Letters in Applied NanoBioScience
Platinum Open Access Journal (ISSN: 2284-6808)

Review
Volume 11, Issue 4, 2022, 3961 - 3974
https://doi.org/10.33263/LIANBS114.39613974

Oil Palm Empty Fruit Bunch as a Potential Feedstock for Composting

Paridah Md Tahir [1], Ang Aik Fei [2], Zaidon Ashaari [2], Seng Hua Lee [1,*], Syeed SaifulAzry Osman Al-Edrus [1]

[1] Institute of Tropical Forestry and Forest Products (INTROP), Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
[2] Faculty of Forestry and Environment, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
* Correspondence: lee_seng@upm.edu.my (S.H.L.);
Scopus Author ID 57191711306

Received: 29.08.2021; Revised: 10.10.2021; Accepted: 15.10.2021; Published: 30.10.2021

Abstract: Oil palm plantation has been widely planted in tropical countries, particularly Malaysia. Oil palm biomasses as by-products of palm oil production, therefore, exist abundantly. Four kilograms of dry biomasses are generated for every kilogram of palm oil produced. Empty fruit bunch is a major solid waste produced by palm oil mills, constituting 23% of the total weight of the fresh palm fruit bunch. As one of the largest palm oil producers, Malaysia generated a huge amount of EFB annually, making the country's disposal process a headache issue. Therefore, utilizing these wastes strategically could be beneficial from both economic and environmental points of view. Ideally, EFB could be used as feedstocks for bioenergy production, composites fabrication, activated carbon, and chemical synthesis. Apart from that, composting is also one of the potential approaches to solving this waste's abundance. Composting oil palm EFB means converting the EFB waste, which is essentially organic in nature, into humus suitable for crop production. The main purpose of composting is to handle organic wastes and enhance soil fertility safely. This paper gives an overview of the latest status and technologies dealing with composting of oil palm EFB, its limitations, current issues, and way forward.

Keywords: empty fruit bunch; enzymatic process; biomass; composting; feedstocks.

1. Introduction

Oil palm tree (*Elaeis guineensis*) is common palm species native to west and southwest Africa. In only a few decades, oil palm trees have transformed from a small-scale plantation crop in Africa into the most profit-making agricultural commodities worldwide, particularly in South East Asia. In 2016, both Indonesia and Malaysia were the major producers of palm oil, where both countries account for 85% (approximately 49.56 million tons) of the world's palm oil output [1].

The productivity of palm oil per hectare is much higher than the productivity of soybean oil per hectare; the global production of palm oil is recorded as 58.31 million tonnes with an estimation of oil palm planting at 12.82 million hectares, while the global production of soybean oil is only 40.22 million tonnes with soybean planting at 104.55 million hectares. As a perennial crop, the long productive life span (25 years) of oil palm is another privilege over those annual oil crops, which have to be planted on a year-to-year basis. These facts revealed that oil palm is much more competitive than the other oil crops due to its very productive characteristic in nature, producing 3 to 8 times more oil per hectare than other oil crops [2].

1.1. Availability of Empty Fruit Bunch (EFB).

In the oil palm industry, both the fields and palm oil mills generated plenty of oil palm biomass, such as fronds, oil palm trunks, mesocarpfiber, empty fruit bunches, palm shells, and effluent. Due to the many recent advances in research and technological innovations, these oil palm biomasses have strategically turned into feedstocks for multiple ends uses ranging from wood-based products such as lumber, plywood, particleboard, fibreboard, pulp, and paper) to biochemicals and bioenergy.

Four kilograms of dry biomass are generated for every kilogram of palm oil produced. These biomasses comprise empty fruit bunch, oil palm trunks, and fronds [3]. According to Kassim *et al*. [4] and Kheang *et al*. [5], oil palm EFB is generated in the palm oil mills during the processing of fresh fruit bunch (FFB). It constituted approximately 23% of the weight of the FFB. Disposal of EFB is a major issue in palm oil mills for Malaysia as it is one of the world's largest producers of palm oil. Every year, around 50 million tonnes of dry oil palm residues are generated. The amount is expected to gain 2-folds by 2020 [6]. For instance, some of this renewable lignocellulosic material is used for organic fertilizer and soil cover materials for the plants, while the rest of this solid waste is dumped in areas adjacent to the mill [7]. Due to its biorenewable and readily available, EFB is the potential to be used as feedstock for other useful applications so that the disposal and environmental issues in palm oil mills can be mitigated.

