifugation and sonication	NR	(Ismail et al., 2020)
Carbon nanotubes (CNTs)	Pyrolysis using ferrocene as catalyst	NR	(Nurdin et al., 2019)
Acetic, propionic, and butyric acids	Anaerobic treatment	NR	(Mumtaz et al., 2008)
Sludge ash	Ashing	Removal of methylene blue from water	(Zaini et al., 2014)
Biochar	Pyrolysis	Sorption of cadmium from water	(Thangalazhy-Gopakumar et al., 2015)
Gold nanoparticles (AuNPs)	Bioreduction	NR	(Gan et al., 2012)
Syngas	Catalytic steam reforming	NR	(Ng et al., 2019)
Fermentable sugars	Enzymatic hydrolysis	NR	(Silvamany et al., 2015)
Phosphorus	Combustion of POME sludge, followed by acid leaching and extraction using sulphuric and oxalic acids	NR	(Damaraju et al., 2019)
Syngas	Steam reforming over lanthanum cobaltite	NR	(Cheng et al., 2020)

NR -not reported

6. Biotechnological Applications of POME

6.1 POME as biomass for biomethane and biohydrogen production

Biohydrogen is considered clean energy given that it is generated from biological sources; it can be used as direct combustion fuel or in fuel cells. Hydrogen as a fuel is highly efficient and recyclable (Kamaraj et al., 2020). However, there is limited hydrogen for consumption, given its scarce availability naturally and expensive production measures (Manoharan et al., 2019). Also, a greater percentage of hydrogen currently available for industrial use is gotten from natural gas by steam reformation, which demands enormous energy in addition to its greenhouse effect (Xu & Armstrong, 2013). Biohydrogen production is the safest, most environmental friendly and cost effective compared to other forms of hydrogen production (Taifor et al., 2017).

POME has been effectively utilized for the production of useful bioenergy such as biogas, which contains biomethane and biohydrogen, among other constituents. During the production of biogas from POME, biohydrogen is produced and biomethane can be obtained as by-product (Aznury et al., 2018). POME is a readily available feedstock for biomethane and biohydrogen production in a batch, fed batch or continuous anaerobic fermentation process (**Table 5**). The suitability of POME as biomass for the production of biogas is informed by its high nutrient content such as carbohydrate, proteins lipids etc. which are pivotal to microbial degradation for biogas production (Aznury et al., 2017; Hii et al., 2012).

The process of biomethane and biohydrogen production from POME is coordinated by the activities of various microorganisms through four stages of hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Kumaran et al., 2016). The first stage involves the breakdown of the complex nutrients to smaller subunits by hydrolytic bacteria such as *Bacillus* and *Clostridium* (Wong et al., 2014). Intermediary compounds such as alcohols, aldehydes, acetic acids are formed from the hydrolyzed compounds by the activities of acidogenic bacteria viz: *flavobacterium* and *Pseudomonas* in the next stage (Divya et al., 2015). Thereafter, acetogenic bacteria such as *clostridium*, *Desulfovibro E. coli* etc. biodegrade the intermediaries to produce acetate, carbondioxide and hydrogen (Bajpai, 2017). Finally, acetotrophic methanogens of the *Methanosarcina spp*. form 70% of the methane by splitting acetate into methane and carbon dioxide while 30% of the methane is formed from hydrogen by hydrogenotrophic methanogens of the *Methanoculleus spp*. (Aziz et al., 2020; Sasaki et al., 2011).

Highest yield of methane is obtained from POME in relation to other comparable substrates (Aziz et al., 2020). To enhance yield potential and biodegradability of POME, it is co-digested with other subtrates or pretreated. The bioenergy yield potential of POME is more pronounced when it is co-digested with brewer's spent grain (Ndubuisi-Nnaji et al., 2020), compost manure (CM) or empty fruit bunches (EFB) (Nurliyana et al., 2015; O-Thong et al., 2012; Sidik et al., 2013). In comparison, POME produces biogas from the first day of fermentation unlike CM which takes some days, and when co-digested in the ratio 7:3 POME to CM, highest biogas yield with methane content were obtained (Fajar et al., 2018; Sidik et al., 2013). Other co-substrates used with POME include rumen fluid (Alrawi et al., 2011), refined glycerin wash water (Sulaiman et al., 2009), and decanter cake (Suksong et al., 2015).

