AEROBIC COMPOSTING OF OIL PALM FRONDS – A REVIEW

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Abstract. The palm oil industry is a major agricultural industry in Malaysia and is also one of the major suppliers of palm oil in the world. The growth of this industry has also increased the quantity of waste generated. Lignocellulosic biomass produced from the palm oil industry, such as oil palm fronds (OPF), oil palm trunks (OPT), mesocarp fibers (MF), palm kernel shells (PKS), and palm oil mill effluent (POME), can affect air, water, soil, and environmental ecosystems. Of the total biomass waste generated, OPF is generated at a higher rate than others. Therefore, composting is the most viable treatment for reusing and recycling OPF, an environmentally friendly treatment that provides economic potential. This review focuses on OPF composting studies and provides important insights into the possible use of this waste as an alternative approach to treat biomass produced by the palm oil industry and resolve pollution issues in the environment. Furthermore, this review covers the use of inoculum in the composting process, including white-rot fungi (WRF), sewage sludge, palm oil mill effluent (POME), and thickened POME anaerobic sludge for rapid decomposition of lignocellulose OPF while exploring the effects of composting on the environment.
Keywords: *lignocellulosic biomass, OPF compost, white-rot fungi, palm oil mill effluent sludge, lignocellulolytic microorganisms, lignin degradation*

Abbreviations: OPF: oil palm fronds, OPT: oil palm trunks, MF: mesocarp fibers, PKS: palm kernel shells, POME: palm oil mill effluent, WRF: white-rot fungi, WWF: World Wildlife Fund, GHG: greenhouse gas, EFB: empty fruit bunches, MPOB: Malaysia Palm Oil Board, AIM: Agensi Inovasi Malaysia, EM: effective microbe, VOCs: volatile organic compounds, PF: phenol formaldehyde, OLPG: organosolv lignin phenol glyoxal, COD: chemical oxygen demand, BOD: biochemical oxygen demand, TSS: total suspended solids, RH: relative humidity, AKD: alkyl ketene dimer, OCC: old corrugated container, CM: chicken manure, RB: rice bran, N: nitrogen, P: phosphorus, K: Potassium, PL: poultry litter, POB: palm oil biowaste, CD: cow dung, EC: electrical conductivity, PCR-DGGE: polymerase chain reaction-denaturant gel gradient electrophoresis, CEC: cation exchange capacity, CCD: coconut coir dust, CCDP: CCD and peat mixes, $CCDC_A$: CCD and OPF compost A, $CCDC_B$: CCD and OPF compost B, $CCDC_C$: CCD and OPF compost C, OM: organic matter, HS: humic substance, LiP: lignin peroxidase, Lac: laccase, MnP: manganese peroxidase, VP: versatile peroxidase, GLOX: glyoxal oxidase, AAO: aryl alcohol oxidase, MSW: municipal solid waste, C/N: carbon to nitrogen ratio, SSB: solid-state bioconversion, SEM: scanning electron microscope, WWTPs: wastewater treatment plants, SS: sewage sludge, GW: green waste, OMW: olive mill waste, GI: germination index, Ni: nickel, Pb: lead, Cd: cadmium, Cr: chromium, 16S rRNA: 16S ribosomal RNA, 18S rRNA: 18S ribosomal RNA, USEPA: United States Environmental Protection Agency

Introduction

The worldwide palm oil sector is predicted to expand significantly to meet the escalating global demand for edible oil, which is utilised in various industries. The palm oil processing sector is expected to increase its overall production to 25 million tonnes by 2035 (Arisht et al., 2020). Over the past four decades, palm oil has experienced a tremendous and consistent expansion in the world market, with a projected average annual output of 15.4 million tonnes in Malaysia between 2016 to 2020 (Abdullah and

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Sulaiman, 2013). Palm oil has been reported to contribute to the socioeconomic sustainability of Malaysia; however, several international pressure groups, such as the Rainforest Action Network, Greenpeace, and World Wildlife Fund (WWF), have deemed the industry unsustainable due to industry practices that contribute to increased greenhouse gas (GHG) emissions, deforestation, and biodiversity loss (Dalton et al., 2017; Bateman et al., 2010). High solid waste production, such as oil palm fronds (OPF), oil palm trunks (OPT), empty fruit bunches (EFB), mesocarp fibers (MF), palm kernel shells (PKS), and palm oil mill effluent (POME), are all the environmental implications of unsustainable palm oil production practices (Foo and Hameed, 2010; Abdullah and Sulaiman, 2013).

As previously noted, most of the biomass is abandoned in the plantations, indicating that this primary lignocellulose feedstock is underutilised. OPF and OPT, which are abundantly accessible in plantations, account for about 75% of the solid waste, while the remaining 25% is contributed by EFB, MF, and PKS that are typically available at the mills (AIM, 2013). According to Awalludin et al. (2015), during oil palm fruit harvesting, over 44 million tonnes of OPF (dry weight) are produced annually, and during the replanting season, around 15 tonnes of dry OPF are typically chopped off and allowed to deteriorate naturally. Dalton et al. (2017) reported that OPF produced through pruning represents the majority of solid waste generated in the palm oil sector at 58.8%. The sector has attempted sustainable approaches such as mulching and enriching soil nutrients by laying frond piles in plantations (MPOB, 2014). According to the results of the field experiments, these methods could recover 7.5 kg of nitrogen into the soil, with 106 kg of phosphorus, 9.81 kg of potassium, and 2.79 kg of magnesium which also benefit soil enrichment. It reduces dependence on inorganic fertiliser, alleviates fertiliser costs, and improves environmental conservation (MPOB, 2014). Moreover, OPF has been reported as a viable raw material for producing paper through the chemical pulping process. In addition, OPF is also used as livestock feed, biofuel regeneration, heavy metal ion absorber in wastewater, renewable sugars, and composite boards (Hussin et al., 2013). Abandoning OPF in the plantation without further treatment can cause environmental issues due to the large accumulated organic content on the ground. According to Ahmad et al. (2011), the traditional method of OPF disposal for oil palm replanting through the burning method at the plantation can result in air pollution. Furthermore, allowing OPF to decompose naturally inhibits the replantation process and increases the spreading of diseases such as *Ganoderma* as well as insects such as rhinoceros beetles (*Dynastinae)*, which could damage the oil palm trees (Abdullah and Sulaiman, 2013). Due to the increased availability of OPF during harvesting and replanting, an alternative strategy for disposing of OPF is required. As a result, composting is recommended as an alternative method to convert bulky biomass such as OPF into profitable and manageable products for use in plantations or as market products (Shafawati and Siddique, 2013).