1.2. Composting of EFB.

Composting is among the potential approaches in solving the abundance of these wastes. Composting of oil palm EFB is means to convert the essentially organic EFB waste into humus suitable for crop production [8, 9]. The higher plant material, a complex organic, degrades to simpler elements rich in organic nutrients under the stimulus of aerobic thermophilic microorganisms present in the EFB waste during the composting process. The main purpose of composting is to handle organic wastes and enhance soil fertility safely. Researchers have indicated that wastes from the palm oil industry are one of the most promising agricultural waste sources to be used as organic fertilizers.

According to Then *et al*. [10], several palm oil mills in Malaysia are now practicing bioconversion of EFB into compost in their waste management system to mitigate the disposal issue of this waste and return the nutrients to the plant nutrient cycle. Management of EFB waste through composting is a better method as composting offers several advantages. The advantages include lower cost, friendly to the environment, sustainability, reducing greenhouse gas emissions, and improving material recycling.

This paper gives an overview of the latest status and technologies dealing with composting of oil palm EFB, its limitations, current issues, and way forward.

1.3. Palm oil production process.

Two oil types are produced from the fresh oil palm fruits, e.g., palm oil from the fibrous mesocarp and lauric oil from the palm kernel.

2. EFB - A By-product from Palm Oil Mills

In Malaysia, although the palm oil industry is a key industry for national income and economic expansion, it also imparts negative effects to the environment. Both the input and output sides of activities in this industry contribute to environmental degradation. On the input side, emission of greenhouse gases during the transportation of FFB from estates to the crude palm oil mills; consumption of the huge amount of water and energy in the production process in mills. On the other hand, wastewater, solid waste, and polluted air were generated during the manufacturing processes as output [11].

Apart from this, the palm oil industry is also a land-intensive industry [12]. Any unplanned exploration of lands to establish oil palm plantations will cause the forest systems to be degraded. Consequently, the habitats for flora and fauna are destroyed. On the other hand, applying herbicides and pesticides to maintain the plantations also causes water and air pollution problems.

EFB is the most generated solid wastes from palm oil mills [13]. EFB generated from the threshing process possesses high moisture content, approximately 60-70%; this inhibits the possibility of EFB being used as fuel for power boilers [7]. Nonetheless, despite EFB being the most abundantly available solid waste generated in palm oil mills, its current utilization as feedstock for other end uses is rather limited. For instance, only a small amount is used as fertilizers and soil cover materials (mulching mats) in palm oil plantation areas. Due to the high transportation cost and logistic convenience, in some areas, the EFB is just dumped in areas adjacent to the mill [7]. However, burned EFB can be adopted as fertilizer by mulching in plantations because burned EFB could generate potash [13].

According to Siddiqui *et al*. [14], the gradual accumulation or incorrect disposal of EFB may cause environmental problems (e.g., disease inocula, homes for pests, etc.). On the other hand, Stichnothe and Schuchardt [15] reported that improper handling with the disposal of EFB causes e considerable environmental burdens, particularly greenhouse gas emissions.

Traditionally, palm oil mills' usual practice to deal with the disposal of EFB is burnt in simple incinerations and their ash recycled into the plantation as fertilizer [12]. However, this practice causes air pollution and has been banned by the authorities. In addition, combustion of EFB also causes severe slagging and fouling on the boiler heat-transfer surfaces due to the condensation and deposition of substances evolving from alkali metal forming ash on the low-temperature surfaces [16-19].

Furthermore, this practice also wasted the EFB, which, as a renewable and abundantly available organic material, could have been used as feedstock for other value-added applications, such as converting it into bioenergy [20, 21], green composites [22-23], preparation of activated carbon to remove harmful substances [24, 25], production of chemical precursors [26, 27], and fertilizer enriched compost [14, 28]. This application will be discussed thoroughly in Section 4.0.