Pretreatment of POME with ozone enhances the POME constituents' biodegradability, subsequently increasing POME methane yield potential. Comparing the yield between raw POME and ozonated POME, Tanikkul et al. found out that POME of concentration 15,000 mgL^{-1} gave the maximum methane yield of 177.8 mL g^{-1} COD for raw POME and 273.8 mL^{-1} COD for ozone-treated POME (Tanikkul et al., 2014). Also, Chaiprapat and Laklam (2011) were able to obtain up to 64.1% methane content (410 L CH_4/kgCOD) while attaining 64.2% COD when POME was pretreated with ozone.

POME can be used as raw material for the production of biohythane. In a pilot-scale production of biohythane from POME, a yield of 73 mL H_2/gCOD hydrogen and 342 mL CH_4/gCOD were obtained (Seengenyoung et al., 2019). Biohythane is a combination of hydrogen and methane gas. It has been recognized as a more efficient fuel for transportation as the combined composition help in complementing and discarding each other's advantages and disadvantages respectively as energy source.

The utilization of POME for the production of renewable energy serves two important purposes of providing alternative energy source to fossil fuel and reduction of environmental pollution. POME is a suitable biomass for biomethane and biohydrogen production as it has useful physicochemical characteristics, rich in nutrient and microbial composition, and has negative environmental impacts if left unutilized. However, problems such as low substrate conversion, long retention time, and bioreactor design limit the utilization of POME for commercial production of bioenergy (Rosa et al., 2020).

Table 5. The use of POME in the production of bioenergy

Biohydrogen						
Pre-treatment method	**Yield (mL$_{H2}$ gCOD^{-1})**	**COD (mg/L)**	**pH**	**Temperature (°C)**	**Temperature / bioreactor condition**	**References**
Microbial electrolysis	163	66,000	6.5	79	Thermophilic	(Khongkliang et al., 2019)
Two-stage dark fermentation and microbial electrolysis	236	66,000	6.5	79	Thermophilic	(Khongkliang et al., 2019)
Pre-hydrolyzed	2.58	-	6.5	35	Mesophilic	(Garritano et al., 2017)
Hydrolyzed	462	85714	4.31	30	Anaerobic	(Rosa et al., 2020)
Hydrolyzed	2.56	-	6.5	35	mesophilic	(Garritano et al., 2017)
Ozonated	77.1	35,000	6.0	55	Thermophilic	(Tanikkul & Pisutpaisal, 2014)
Ozonated	182.3	30,000	6.0	37	Mesophilic	(Pisutpaisal et al., 2014)
Ultrasonicated	17.1	38,400	7	44	-	(Leaño et al., 2012)
Heat shock	10.0	49,000	5.5	35	Anaerobic	(Mohammadi et al., 2011)
Phenol removal	27.1	45,200-56,300	6.0	37-55	Thermophilic	(Mamimin et al., 2012)
Co-digested with decanter cake	16	60,000	5.5	60	Thermophilic	(Suksong et al., 2015)
Co-digested with empty fruit bunch	16	60,000	5.5	60	Thermophilic	(Suksong et al., 2015)
None	73	66,000	6.5	79	Thermophilic	(Khongkliang et al., 2019)

Table 5 (continued)

None	2.26	-	6.5	35	Mesophilic	(Garritano et al., 2017)
None	205.0	56,500	5.5	55	-	(Krishnan et al., 2016)

Biomethane

Pre-treatment Method	**Yield (mL_{CH4} $gCOD^{-1}$)**	**COD (mg/L)**	**pH**	**Temperature (°C)**	**Temperature / bioreactor condition**	**References**
Ozonated	273.8	15,000	7.0	37	Mesophilic	(Tanikkul et al., 2014)
Co-digested with RGWW	150.0	26,700-36,000	4.2-5.2	-	-	(Sulaiman et al., 2009)
Co-digested with EFB	203.0	106,934	5.6 - 8.0	-	Mesophilic	(Nurliyana et al., 2015)
Co-digested with decanter cake	391	60,000	5.5	60	Thermophilic	(Suksong et al., 2015)
Co-digested with empty fruit bunch	240	60,000	5.5	60	Thermophilic	(Suksong et al., 2015)
None	289.8	75,000	4.3	-	-	(Tabassum et al., 2015)
None	310.0	56,500	5.5	55	-	(Krishnan et al., 2016)
None	177.8	15,000	7.0	37	Mesophilic	(Tanikkul et al., 2014)
None	61.5	22,000	7.0	-	Anaerobic	(Chaiprapat & Laklam, 2011)
None	346.0	2,500–55,700	3.8–4.4	38	Anaerobic	(Najafpour et al., 2006)
None	240.0	70,000	4.5	-	Anaerobic-aerobic	(Chan et al., 2012)