Organic waste composting is now recognised as a feasible strategy for enhancing soil health, establishing soil ecosystems, and assuring the sustainability of agricultural output. Composting is an alternate method of dealing with agricultural and industrial wastes created worldwide. Composting of agricultural waste is a recycling technology that has been proven to be used to make biofertilisers and soil conditioners. Stable compost products help replenish plant nutrients, maintain soil organic matter and improve soil physical and microbiological characteristics (Fadzilah et al., 2017). Composting is a series of interconnected biological processes involving various types of microorganisms required for the degradation of organic materials. The composting process involves

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numerous biological, chemical, and physical changes. Erwan et al. (2012) revealed that in the existence of microorganisms, great numbers of organic compounds, such as carbohydrates, sugars, and cellulose, will undergo biochemical changes and in turn produce heat, water, and CO_2. Aerobic, anaerobic, and vermicomposting are the three most common composting methods. Aerobic composting refers to the biological degradation of organic waste under controlled aerobic conditions. Aerobic composting requires the presence of oxygen during the decomposition process and is characterised by high temperatures, the absence of bad odors, and brief stabilisation. Weed seeds and other pathogenic organisms will be eliminated by high temperatures. In general, factors influencing aerobic composting consist of moisture content, carbon to nitrogen (C/N) ratio, particle size, pH, temperature, lignin degradation, and oxygen content (aeration) covering important aspects of physical, chemical, and biological properties. Three main composting methods that are often practiced in the organic waste composting process which includes windrow, aerated static pile (ASP), and mechanical or in-vessel composting. *Table 1* shows the comparison between the characteristics of these three methods. Composting of oil palm biomass, particularly OPF, into microbial-based biofertilisers is critical to reducing the impact of pollution and waste generation in the oil palm industry (Ahmad et al., 2012). Composting is becoming increasingly popular as a disposal method of solid waste or oil palm biomass. The main purpose of composting is to produce a stable product rich in nutrients that are easily absorbed by plants. Several academics have looked at the possibility of using OPF as an organic source of compost (Nahrul Hayawin et al., 2010; Ahmad et al., 2012; Erwan et al., 2012; Vakili et al., 2014; Fadzilah et al., 2015; Fadzilah et al., 2017).

Table 1. *The comparison between the characteristics of the windrow, aerated static pile, and in-vessel composting methods*

Characteristics	Windrow composting	Aerated static pile (ASP) composting	In-vessel or mechanical composting
Definition	• the organic wastes are mixed and piled in a long, thin heap, frequent turning is manually performed for aeration purposes. • requires a large area of land	• a method similar to the windrow method but the air is supplied through a network of porous pipes and an air blower built under the pile. • requires a medium space of land	• entails restricting the composting process to various containers or vessels • more efficiently than windrow and ASP methods and requires minimal land space.
Operation control	• Moisture content: 50-60% (optimum) • C/N: 25-30 (optimum) • pH: 6.5 – 7.5 (optimum), 7.0-8.0 (final) • Aeration control: Limited. Unless forced ventilation is performed	• Aeration control: Not limited.	• Aeration control: Not limited.
Duration	Long	Long	Short
Compost quality	Medium to good	Medium to good	Good
Capital cost	Low	Medium	High
Environmental impact	High	Medium	Medium

Source: Lim et al. (2017), Sabiani (2008), Huang et al. (2004), Liang et al. (2003), Agamuthu (2001), Wong et al. (2001)

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Inoculum is an additive material in composting through the addition of specific organisms to improve population growth known as the compost inoculation process. According to Rastogi et al. (2020), inoculum can be extracted from microbial communities based on certain degradative activities or produced from a mixture of cow dung, straw, soil, and so on. Inoculum can also be obtained from mature compost, an effective microbe (EM), or a mixture of commercial strains. Because of the existence of mesophilic and thermophilic bacterial populations in considerable proportions, the addition of inoculum into the composting mixture will result in changes in temperature distribution and ammonia emission, increased enzymatic activity, shortened the biological process's initial lag period, and hastened the composting process (Rastogi et al., 2020). It can also minimise odorous emissions, particularly volatile organic compounds (VOCs), and generate compost with greater nutrient content.

This review highlights the studies on the composting of OPF and alternative treatment methods that will provide useful information on the potential use of this waste for the production of value-added products. This review also discusses the utilisation of inoculum in the composting processes such as lignocellulolytic microorganisms, namely white-rot fungi (WRF), sewage sludge, palm oil mill effluent (POME), and thickened POME anaerobic sludge for rapid breakdown of lignocellulosic OPF. Furthermore, the environmental consequences of composting are also investigated in this review since the composting process might indirectly minimise problems associated with environmental pollution affecting air, water, and soil.

Oil palm

Oil palm (*Elaeis guineensis*) is a native plant from West Africa that is beneficial for a variety of applications and is now extensively cultivated, notably in the South American and Asian continents (Onoja et al., 2018). Nigeria was the world's largest producer of palm oil until the mid-1960s when Malaysian palm oil production exceeded Nigeria's due to the fast expansion of the oil palm sector (Oviasogie et al., 2010). Malaysia was the world's biggest palm oil producer and exporter and related goods until 2007 when Indonesia surpassed that position (Paterson et al., 2009; Mazaheri et al., 2010; Rupani et al., 2010). Tropical weather conditions and high rainfall reception cause oil palm trees to grow fertile (Yaap et al., 2010); promising the success of its cultivation in Malaysia and Indonesia. Mohammad et al. (2010) revealed that these two countries produce almost 85% of the world's palm oil, with Indonesia and Malaysia accounting for 44% and 41% of output, respectively.

The British initially introduced oil palm trees to Malaysia in 1871 as ornamental plants (Onoja et al., 2018). The commercial-scale farming of oil palm trees in Malaysia began almost 100 years ago, with the initiation of the first palm oil plantation at Tenamaran Estate in Selangor in 1917 (Awalludin et al., 2015). After achieving independence in 1957, Malaysia experienced a continuous expansion in the cultivation of oil palm trees. This achievement was made possible by the Malaysian government's introduction of several initiatives, which resulted in the rapid growth of the oil palm sector (Awalludin et al., 2015), with oil palm plantations occupying more than 16% of the country's accessible land by 2014 (Hosseini and Wahid, 2014).

In 2012, solid and liquid wastes from oil palm biomass totaled 83 million tonnes of solid waste, and 60 million tonnes of liquid waste were produced (AIM, 2013). This amount is predicted to reach 85–110 million tonnes for dry solid waste and 70–

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110 million tonnes for liquid waste by 2020 (AIM, 2013). This forecast is in line with the continued expansion of oil palm plantation areas in Malaysia. The planting and cutting of oil palm trees to produce palm oil in Malaysia have indirectly increased the generation of solid waste such as OPF and OPT. Meanwhile, EFB, MF and PKS resulting from palm oil processing activities also have adverse implications for the environment.

Oil palm fronds (OPF)

Oil palm fronds (OPF) are the most abundant biomass available in the world surpassing rice straw and corn stover, particularly in South-East Asia (Tan et al., 2016). OPF has sponge-like fibres. As illustrated in *Figure 1*, OPF consists of four primary parts: petiole, stem, rachis, and leaflet (Roslan et al., 2014). The petiole portion is responsible for half of the weight of the OPF. SEM micrographs of stem and petiole indicated the presence of porous lignocellulosic fibres with silica bodies comparable to those of EFB (Simarani et al., 2009). Rachis, stem, and petiole are mostly composed of cellulose, whereas leaflet is mostly composed of hemicellulose and lignin.