3. EFB as a Potential Feedstock for another End Uses

The building block of native EFB fiber comprises a complex matrix of three main polymers: cellulose, hemicellulose, and lignin. It is composed of approximately around 47.6% cellulose, 28.1% hemicellulose, and 13.1% lignin [29]. It also reported that EFB is composed 32.9% glucan, 22.4% xylan and 1.4% arabinan [30]. Cellulose and hemicellulose can be hydrolyzed chemically by acid or enzymatically into glucose and various pentose and hexose sugars, which can then be fermented to produce bioethanol. In contrast, lignin can be modified chemically or biologically into low molecular weight phenolic compounds to generate various useful biochemicals.

3.1. EFB for bioenergy production.

As mentioned earlier, EFB can serve as a good feedstock for another application attributed to its sustainability and lignocellulosic nature. Due to these reasons, using EFB as feedstock to produce bioenergy as a substitution for non-renewable fossil fuels and thus help mitigate greenhouse gas emissions is possible. Furthermore, EFB is considered a good feedstock for producing second-generation bioenergy, as this biomass is not an edible food for humans. Studies have shown that the bioethanol production process from NaOH pre-treated EFB was effective, and it may be feasible for the high production of bioethanol of this waste in the near future [20].

In addition, Mohammed *et al*. [21] utilized EFB as feedstock to produce bio-oil, which later could be upgraded as biofuel. The EFB was saccharified into bio-oil using a green extraction method known as supercritical fluid extraction with supercritical CO_2. Results showed that hexadecanoic acid (palmitic acid, C_{16}), dodecanoic acid 1, 2, 3-propanetriyl ester (glycerol trilaurate, C_{39}), and 6 octadecanoic acid (stearic acid, $C_{18:0}$) were identified as the major compounds.

A group of researchers had produced anhydrous ethanol using EFB in a pilot plant [31]. This study indicated that using an automatically controlled integrated process, the ethanol conversion rate, distillation, and dehydration efficiency were high (83.6%, 98.9%, and 99.2%, respectively). As a result, 123.6 kg anhydrous ethanol (99.7 wt%) was possible to generate from 1000 kg EFB.

3.2. EFB for composites production.

EFB is a lignocellulosic material that has potential as a natural fiber resource. It can serve as an alternative raw material supply to substitute wood to produce composites since the current wood supply has become lesser. Moshiul Alam *et al*. [22] fabricated polylactic acid and oil palm empty fruit bunch fiber-reinforced green composites through extrusion followed by injection molding. The authors found that 30-mm long and 40 wt% empty fruit bunch fiber-incorporated composites show the optimum tensile strength and modulus. Compared to untreated fiber-reinforced composites, simultaneous ultrasound and alkali-treated empty fruit bunch-reinforced composites exhibited enhanced mechanical performances, crystallinity, thermal stability, and durability against fungi degradation.

EFB has been used as a fiber resource to fabricate eco-composite boards with 500, 600, and 700 kg/m^3 densities using 10, 12, and 14% urea-formaldehyde resin as a binder [23]. The authors reported that the density of boards and amount of resin used to affect the overall performance of boards, and they concluded that the performance of the boards having a density of 700 kg/m^3 density bonded with 14% resin content is excellent accompanied by superior dimensional stability.

Research has been carried out to develop EFB and seaweed composite for soil erosion mitigation [32]. This study revealed that alkaline pre-treated EFB and seaweed composite can be applied as a soil stabilizer. It exhibits higher thickness swelling percentage and is sustained longer during water immersion than non-treated composite due to the better interface adhesion between EFB fiber and seaweed.

3.3. EFB for activated carbon.

EFB is suitable to be used as raw material for activated carbon production due to its high carbon content. Conversion of EFB to activated carbon offers some advantages, such as this could directly solve part of the environmental problem while offering better handling of this abundant and cheap solid waste to serve as a substitute to costly activated carbon.

Alam *et al*. [24] studied the suitability of activated carbons derived from EFB to remove heavy metal (Zinc) through the adsorption process. The authors found that activated carbon derived from 1000°C and 30 minutes has the maximum adsorption capacity (1.63 mg/g) to remove zinc (98%) in the aqueous solutions.