Biogas

Co-digestion with compost manure	1875 mL (61.13 %)	8,215	7.03	28	Anaerobic	(Sidik et al., 2013)

6.2 Biofertilizer potential of POME

Biotechnology has been widely applied in treating POME and its subsequent use as a biofertilizer for enhanced crop production. For POME to be used as a biofertilizer, it has to undergo some form of treatments, as using it in its raw state would have adverse effect on the environment. POME is one of the many wastes generated from the extraction and processing of crude palm oil (CPO) and the most polluted organic residue generated from palm oil mills (Alkarimiah & Rahman, 2014). It makes up the largest portion of the entire waste from the palm oil mill industry. Other wastes generated include empty fruit bunches (EFB), mesocarp fibres, palm kernel shells etc. It is estimated that a tonne of fresh fruit bunch (FFB) processed, generates about 0.67 tonne of POME (Nurul-Adela et al., 2016). Also, Mubarak et al. asserts that for a tonne of CPO to be produced, about 5.0 to 7.5 tonnes of water is needed with over 50% of that water used in the extraction process ending up as POME (Mubarak et al., 2020).

POME generates large amount of sludge, which has high moisture content with a high amount of organic substance suitable for use as a biofertilizer (Khairuddin et al., 2016). The sludge generated is treated using various methods such as ponding (Chin et al., 1996) anaerobic digestion (Yacob et al., 2005), aerobic digestion (Abdul Karim & Ahmad Kamil, 1989) open digested tanks, evaporation method, aerobic activated sludge reactor and membrane technology, etc. (Alkarimiah & Rahman, 2014).

Microbes such as Streptomyces, *Trichoderma harzianum*, *Aspergillus niger*, and *Phanerocheate chrysosporium* play a critical role in the degradation of high organic matter, as well as high BOD and COD concentrations present in POME making it suitable for use as biofertilizer (Alkarimiah & Rahman, 2014). The use of POME sludge as biofertilizer is an eco-friendly approach to waste management because it improves soil aggregate stability, porosity and water infiltration rate and supplies it nutrient-rich organic matter and other major nutrients such as nitrogen, phosphorus, and calcium to the soil (Haryani et al., 2019). Studies have shown that POME contains substantive amount of these mineral nutrients which are essential for plant growth (Habib et al., 1997).

Wu et al. (2009) in their report submitted that biologically treated POME has been widely used in oil palm plantation for irrigation purposes and as liquid fertilizer. POME as a cheap organic fertilizer, offers an alternative to the excessive application of chemical fertilizers (Wu et al., 2009). The use of POME has shown to improve soil productivity and increase the yield of crops as well as contribute to better root health by improving the soil structure. Studies have shown that the application of fermented/treated POME to soil can increase the growth and yield of crops like maize, palm plantation, elephant grass (*Pennisetum purpureum*) used as feed for livestock (Haryani et al., 2019; Wu et al., 2009). Thus, the bioconversion of POME into other value-added products such as biofertilizers, bioflocculants etc. has become very pertinent in the waste management system. Since POME is cheap, cost-effective, renewable and readily available in Nigeria, its use as biofertilizer is considered an attractive alternative to mineral/inorganic options that are very expensive.

6.3 POME as Substrate for Fermentation

Fermentation as a metabolic process, takes place on several organic substrates including POME to produce chemical changes through the action of microbes/enzymes. Microorganisms produce enzymes that act on substrates particularly carbohydrates to form new products. Since cost is a critical factor in the choice of substrates used as feedstock, POME offers a suitable alternative to common substrates such as L-glutamate, glucose, sucrose, and fructose (Nurul-Adela et al., 2016). This could crash the cost of production; raise the possibility of scale-up of the intended product. POME has been reported to contain substantial concentrations of carbohydrates, proteins, lipids, nutrients, and minerals that support microbial growth and this makes it a potential fermentation substrate (Nurul-Adela et al., 2016). Aljuboori et al. (2014) has reported the use of raw POME as source of substrate for fermentation. Soluble and insoluble carbohydrates are present in POME with the soluble part being low in concentration; the insoluble ones such as cellulose, hemicellulose, lignin, and starch have high molecular weight which may require hydrolysis (pretreatment) to aid microbial action during fermentation (Nurul-Adela et al., 2016).