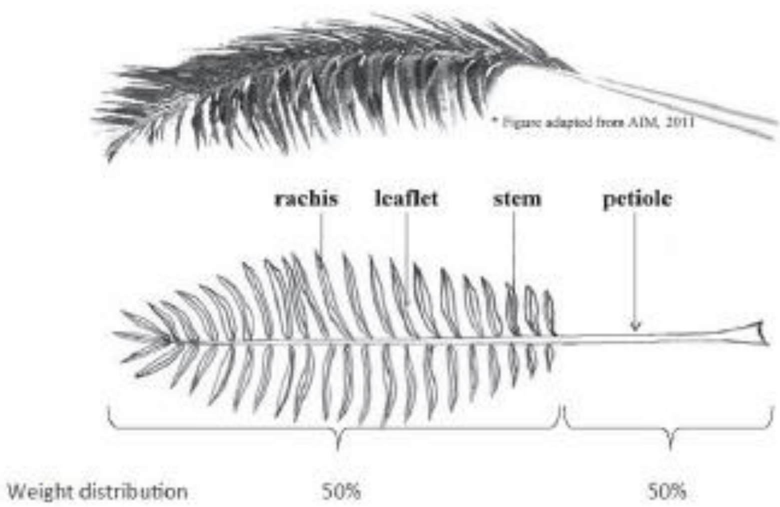

Figure 1. *Oil palm fronds (OPF) parts (Roslan et al., 2014)*

The major components of OPF are extractives, cellulose, hemicellulose, and lignin, which are found in vascular bundles and parenchyma (Kumneadklang et al., 2019). OPF contains 2.4-2.8% nitrogen, 0.15-0.18% phosphorus, 0.90-1.20% potassium, 0.25-0.4% magnesium and other trace elements (Sunarti et al., 2016). According to Onoja et al. (2018), the cellulose, hemicellulose, and lignin contents of OPF are 40.01%, 30.78%, and 29.50%, respectively. Carbon (C), hydrogen (H), nitrogen (N), sulfur (S), and oxygen (O) have been identified in the ultimate analysis of OPF. Several researchers such as Guangul et al. (2012), Abnisa et al. (2013), and Loh (2016) reported that the percentage ranges of C, H, N, S, and O contents observed in OPF were 42.76-48.43%, 4.53-10.48%, 0.39-12.40%, ND-0.07%, and 46.75-50.88%, respectively. According to Ho et al. (2015), one of the benefits of OPF is that it contains a high proportion of oxygen which requires less external air for complete combustion, thus making it a cost-effective fuel source together with other parts of the oil palm, such as leaves, trunks and empty fruit bunches. Because of its low nitrogen and sulfur content, OPF can be an environmentally friendly source of energy with a reduced risk of greenhouse gas emissions (Onoja et al., 2018). From

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proximate analysis, OPF has been reported to contain 13.84% moisture content, 82.70% volatile matter, 0.24% ash, and 3.22% fixed carbon (Abnisa et al., 2013). The presence of volatile matter and fixed carbon in OPF indicates that it has a high calorific value and can be ignited, gasified, or oxidized to some extent (McKendry, 2002). OPF has been recognised as an excellent source of fuel that can be converted into biogas (Mekbib et al., 2013; Herbert and Unni Krishnan, 2016) and biofuels through appropriate technology by referring to data related to volatile matter and fixed carbon. Furthermore, research on the volatile matter has revealed that OPF is composed of organic compounds such as cellulose, hemicellulose, and lignin. Because OPF is lignocellulose, it is easily transformed into simple sugars, which are subsequently processed into important biochemicals and biofuels (Loh, 2016).

Utilisation of oil palm fronds

Earlier, OPF was mostly utilised as soil mulching and allowed to degrade naturally in the plantation (Sulaiman et al., 2010; Mulakhudair et al., 2016), cattle feed (Daud and Law, 2010), and hydrogen gas supplies (Kelly-Yong et al., 2007). The application of OPF has expanded in numerous fields as a result of recent technological breakthroughs and research. Efforts in utilising OPF lignocellulose biomass in Malaysia are supported by the Malaysian National Biomass Strategy. Conversion of OPF into more valuable products has recently been reported, such as the production of bio-oil and biochar (Jadhav et al., 2019; Lawal et al., 2020), adsorbent for dye removal (Chew and Husni, 2019), wood adhesive production (Hussin et al., 2018), wastewater filtration media (Lee et al., 2021), renewable sugars (Manaf et al., 2018), composite boards (Iling et al., 2019), activated carbon production (Maulina and Anwari, 2018), bioethanol production (Syed Abdullah et al., 2021) and papermaking (Jarupan et al., 2021).

Jadhav et al. (2019) used the hydrothermal liquefaction method to create biochar solid and bio-oil liquid from OPF in a batch autoclave reactor. The results demonstrated that the percentage of bio-oil yield increased from 27.3% at 160°C to 41.9% at 260°C, whereas the percentage of biochar yield declined from 65.2% at 160°C to 43.2% at 260°C. Moreover, the percentage of carbon in biochar and bio-oil increased from 42.73% in OPF to 59.42% and 60.47%, respectively. In contrast, the percentage of oxygen in biochar and bio-oil declined from 52.51% to 36.30% and 35.61%, respectively. Phenolic compounds and their derivatives, alcohols, ketones, and esters are the most common chemical compounds found in bio-oil. The application of biochar in wastewater treatment has expanded due to advances in biochar synthesis and modification. Lawal et al. (2020) synthesized biochar from OPF using the pyrolysis method at a steam temperature of 500°C, which was then mashed into granulated and micro-fine particles. These biochar particles were characterised and employed as adsorbents in the final discharge treatment of POME. By raising the dosage of micro-fine biochar from 5 to 30 g/L, they discovered that the adsorption capacity reduced chemical oxygen demand (COD) and color. The micro-fine biochar effectively reduced the COD and color of wastewater by 81.4% and 95.6%, respectively, making it appropriate for recycling in processing plants and harmless for discharge into the natural water bodies at a concentration of 30 g/L.

The disposal of industrial wastewater containing dye leftovers that are detrimental to persons and the environment is one of the environmental challenges. The search for low-cost and environmentally friendly adsorbents that can help eliminate dye appears challenging. Therefore, Chew and Husni (2019) conducted a study to investigate the ability of OPF as an absorbent to eliminate Janus Green B dye. In the study, the adsorption

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capacity of OPF-based adsorbent was investigated based on the concentration of initial dye solution (50-250 mg/L), OPF loading (1–7 g/L), and pH (2–8) employed. Chew and Husni (2019) observed that the OPF-based adsorbent has an initial dye solution concentration of 150 mg/L, an adsorption capacity of 67 mg/g at pH 8, and an organic loading of 1 g/L for eliminating Janus Green B dye. Hussin et al. (2018) explored the use of lignocellulosic materials such as OPF in the production of environmentally friendly wood adhesives. In their research, they employed organosolv lignin generated from black liquor by organosolv pulping of OPF and regarded it as an alternative to phenol to manufacture glyoxal-phenolic resins for plywood. When compared with commercial phenol-formaldehyde (PF) adhesives, they discovered that the adhesive composition of 50% organosolv lignin phenol glyoxal (OLPG) with 50% (w/w) phenol replaced by organosolv lignin had maximum adhesive strength.

The amount of wastewater and biomass waste generated by palm oil processing activities has increased in tandem with the increasing demand for palm oil. Lee et al. (2021) employed OPF fiber as a media filter material to treat POME as an alternative strategy. OPF fiber was chosen for its unique properties, including high cellulose content, availability, biodegradability, and non-toxic. Chemical oxygen demand (COD), biochemical oxygen demand (BOD), total suspended solids (TSS), and pH were the criteria used to determine the pollutant reduction performance in their study. To identify optimal treatment results, OPF filters were arranged in various ratios, particle sizes and also coupled with other filter media materials such as activated carbon and sand. The findings of the study showed that pH 5.77 recorded the best results for BOD, COD, and TSS removal at 26.44%, 55.21%, and 98%, respectively. OPF has become increasingly popular as a source of sustainable fermentation feedstock. Manaf et al. (2018) studied the potential utilisation of soluble OPF bagasse products during dilute acid hydrolysis. Evaluation of experimental parameters such as nitric acid concentration, temperature, and contact duration resulted in optimal xylose release from OPF. Using 4% (v/v) HNO_3 at 130°C for 20 minutes, the maximum sugar levels obtained were 18.4 g xylose and 8.9 g glucose per 100 g OPF. There were 22.1 g/L xylose, 8.9 g/L glucose, and 4.6 g/L total inhibitors in the liquid fraction. In the fermentability test of xylitol production utilising OPF hydrolysate, the highest production of 0.35 g xylitol per gram of sugar was achieved. The study deduced that the use of dilute nitric acid to hydrolyse xylitol is a cost-effective and environmentally friendly method in biorefinery.