Microorganisms such as *Penicillium chrysogenum, Bacillus thuringiensis, Clostridium acetobutylicum, Aspergillus niger, Trichoderma harzianum, Thermophilic microflora, Chryseomonas luteola, Staphylococcus cohnii spp.,* have been involved in fermentation processes using POME as substrate (Syafalni et al., 2012; Wong et al., 2012). Although the use of POME as substrate is still emerging, there are studies on its use as substrate. Nurul-Adela and co-workers reported the use POME for the production of bioflocculant with *Bacillus marisflavi* NA8 as the inoculum (Nurul-Adela et al., 2016). Results show that 30.5 g/L of fermentable sugar was produced from POME after 24 hours of hydrolysis which was acted upon by *Bacillus marisflavi* NA8 to produce 6.4 g/L or 32 kg bioflocculant per ton of

POME. Also, some researchers have independently demonstrated the fermentative production of biological H_2 (biohydrogen) from raw POME as substrate using different microbial consortia (Mubarak et al., 2020; Rosa et al., 2020). Whereas Mubarak et al. (2020) used *Clostridium* sp. and other obligate anaerobic non-spore forming bacteria, mostly belonging to the *Firmicutes* and *Bacteroidetes* phyla to carry out the work, Rosa et al. (2020) used *Clostridium beijerinckii*. Both works showed great bio-H_2 production potential under controlled conditions.

POME has also been utilized as substrate for the continuous production of biomethane (BCH_4) using a two-stage anaerobic digestion approach. Mixed culture from thermophilic anaerobic seed sludge obtained from a local palm oil mill anaerobic pond was used for the continuous methanogenic process. *Methanothermobacter* sp. was the dominant thermophilic archaea that was responsible for the production of 4.3 litres of BCH_4 per litre of POME per day at HRT of 2 days (Mahmod et al., 2020). Acetone-buthanol-ethanol (ABE) is another major product of the many direct fermentative utilization of POME as substrate. As reported by Kalil and his co-workers (Kalil et al., 2003), ABE production by *Clostridium acetobutylicum* NCIMB 13357 and *C. saccharoperbutylacetonicum* N1-4 from sedimented POME yielded 4g of ABE per litre of POME with initial pH of 5.8.

A plethora of other works has also demonstrated the reuse of POME as fermentation media. The use of ultra-filtered POME concentrates for the production of antibiotics with *Penicillium chrysogenum* as inoculum has been reported (Wu et al., 2009). Production of bioinsecticides, polyhydroxyalkanoate (PHA) organic acids such as citric acid and Itaconic acid; enzymes such as cellulase, and xylanase production from *Aspergillus niger* ATCC 6275 under submerged and solid-state fermentation has also attracted wide attention (Jamal et al., 2005). Bio-products from POME with its associated microorganisms are shown in **Table 6**.

6.4 POME as Nutrient sources for Microbes and Animals

The exploration of POME as a source of nutrient either in full or in part is currently gaining wide interest. Palm oil effluent has lots of nutrients and has been used as feed for growing-finishing pigs where the POME was augmented with other substances such as cassava root meal and palm kernel cake (Wu et al., 2009). POME-based animal feed is economical because it reduces the cost of feed and animal meat production. Devendra demonstrated that POME can be fed directly to pigs (10-12 litres/head/day) with palm oil and other ingredients (Devendra, 2004). About 10% of POME in sheep diet gave an appreciable result with respect to crude fiber digestibility as it decreased significantly from 80.6% in a 10% POME diet to 27.0% in a 60% POME diet. Pasha used a combination of 20% POME, 30% oil palm frond and 50% palm kernel cake for the production of good diet for an acceptable growth rate and quality meat in cattle (Pasha, 2007). In poultry, Pasha has also reported the use of POME as a source of supplementary feed using 10-15% of dried POME in chicken feed for growth and egg production with optimum levels of POME in the diet being 10% and 15% for layers and broilers respectively (Pasha, 2007). Dehydrated POME has been supplemented with rice straw and used as feed for goats and this has satisfactorily promoted performance levels of the animals (Phang & Vadiveloo, 1991). It is generally accepted that POME contains a substantial concentration of nutrients such as carbohydrates, proteins lipids etc. required by microbes to carry out their metabolic activities and as these substrates are utilized by specific microorganisms, value-added products are formed.