The selection of raw materials and fabrication variables has a significant impact on the performance of composite boards. Iling et al. (2019) evaluated the impact of various amounts of applied pressure on the performance of the OPF composite board as the end product. Using a crusher machine, OPF was crushed into small particles. Composite boards having a density of 0.7 g/cm^3 were made from sieved OPF particles retained on a 0.60 mm sieve screen. Composite boards with dimensions of 20 cm x 20 cm x 0.50 cm were produced at 160°C for three distinct applied pressures, namely 5 MPa, 6 MPa, and 7 MPa. The results showed that when the applied pressure increased, the performance of OPF composite boards improved. Composite boards produced from OPF are widely applied as base materials, decorative boards, and teaching aids. The presence of cellulose, hemicellulose, and lignin in OPF highlights its potential to be processed into a more valuable product. Therefore, using pyrolysis and impregnation methods, Maulina and Anwari (2018) utilized this waste to produce activated carbon. The OPF was pyrolyzed in reactors for 60 minutes at temperatures of 1500°C, 2000°C, and 2500°C. Subsequently, the pyrolyzed charcoal was smoothed using a ball mill, sieved to 140 meshes, and

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impregnated for 24 hours with sodium carbonate (Na_2CO_3) at concentrations of 0, 2.5, 5, and 7.5% (w/v). The activated carbon produced was porous, coarse and uniformly distributed in addition to having 72.75% fixed carbon, 35.13% charcoal yield, 24.75% volatile matter, 14.25% ash content, 8.6% water content, and 492.29 iodine number.

On the other hand, OPF juice is an effective fermentation feedstock for bioethanol production due to its high fermentable sugar content. The rapid deterioration of fermentable sugars in the juice during storage is a key drawback of using it as a feedstock. Thus, Syed Abdullah et al. (2021) investigated the impact of OPF juice concentration and moderate temperature storage on the juice's glucose content. Squeezing fresh OPF petiole was used to extract the juice, which was then concentrated by evaporating 30–70% (v/v) of the water. The juice was kept at varying temperatures (30 – 60^{o}C) for 20 days before being utilised for bioethanol production. The results showed that although there were various concentrations of OPF juice, the glucose content remained unchanged at storage temperatures of 50°C and 60°C. Furthermore, when OPF juice was stored at 50°C, bacterial deterioration was significantly reduced, and when kept at 60°C, it was destroyed. When compared to freshly made OPF juice, bioethanol production utilising OPF juice stored at 50^{o}C yielded about 15% higher bioethanol. Previously, the mold pulp trays used were made from newspaper waste. The transition to the digital age has resulted in a decline in this key feedstock. Therefore, alternative fiber sources such as OPF are beginning to be explored. Jarupan et al. (2021) found that fibers from OPF have great potential for waterproof containers in humid environments. Fibers were recovered from petioles with a yield of 30.72% using sulfate pulping in their investigation. The high α-cellulose content (38%) proved to be beneficial for papermaking. Properties such as Runkle's ratio (0.63), rigidity coefficient (38.46), and slenderness value (100) of the resulted paper all showed that it would have good mechanical quality. In cold chain logistics, packaging must withstand high humidity and low temperatures (90% RH, 12°C). Significant increases in water absorption resistance (from 59 to 23250 s), burst (6.68%), and tensile index (26.47%) were recorded when the addition of 1.4% cationic starch and 0.5% alkyl ketene dimer (AKD) was performed. The compressive strength of the mold pulp trays made of 70% sized frond fibers and 30% old corrugated container (OCC) fiber was 7.71% higher than that of a neat OCC tray.

Composting of oil palm fronds

The unique physical, chemical and biological characteristics of each organic matter provide a significant influence on the aerobic composting process. *Table 2* briefly shows the comparison of characteristics between OPF and typical softwood waste. Factors such as moisture content, pH, carbon, hydrogen, nitrogen, sulfur, oxygen, and organic content of lignin, cellulose, and hemicellulose were found to be interrelated with each other. The presence of high carbon and oxygen content will produce compost rich in organic matter and these elements play an important role in microbial activity during the composting process. Garcia et al. (2012) reported that the nitrogen present in OPF will be converted to ammonia gas which adversely affects the environment. Thus, the composting method is seen as the best alternative to manage OPF while solving the disposal problem and providing economic potential.

The biological characteristics of OPF consist of a high percentage of cellulose and hemicellulose, which are primary carbon sources and are followed by lignin. A study by Garcia et al. (2012) showed that enzyme degradation is an essential element in the degradation of lignocellulose via the aerobic composting method. A sufficient additional

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amount of nitrogen in the mixture corresponding to the amount of carbon is needed, where an appropriate C/N ratio can be achieved. Therefore, a precise understanding of OPF properties will ensure the practical configuration of composting towards a rapid degradation rate as well as producing a valuable final compost product.

Table 2. *A brief comparison of characterisation between OPF and typical softwood biomass*

Type of analysis	Oil palm fronds (OPF)		Typical softwood biomass	
	Value	**References**	**Value**	**References**
Physical characteristics (mf wt %)				
Moisture content	37.5	Omar et al. (2018)	n/d	Telmo et al. (2010)
pH	3	Atnaw et al. (2012)	2.5	
Chemical characteristics (mf wt%)				
C	42.4	Atnaw et al. (2012)	47.0-54.0	Telmo et al. (2010)
H	5.8		5.6-7.0	
N	3.6		0.1-0.5	
S	0.03		0.01-0.05	
O	48.2		40.0-44.0	
Biological characteristics (mf wt%)				
Lignin	20.5	Atnaw et al., (2012)	25-35	Telmo et al. (2010)
Cellulose	49.8		45-50	
Hemicellulose	23.5		25-35	

Notes: mf wt % is weight fraction percentage of dry material; n/d refers to not defined

Efficient biomass waste management can reduce the problems associated with environmental pollution caused by the disposal of large amounts of waste resulting from the oil palm industry, particularly OPF. Since OPF has a high content of organic matter, the compost resulting from the composting process has great potential to increase soil fertility (Vakili et al., 2014). It can also substitute the role of chemical fertilisers in agricultural activities. Composting is a valuable biomass recycling technology for producing compost that is easy to handle, stable, and high in plant-nutrient content. The conversion of OPF into compost is very interesting and has gained the attention of previous researchers. The studies have encompassed various aspects, including (1) characteristics, physicochemical and biological changes that occur during OPF composting and co-composting of other substrates (Erwan et al., 2012; Vakili et al., 2012, 2014; Ahmad et al., 2014); (2) microbial succession during co-composting of OPF with other substrates (Ahmad et al., 2016); (3) activity and diversity of fungal populations on OPF during the composting process (Fadzilah et al., 2015); (4) chemical and physical properties of OPF inoculated with fungi during composting (Fadzilah et al., 2017); and (5) utilisation of OPF compost (Kala et al., 2009; Erwan et al., 2013; Stevanus et al., 2016; Sunarti et al., 2016).

Erwan et al. (2012) investigated the physicochemical and biological changes that have occurred during OPF composting. Compost A, B, and C were prepared by mixing OPF, chicken manure (CM), and rice bran (RB) in the following proportions: 40:40:20, 40:30:30, and 40:20:40. Compost A had the lowest C/N ratio and the greatest amounts of nitrogen (N), phosphorus (P), and potassium (K) after 21 days, with values of 15.79, 2.33, 2.02, and 1.80, respectively. Compost A also had more bacteria than the other two composts, indicating that by day 21, OPF in compost A had matured enough to be used as soil supplements in agricultural areas. Vakili et al. (2012) examined the optimum ratios

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of poultry litter (PL) to palm oil biowaste (POB) composting process while observing the properties and physicochemical changes in bin composting of POB and PL. The POB utilised throughout their study was a combination of OPF and EFB. To achieve nutrient balance in the compost mixture, PL was combined with POB in three different ratios, namely 3:1, 1:1, and 1:3, and the moisture content was set to 40%. The composting materials were watered and turned periodically. Then, the materials were left under the shade for 11 weeks to decompose. The pH of all samples at the end of the process was close to natural. All samples exhibited a C: N ratio in the optimal range (25:1); however, the POB and PL ratio of 1:3 had the lowest C: N ratio. Moreover, Vakili et al. (2015) used a co-substrate different from previous to obtain the best ratio when conducting composting of POB (mixture of OPF and EFB) and cow dung (CD) to produce compost suitable for use in agriculture. In the study, Vakili and his co-workers provided four different POB and CD ratios, namely 4:0, 3:1, 1:1, and 1:3. The composting process, which took 11 weeks, was performed in plastic bins under the shade. Throughout this process, the composting materials were moistened to maintain optimum moisture content and the turning process was performed periodically. From the study, it was found that the 1:3 ratio (POB: CD) produced better quality compost than other ratios with C: N ratio, electrical conductivity (EC), and pH for mature compost recorded were 22.2, 2.83 mS/m, and 7.81, respectively. The use of POME as a co-substrate in the composting of chipped-ground OPF was investigated by Ahmad et al. (2014). The co-composting of chipped-ground OPF and POME took 60 days and had an average C/N ratio of 23. The temperature of the compost rose to a thermophilic phase (53.5^{o}C) after 4 days of composting. On the 21st day, the maximum temperature recorded during the thermophilic phase was 56^{o}C. The oxygen level, moisture content, and pH of the compost were sustained at 1.7 - 12.2%, 60.6 - 70.7%, and 7.9 - 8.5, respectively, during the 60-day composting period. The initial bacteria count was 55x10^{10} cfu/mL, which decreased to 14.7x10^{10} cfu/mL on on the 25th day and 3.7x10^{10} cfu/mL on the 60th day. The C/N ratio began at 63.9 and decreased to 24 on the 60th day.

Composting is a self-heating aerobic process involving microbial organic breakdown and stabilisation. This process can also be interpreted as a microbial succession that is constantly adapting to nutritional changes and ambient conditions. Mesophilic bacteria, which rapidly use decomposing materials, generally dominate the composting process initially. However, high metabolic activity contributes to heat production, resulting in a rapid temperature rise. As a result, thermophilic bacteria have taken over the mesophilic population. According to Baffi et al. (2006), a composting process involves lignocellulose biomass occurring in the thermophilic phase. In the maturation phase, new mesophilic populations will reappear to replace thermophilic populations. Microbial succession during co-composting of chipped ground OPF with POME was studied by Ahmad et al. (2016). Succession and phylogenetic profiles of microbial communities during the composting process were studied using polymerase chain reaction-denaturant gel gradient electrophoresis (PCR-DGGE) analysis. The findings revealed that the dominating microbial population was *ɤ-Probacteria* (e.g., *Pseudomonas sp.*) throughout the composting process. Meanwhile, *Bacillales* (e.g., *Bacillus psychrodurans*) were also detected in compost heaps when the composting process was heading towards the final stage. *Pedobacter solani* from the *Bacteroidetes* group was detected in the compost heap during the final stage of composting.

Improper and inefficient disposal of OPF will contribute to environmental problems. With proper compost management, OPF has the potential to be converted into organic

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compost that can be used as a soil amendment to promote crop growth. OPF is reported to have the potential to be utilised as an organic fertiliser that helps the growth of crops such as organic rice, rubber, cauliflower, and ornamental plants. Stevanus et al. (2016) examined the optimum dosage of OPF-based compost to promote the growth of rubber plants. The study analysed the OPF composting process as well as applied the resulting compost as a medium to improve the soil in the rubber plantation area. They stated that, except for K_2O concentration, the resulting compost met the Indonesian National Standard for compost quality. When compared with other treatments, the application test indicated that 20% compost + 80% subsoil treatment was the best dosage to enhance rubber plant growth. The final cation exchange capacity (CEC) value of the control declined compared to the initial value, but the CEC value of compost-added media increased with higher compost dosages. Compost-added media also had higher levels of P, K, Ca, and Mg than control media. Sunarti et al. (2016) made a comparison of three types of fertilisers consisting of OPF compost, cow manure, and synthetic fertiliser in organic rice cultivation. All these three treatments were evaluated at three distinct dosage levels, namely 60, 90, and 120 kg N/ha. In terms of quantity of tillers and productive tillers, the study found that OPF compost outperformed cow dung and synthetic fertiliser. However, there were no significant differences in plant height or rice production in the three fertilising treatments. On the other hand, an increase in nitrogen concentration will improve rice growth and production. Erwan et al. (2013) investigated the feasibility of using coconut coir dust (CCD) mixed with OPF compost soilless growth medium for cauliflower cultivation. In a tropical humid plant house, five distinct soilless growth media were evaluated: CCD alone, CCD and peat (CDP) mixes, CCD and OPF compost A ($CCDC_A$), CCD and OPF compost B ($CCDC_B$), and CCD and OPF compost C ($CCDC_C$). Due to superiority in physiological characteristics (stomatal conductance, photosynthesis rate, and chlorophyll content in leaves) and higher nutrient uptake rate. Throughout the growing phase, $CCDC_A$ treatment offered optimal plant development conditions for cauliflower, resulting in maximum total dry mass production and economic yield, i.e. the largest curd production (302 g/plant). Plants grown on a $CCDC_A$ medium also matured six days quicker than control plants. As a result, plants grown in soilless media, such as $CCDC_A$, may be appropriate for commercial cauliflower production in tropical conditions.

Factors such as acid reaction, high organic acid content as well as low micronutrient and macronutrient content contribute to low crop production rate. To overcome this problem, the use of OPF with ameliorants such as Cu^{2+}, Fe^{3+}, and Zn^{2+} can enhance peat soil while having a low environmental effect. Zahrah (2020) investigated the effects of ameliorants, namely Cu^{2+}, Fe^{3+}, and Zn^{2+} as well as OPF compost treatments on the growth of mung beans. The first factor was the application of four-level ameliorants (Cu^{2+}, Fe^{3+}, and Zn^{2+} without ameliorant). The second factor was the four levels of OPF compost dosages (0, 12, 24, and 36 g per plant). The combination of Cu^{2+}, Fe^{3+}, and Zn^{2+} with OPF compost considerably affected the percentage of filled pods, seed dry weight, and root volume of mung beans. According to the findings, the mixture of Cu^{2+} with 24 g/plant OPF compost yielded 26.67 g/plant seed dry weight, 94.7% filled pods, and 27.4 cm^3 root volume, representing a 175.5%, 32.8%, and 109.2% increase, respectively, over untreated soils.

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Utilisation of white-rot fungi (WRF), sewage sludge (SS), palm oil mill effluent (POME), and POME anaerobic sludge in lignocellulose biomass composting

According to Awasthi et al. (2017), organic matter (OM) is digested and transformed into a stable humic substance (HS) during composting under suitable circumstances. Organic macromolecules including lignocellulose, protein, and lipid are commonly found in the composting of raw materials. Because of its complicated physicochemical composition and structure, lignocellulose is the most stable organic component in composts. The presence of lignocellulose materials not only decelerates composting but also inhibits HS production. As a result, improving lignocellulose biodegradation is critical for enhancing organic waste composting efficiency and compost quality (Zhu et al., 2021).