Table 6. Other biotechnological applications of POME

Bioproduct from POME	Associated microbes	Functions/Uses	References
Acetone-butanol-ethanol (ABE)	*Clostridium saccharoperbutylacetonicum* N1-4 (ATTC 13564) *C. acetobutylicum* NCIMB 13357	ABE is used in plastic industries for the production of synthetic rubber. Also, as a universal solvent and in the preparation of explosives like trinitrotoluene etc.	(Hipolito et al., 2008; Kalil et al., 2003)

Table 6 (continued)

Antibiotics	*Penicillium chrysogenum*	Used to kill and/or inhibit the growth and replication of bacteria.	(Wu et al., 2009)
Bioflocculant	*Bacillus marisflavi* NA8, *Chryseomonas luteola, Staphylococcus cohnii* spp.	Used in industrial processes like water treatment, sludge dewatering, landfill leachate treatment, heavy metal removal, soil remediation and reclamation etc.	(Nurul-Adela et al., 2016; Syafalni et al., 2012; Wong et al., 2012)
Biohydrogen	*Thermoanaerobacterium thermosaccharolyticum* PSU-2, *Clostridium beijerinckii*, *Escherichia* spp, *Bacillus* spp	It is a good source of fuel for vehicles and vessels. The chemical energy therein can be converted into electricity. BioH_2 also serves as a coolant in electrical generators at power stations and in rocket propulsion	(Mubarak et al., 2020; Rosa et al., 2020; Yang et al., 2019)
Bioinsecticides	*Bacillus thuringiensis*	Used control of mosquitoes and other insects	(Wu et al., 2009)
Biomethane	*Methanothermobacter* sp.	Used to generate heat and electricity, in ovens for cooking, as an energy source in vehicles for transportation etc.	(Mahmod et al., 2020)
Organic acids	*Aspergillus terreus* IMI 282743 *Rhodobacter sphaeroides* IFO 12203	Used for myriad purposes example: as additives, preservatives, flavorants, etc. They also prevent/inhibit the growth of foodborne pathogens and other spoilage microbes.	(Jamal et al., 2005)
Polyhydroxyalkanoate (PHA)	*Rhodobacter sphaeroides* IFO 12203, *Alcaligenes eutrophus*, *Pseudomonas* spp, *Bacillus* spp	Wide application in biomedical, pharmaceutical, agricultural and packaging fields. PHAs are used as biofuels and bioplastics; applied in food packaging which makes use of the barrier properties of these polymer as a significant trait.	(Md Din et al., 2006; Poltronieri & Kumar, 2019)

7. Conclusion and future perspectives

In conclusion, the current state of the art in POME treatment technologies as mentioned above offers a range of promising options for improving the sustainability and efficiency of POME treatment. However, there are still gaps in our knowledge about the long-term sustainability and effectiveness of these technologies. Further research is needed to fully understand the environmental, economic, and social implications of these technologies. Future perspectives on POME treatment include the development of more efficient and sustainable technologies, as well as the integration of POME treatment with other waste management systems. Overall, the future of POME treatment looks promising, with a focus on sustainability, efficiency, and environmental responsibility.

In accordance with goal seven (7) of the Sustainable Development Goals (SDGs), the most suitable POME treatment option is one that is cheap (cost-effective and economically viable) as well as eco-friendly. In this case, biological techniques like (an)aerobic digestion for bioenergy, composting and co-composting, phytoremediation, and vermicomposting present veritable technologies for the management of POME. However, they are not without some drawbacks and are yet to be applicable on a commercial and/or industrial scale. Other limitations include the prolonged period of treatment and heat loss, which can be harnessed for energy. On the other hand, chemical and physical treatment techniques have raised concerns about environmental sustainability as they have been shown to utilize chemicals and metabolic end-products that may produce unintended yet undesirable environmental effects. More so, the physicochemical treatment processes are inadequate and should not be applied in isolation for the holistic management of POME wastewater. A combination of all integrated treatment procedures should be advanced and is proposed for efficient and wholesome management of palm oil mill effluent. The collaboration of industrial experts, researchers, and policymakers should develop stringent legal and administrative frameworks and enforceable penalties to encourage those in the oil palm production value chain to adopt adequate methods for all-inclusive POME waste management.

Statements and Declarations

Ethical Approval
Not applicable

Consent to Participate
Not applicable

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Authors' Contributions

Conceptualization and design: U.A.O., U.U.N., S.E.S., N.O.O.; Supervision and resources: U.U.N., S.E.S., N.O.O.; Methodology and data curation: U.A.O., S.E.S., O.K.F., O.D.A., N.O.O., I.Y.S., E.J.E.; Investigation, data collection, analysis and interpretation: U.A.O., S.E.S., O.K.F., O.A., N.O.O., I.Y.S., E.J.E., N.D.I.; Writing -original draft: U.A.O., S.E.S., N.O.O.; Writing -editing and review: U.A.O., U.U.N., S.E.S., N.D.I., O.K.F., O.D.A., N.O.O., I.Y.S., E.J.E. All authors read and approved the submitted version.

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Availability of data and materials
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