Inoculation with lignocellulolytic microorganisms, such as bacteria and fungi, is a potential method to improve lignocellulose decomposition. Fungi that are active in the biodegradation of lignocellulose biomass can be divided into three major categories, namely white-rot, brown-rot, and soft-rot fungi. White-rot and brown-rot fungi belong to *Basidiomycetes*, whereas soft-rot fungi belong to *Ascomycetes* (Isroi et al., 2011). White-rot fungi (WRF) break down lignin using two mechanisms: selective and non-selective decays. The selectivity of WRF lignin degradation is affected by lignocellulose species, culture period, and other variables (Hatakka and Hammel, 2010). *Ceriporiopsis subvermispora, Dichomitus squalens, Phanerochaete chrysosporium*, and *Phlebia radiata* are examples of WRFs that exhibit selective decay under specific conditions, while *Trametes versicolor* and *Fomes fomentarius* are two WRFs with non-selective decay. Lignin peroxidase (LiP), laccase (Lac), manganese peroxidase (MnP), versatile peroxidase (VP), and H_2O_2-forming enzymes such as glyoxal oxidase (GLOX), and aryl alcohol oxidase (AAO) are enzymes involved in lignin breakdown (Hatakka, 2001; Wong, 2009). WRF generates a variety of enzymes involved in the breakdown of lignin, cellulases, xylanases, and other hemicellulases. Most WRFs produce manganese peroxidase (MnP) and laccase (Lac), but only a few produce lignin peroxidase (LiP) (Isroi et al., 2011). WRF has a great potential for delignification, although its effectiveness varies depending on the species selected for pretreatment (Rouches et al., 2016).

For example, Heidarzadeh et al. (2019) found a drop in the C/N ratio and a decrease in process time when *Aspergillus Niger* was inoculated to municipal solid waste (MSW) compost. Due to the enhanced diversity of fungal populations, Hu et al. (2019) discovered that incorporating lignocellulolytic microbial consortia into swine manure and mushroom waste co-composting improved lignocellulose breakdown by 8.77–34.45%. According to Awasthi et al. (2014), inoculating thermophilic fungal consortia (Trichoderma and Aspergillus) in the MSW composting mixture dramatically increased organic carbon mineralisation and expedited compost maturity. After WRF (*Phanerochaete chrysosporium, Trametes versicolor,* and *Fomes fomentarius*) was inoculated in the organic fraction of MSW, Voberkova et al. (2017) discovered that solid waste degradation was expedited, as demonstrated by modifications in the C/N ratio, electrical conductivity, pH, greater degradation ratio, better maturity degree, and enhanced enzymatic activity. During the second fermentation stage of rice straw composting, Zeng et al. (2010) discovered that inoculation of *Phanerochaete chrysosporium* enhanced cellulase and ligninase activities.

Inoculation with WRF during oil palm biomass composting is an approach that could positively affect lignocellulose degradation. Alam et al. (2006) conducted solid-state bioconversion (SSB) of mixed substrates consisting of EFB and POME in a laboratory-

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scale rotary drum bioreactor. In the study, different lignocellulolytic microorganisms such as *Trichoderma, Aspergillus, Penicillium,* and *Phanerocheate chrysosporium* (a type of WRF) were inoculated in composting materials (EFB and POME) in the drum. Four distinct fungal species were involved in the composting process through SSB depending on their activity in the rotary drum bioreactor for 2 months. They found that after 20 days of composting, the C/N ratio decreased from 70 to 25. A germination index of 50-70 showed that the compost generated was phytotoxic-free and only attained mature compost after 45 days of composting time. Fadzilah et al. (2015) employed a scanning electron microscope (SEM) and traditional identification methods to assess the activity and diversity of fungal populations on OPF during the composting process. Two WRF species, *Trametes versicolor* and *Schizophyllum commune,* were used as inoculants to shorten the composting time and produce high-quality compost. OPF was composted for 14 weeks in four distinct treatments: control (untreated OPF), OPF treated with *T. versicolor,* OPF treated with *S. commune* and OPF treated with both *T. versicolor* and *S. commune*. Each treatment was repeated four times. From the composted OPF, they isolated and identified eight fungi genera, including *Aspergillus, Trichoderma, Absidia, Geotrichum, Trametes, Schizophyllum, Syncephalastrum,* and *Beauveria.* Although *T. versicolor* and *S. commune* were added as accelerating agents, other fungal species were also present which could be due to the indigenous microflora in OPF, resulting in the succession of various fungal species depending on the complexity of biological processes in composting feedstock. Through the same study, the chemical and physical characteristics of OPF for 14 weeks of composting were also examined. They discovered that the finished compost was brown in colour, consistent in appearance, and odourless. When compared with other treatments, *S. commune* inoculation produced the lowest C/N ratio of 63.2 at the end of the composting period (Fadzilah et al., 2017). A single inoculation of *S. commune* produced a greater volume reduction percentage of 62.8% than other treatments. They conclude that a single *S. commune* inoculation offers an appropriate medium for OPF composting.

In addition, sewage sludge is also seen to have the potential to play a role as an inoculum in organic waste composting to produce compost or organic soil amendments. Municipal wastewater treatment plants produce a large volume of sewage sludge as a secondary waste product. It is a semi-solid or liquid residue generated during residential wastewater treatment and must be disposed of or removed from the system regularly to ensure the biological treatment process functions optimally (Ivanov et al., 2004). The use of sewage sludge for other applications often results in cost savings over disposal. According to Samaras (2007), sludge management via aerobic/anaerobic digestion, mechanical dewatering, and incineration often account for half of the total investment in wastewater treatment facilities. Sewage sludge contains a high amount of microbial diversity, which may impact the efficiency of wastewater treatment plants (WWTPs) and soil quality if used as fertiliser. Using molecular biology, Nascimento et al. (2018) investigated the diversity and structure of microbial communities in 19 sewage sludges from Sao Paulo, Brazil, as well as their connections to sources, biological treatments, and chemical properties. Although all sludges had a great amount of bacterial diversity, the sources, redox operating conditions, and liming did not have a consistent effect on the bacterial community structures. The main phylum was *Proteobacteria,* followed by *Bacteroidetes* and Firmicutes, while the leading genus was *Clostridium*, followed by *Treponema, Propionibacterium, Syntrophus,* and *Desulfobulbus.* As the biological sludge produced during the activated sludge process contained a wide variety of potentially

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heterotrophic bacteria, it is an appropriate microbial consortium for the decomposition of MSW organic waste fractions. For example, Deepesh et al. (2014) claimed that by using sewage sludge as an inoculum, the segregated MSW may be efficiently valorized, and the quality of the compost produced is equivalent to compost intended for unrestricted applications. During chicken manure-cornstalk composting, Li et al. (2017) found that inoculum derived from sewage sludge exhibited the best performance in terms of composting stability and maturity (the C/N ratio was lowered from 15.5 to 10, while the germination index was increased to 109%).

In addition, co-composting of lignocellulosic biomass and sewage sludge can also produce quality compost and is suitable for use as a natural fertiliser for crops. For example, Dzulkurnain et al. (2017) used a pilot-scale bioreactor system of 10 m^3 to co-compost municipal sewage sludge and landscaping waste as a soil amendment. Throughout the composting process, temperature, oxygen level, moisture content, and pH were all recorded. They found that the finished compost has 3.01% nitrogen, 0.27% phosphorus, and 0.68% potassium, making it ideal for ornamental plant growth. The Solvita® compost maturity kit produced an index result of 7, indicating that the product has reached maturity. The compost pathogenicity test revealed that coliforms and *Escherichia coli* were eradicated after 15 days of composting at the thermophilic stage, proving that the compost was safe for use in the natural environment. Kebibeche et al. (2019) studied the influence of co-composted sawdust with sewage sludge and wheat straw on seed germination. For 90 days, the two mixes were heaped and composted. The first mixture (C1) contained sewage sludge and wheat straw, whereas the second mixture (C2) contained sewage sludge, wheat straw, and wood sawdust. Temperature (> 55°C in the thermophilic phase), moisture content (30%), pH (6.73 for C1 and 7.19 for C2) and EC (1.81 mS/cm for C1 and 1.32 mS/cm for C2) of both composts met the necessary maturity level. The compost produced also showed a high level of maturity with C: N value below 12. In addition, no pathogenic bacteria were found in the finished compost. As shown by a germination index of over 80%, the concentration of total heavy metals dropped, allowing the elimination of sewage sludge toxicity. The addition of wood sawdust then increased the nitrogen content of the compost, resulting in slightly alkaline conditions. Meanwhile, Asses et al. (2018) evaluated the possibility of co-composting sewage sludge with organic waste in terms of management and agricultural value of the end product as a treatment technique. Two composting cycles (P1 and P2) were performed using sewage sludge (SS) to generate two mixtures, one with olive mill waste (OMW) and the other with green waste (GW). The co-composting of SS with both organic wastes resulted in hygienic compost of sufficient agronomic grade. The buildup of phenols from OMW-containing mixture resulted in a significant reduction of pathogens in the compost. These products were distinguished by the concentrations of P and K comparable to commercial composts as well as an advanced maturity suitable for direct application in agriculture. The germination index (GI) values for maize and tomato seeds treated with P1 were 79.68% and 97.36%, respectively. However, the GI values declined to 74.45% (maize) and 81.45% (tomato seeds) when using P2.

Several previous researchers in Malaysia have performed studies on the utilisation of oil palm wastes, namely EFB, OPF, and OPT as compost. Sewage sludge is another organic waste that must be disposed of properly in Malaysia. Co-composting of these waste materials has the potential to be converted into value-added products. Kala et al. (2009) examined the optimum ratio of oil palm waste aggregation (EFB, OPF, OPT) with sewage sludge (SS). Experiments were conducted in a glass greenhouse using a

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polystyrene box to produce mature compost, which was then used as potting media in horticulture. The oil palm wastes were chopped and blended with SS in three different ratios of 1:0, 3:1, and 4:1. The moisture content was set at 60%. From the experiments, they concluded that the OPT and SS ratio of 4:1 is the best to be used as an ornamental plant medium as its texture is most suitable as potting media. This ratio gave the following results: pH of 6.2, low C/N ratio of 19, and high nutrient levels such as nitrogen (2.05%), phosphorus (0.640%), potassium (1.39%), calcium (0.705%) and magnesium (0.229%).

Due to its significant level of OM and nutrients such as nitrogen, phosphorous, and potassium, SS can be used as fertiliser to increase crop production (Wu et al., 2010). Utilization of SS directly as a fertilizer is restricted due to the hygienic instability and immaturity of SS as well as the existence of pathogenic organisms and heavy metals. Composting is considered an appropriate SS management method as it converts OM into stable humic compounds via mineralisation and humification while decreasing harmful bacteria during the thermophilic phase (Yanez et al., 2009). To achieve compost maturity, many environmental parameters such as temperature, pH level, aeration, moisture content, the particle size of composting materials, and free air space should be carefully managed (Ge et al., 2015; Kim et al., 2016). A phytotoxicity test is usually conducted to determine the toxicity and maturity of the compost before the compost is used for agricultural purposes as well as to avoid any risk to the environment. According to Brewer and Sullivan (2003), unstable and immature compost use will contribute to problems such as inhibiting seed germination, inhibiting crop growth, and the occurrence of competition for oxygen due to insufficient OM decomposition. SS cannot be composted alone owing to its high moisture content and small particle size (Zhao et al., 2016). Furthermore, its low C/N ratio is detrimental to the composting process and results in a high volume of ammonia volatilization (Wang et al., 2014; Kulikowska, 2016). To increase gas permeability and minimise ammonia volatilisation, SS should be composted with dry material rich in carbon sources to modify the moisture content and C/N ratio (Awasthi et al., 2016). Co-composting may offer ideal composting conditions, such as a good C/N ratio, high porosity, and substantial active biomass, and it could also dispose of two or more types of solid waste simultaneously (Meng et al., 2017).

In Malaysia, the majority of research on co-composting of palm oil waste using EFB, OPF, and MF with POME produced from the palm oil milling process or POME anaerobic sludge from the anaerobic reactor or anaerobic pond at the mill. Raw POME is classified as high-strength agro-based wastewater with 95–96% water, 4–5% total solids (Vakili et al., 2014), COD and BOD concentrations of 69,500 mg/L and 25,000 mg/L, respectively (Abdullah et al., 2013), and high oil and grease (8370 mg/L) (Nik Kob, 2017). Raw POME is a hot and acidic brownish colloidal suspension. As Malaysia is one of the world's largest palm oil producers, POME anaerobic sludge is in large volumes and is easily available. The palm oil production process generates a large amount of waste in the form of POME which is subsequently treated through anaerobic digestion and finally produces POME anaerobic sludge. Sabiani (2019) reported that the COD concentrations, total solids, volatile solids, and water content of POME anaerobic sludge were 57,768 mg/L, 8.43%, 68.3%, and 91.5%, respectively. According to Zainuddin et al. (2013), thickened POME anaerobic sludge has high nutrient content comprising nitrogen (4.7%), phosphorus (1.3%), and potassium (6.5%) as well as indigenous microorganisms, making it an excellent microbial seed for the composting process. The application of thickened POME sludge during the composting process may shorten the composting duration while increasing compost yield.

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Alkarimiah and Suja' (2019) used a mechanical rotary drum reactor with a partial sequence feeding approach for co-composting of EFB and POME. According to their findings, the pH value increased during the composting process from 7.6 to 9.74, but as the process progressed, the pH profile began to decline to 7.59, which is the optimal and recommended pH value for final compost. The initial C/N ratio of 22.73 has dropped substantially to 9.11 after 14 days of treatment. After 111 days of composting, the C/N ratio was 10.29, indicating that the compost had matured and could be utilised as a natural fertiliser for agriculture. Furthermore, extremely low amounts of heavy metals (Ni, Pb, Cd, and Cr) were identified in the final compost, and all elements were undetectable. Understanding the role of different microorganisms (fungi, bacteria) in composting is critical to evaluating the efficacy of composting and producing high-quality compost. Krishnan et al. (2017) studied the microbial diversity of the EFB-POME co-composting process. Temperature, pH, and moisture content of the EFB-POME co-compost were determined. Microbial diversity was discovered by metagenomic sequencing analysis of 16S rRNA and 18S rRNA genes. The temperature, pH, and moisture content were 30°C, 7.43, and 58.76% for surface compost, and 45°C, 7.94, and 60.56% for inside compost. According to 16S rRNA gene sequencing for bacterial identification, the main genera in POME are *Parabacteroides, Bellilinea, Levilinea, Smithella,* and *Prolixibacter.* Meanwhile, *Nitriliruptor, Delftia, Filomicrobium, Steroidobacter,* and *Ohtaekwangia* are the predominant genera in surface compost. Major genera in inside compost include *Steroidobacter, Nitriliruptor, Anaeromyxobacter, Filomicrobium,* and *Filomicrobium.* According to 18S rRNA gene sequencing to identify fungi, *Remersonia, Inonotus, Kluyveromyces, Chaetomium, Thermomyces,* and *Candida* are the major genera in the surface compost. On the other hand, *Remersonia, Inonotus, Saccharomycopsis, Chaetomium,* and *Saccobolus* are the main genera present in the inside compost. The most common genera in POME are *Kluyveromyces, Inonotus, Kazachstania, Candida,* and *Cystofilobasidium.* Owing to their capacity to produce ligninolytic and cellulolytic enzymes, the microbial diversity observed in EFB-POME compost and POME may enhance the effectiveness of co-composting. Zainuddin et al. (2017) used 454-pyrosequencing to analyse the bacterial community succession at different phases of pilot-scale co-composting for EFB-POME anaerobic sludge, which was then associated with changes in physicochemical parameters such as temperature, oxygen level, and moisture content. According to the findings, species belonging to *Devosia yakushimensis* and *Desemzia incerta* appeared as dominating bacteria during the thermophilic stage, while *Planococcus rifietoensis* was related to the later stage of co-composting. This proves that the changes in physicochemical properties are parallel to the change of bacterial community at each stage of co-composting and this condition is very useful in monitoring the co-composting progress and as well as the level of compost maturity. In addition to EFB, co-composting of oil palm waste, such as OPF and MF, with POME anaerobic sludge was also conducted by several researchers. Lim et al. (2009) conducted a pilot-scale investigation on the characteristics and physicochemical changes in the windrow co-composting process for MF and POME anaerobic sludge. They found that the utilisation of POME anaerobic sludge as a nutrient source and microbial seeding into MF compost resulted in a thermophilic state (50-68°C) being maintained until day 39 of treatment. The pH value remained constant (6.8-7.8) during the entire process, while the moisture level decreased towards the completion of treatment, with a final moisture content of about 50%. The finished compost was produced in 50 days and has a C/N ratio of 12.6. Furthermore, significant amounts of nutrients and low levels of heavy metals

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were discovered in the final compost. They concluded that windrow co-composting for MF and POME anaerobic sludge could generate acceptable grade compost for fertiliser or soil amendment applications. Meanwhile, the co-composting process of OPF with POME anaerobic sludge has been discussed in the previous section (Ahmad et al., 2011, 2012, 2014, 2016).

Environmental impacts of composting

Composting converts organic matter into more stable compounds that have numerous benefits and can be applied to the soil. The finished product is environmentally safe, clean, and low in hazardous content. Composting has many advantages, including (i) producing a cleaner environment in which the composting process can reduce methane gas production at landfills, (ii) producing soil improvement materials that are useful and suitable for agricultural activities, (iii) reducing the need for solid waste transportation, (iv) increasing the effectiveness of fertiliser application, (v) a process that is flexible and can be implemented at various levels ranging from in-house efforts to large-scale levels, and (vi) may be started with low operational and capital expenditures.

In general, using mature compost made from agricultural waste as a natural fertiliser is less expensive than using chemical fertilisers. Long-term use of chemical fertilisers will adversely affect water, soil, and air as well as ecosystems. Inappropriate and persistent use of chemical fertilisers will cause soil structure degradation, reduction of organic components, and ultimately affects soil aggregation strength, which limits field crop output (Vakili et al., 2014). Easy and fast crop growth increased interest among farmers in using chemical fertilisers and pesticides instead of compost. Compost has long been utilised as a beneficial soil improver. Its more efficient application will improve the agricultural product quality, minimise the need for artificial fertilisers, be cost-effective, and indirectly protect natural resources. Due to its ability to alter the physical, chemical, and biological aspects of the soil, compost has a high potential to improve soil quality and crop productivity. Nevertheless, compost is not only used for crop fertilisation, it is also used to control soil erosion (USEPA, 1997a), landfill cover, landscape improvement (USEPA, 1997a), turf remediation (USEPA, 1997a), road construction projects (USEPA, 1997a), bioremediation and pollution prevention (USEPA, 1997b), disease control for plants and pest control (USEPA, 1997c), reforestation and wetlands restoration (USEPA, 1997d), and energy fuel source via compost palletization (Chia et al., 2020).

The oil palm waste (OPF, EFB, OPT MF, and others) which is largely generated from plantation activities and palm oil processing is seen to have great potential to produce compost. It can substitute chemical fertilisers in oil palm plantations and can be used as organic fertiliser for other agricultural activities such as vegetable farms and nurseries. Furthermore, compost made from oil palm waste has a high potential to be used for purposes other than as crop fertilizer in Malaysia. The conversion of oil palm waste into compost through the composting process can indirectly avoid problems related to environmental pollution involving air, water, and soil.

Conclusion

Research on OPF composting in resolving issues associated with the management of biomass from the oil palm industry has been discussed in detail in this article. Composting is a treatment process that decomposes organic materials in the presence of a group of

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microorganisms under specified conditions to convert organic materials into a stable soil-like product, namely compost. This method can be considered old technology and has been extensively reported in the literature. However, in the case of oil palm waste management focusing on OPF, this approach needs to be further investigated. The OPF pruning process in oil palm plantations is the highest contributor to oil palm waste generation. Various environmental issues will arise if OPF is left untreated as dumping of OPF will increase the organic content in the soil. Typically, the burning method is used to dispose of OPF which in turn results in air pollution. In addition, the problems of Ganoderma infestation and infectious insects will damage oil palm trees if OPF is allowed to decompose naturally on the ground. Therefore, composting is an alternative to disposing of OPF which has the potential to convert lignocellulose OPF into a product that benefits the soil and can generate profit. OPF has high amounts of cellulose and hemicellulose, which are the major carbon sources, followed by lignin. Degrading enzymes are critical components in the aerobic composting process for lignocellulose breakdown. The presence of lignocellulose materials not only delays composting but also limits the generation of humic substances. As a result, increasing lignocellulose decomposition is essential to enhance organic waste composting efficacy and compost quality. To enhance the decomposition of lignocellulose, the inoculation process of lignocellulolytic microorganisms such as white-rot fungi (WRF) can be performed. WRF is a type of fungi that can produce various types of enzymes such as lignin peroxidase, manganese peroxidase, and laccase for the breakdown of lignin, cellulose, and hemicellulose. Apart from WRF, sewage sludge is considered to have the potential to be utilized as an inoculum in organic waste composting. Co-composting of lignocellulose biomass and sewage sludge can also result in high-quality compost that can be used as a natural fertiliser for crops. On the other hand, the use of thickened POME anaerobic sludge as microbial seed may reduce composting time while increasing compost production. Even though a large number of studies have been conducted in this field, given the massive quantity of oil palm biomass produced annually, there are still many gaps in this area that other researchers may address. Among the future studies in OPF composting that can be conducted is by producing biofuels from OPF compost. Biofuel production through compost palletization is one of the ways to address the issues of low-quality compost and compost overproduction. In addition, studies related to the maturity of OPF compost include physical (eg: pile temperature, color, odor), biological (eg: respiration, phytotoxicity, enzyme activity), and chemical tests (eg: C/N ratio, organic matter, cation exchange capacity, electrical conductivity) needs to be done before the resulting OPF compost is applied to the crop. Future studies should also take into account the use of OPF compost so that it is not just limited to organic fertilizer for crops or agricultural activities only. The use of OPF compost can be further expanded to other uses such as soil erosion control, landfill cover, turf remediation, wetland restoration, and also in road construction projects.

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