Hameed *et al*. [25] studied the preparation of activated carbon from EFB through optimization using response surface methodology (RSM) for removal of 2,4,6-TCP. The authors reported that the outcomes under the optimum preparation conditions were 168.89 mg/g of 2,4,6-TCP uptake and 17.96% of activated carbon yield. Another study revealed that the activated carbon derived from EFB shows the capability to absorb trace elements such as arsenic and cadmium in contaminated soil [33]. The result showed that the maximum adsorption capacity (q_{max}) of EFB activated carbon for arsenic and cadmium was 0.4240 and 15.1515 mg g^{-1}, respectively.

3.4. EFB as chemical feedstocks.

Due to the constituents of EFB (cellulose, hemicellulose, and lignin), it could be used as feedstock in biorefinery so that palm oil production would become more environmentally friendly while maximizing profitability. Useful chemicals were extracted from EFB through the solvolysis process using different solvents such as acetone, ethylene glycol (EG), ethanol, water, and toluene [26]. The results showed that these solvents successfully extracted phenolic compounds, alcohol compounds, ketone, and aldehyde compounds from the EFB.

Tang *et al*. [27] used lignin which is derived from EFB, to produce useful chemicals that can be used for another application in the chemical industry. Hydroxybenzoic acid, p-hydroxybenzaldehyde, vanillic acid, vanillin, syringic acid, syringaldehyde, p-coumaric acid, ferulic acid are some of the chemicals that were successfully extracted from the EFB lignin in this study.

Medina *et al*. [34] validated that lignin-derived from EFB exhibits antioxidant capacity as they detected aromatic compounds were present in EFB lignin. Due to this feature, lignin presented promising antimicrobial properties. Furthermore, the authors also reported that lignin possesses α-amylase inhibition properties that enable lignin to be used as a potential source of precursor drugs for the treatment of diabetes.

4. EFB in Composting

This section extensively discusses the methods of EFB composting, which cover the conventional and modified methods. Many studies have reported that composting is time-consuming. The average time to produce good quality compost for EFB ranged from 12 to 300 days. Table 1 summarizes the methods used for EFB composting since the year of 1995. Different organic N-rich sources, such as goats, cattle, and chickens' manure, have always been used as N additives for the composting of EFB [13]. In the field of composting, C:N ratio is important to determine the state of composting. Compost scientists have determined that the C:N ratio of 25-30:1 is the mature state of the compost [35].

Table 1. The conventional and current methods used for EFB composting.

Ref.	Method	Composting Period	Disadvantages	Advantages
[36]	Inhabiting microorganism + supplement (cow dung + chicken manure + goat dung)	60 days (Cow dung; Initial C:N 47:1; final C:N 12:1)	>Bad odors >Long composting time >Not hygienic	>Increasing EFB compost yield and quality (Nitrogen content)
[37]	Natural degradation (Open environment; mulching)	10 months (Weigh of EFB; 100% dgradation)	>Long composting time >High transportation and distribution costs >water pollution by the rest oil (about 1.25 %) > Attract beetles and snakes	>Without supplement
[38]	Inhabiting microorganism + supplement POME and liquid fermentation wastes from the food processing industry (New fermentation method)	52 days (Open; Initial C:N 41:1; final C:N 16:1)	>No reports on inhabiting microorganism	>An opening composting system is better than the closed system
[39]	EFB + POME; Natural degradation (Open environment; Wet tropical)	12 weeks (Initial C:N 50:1; final C:N 15:1)	>No reports on inhabiting microorganism	>Highlight the importance of moisture content during composting process
[41]	Commercial fungal strain + Horizontal rotary drum reactor + solid state fermentation	60 days (Initial C:N 63:1; final C:N 17:1)	>Require specific equipment > Costly	>Microorganism grow in agitation
[42]	Natural compost + *Trichoderma harzianum*	5 weeks	>No report on C:N ratio	>Using specific microorganism
[51]	Natural compost + supplement (open environment)	300 days	>Bad odors >Long composting time	
[40]	EFB + POME; Natural degradation (Open environment; Wet tropical)	20 weeks (Initial C:N 50:1; final C:N 30:1)	>No reports on inhabiting microorganism >Low temperature 23°C >High Moisture	>Highlight the importance of moisture content during composting process
[52]	Inhabiting bacteria + POME anaerobic sludge + open method (under shade and cement base) Brick size 2.1m x 1.5m x 1.5m	40 days (Initial C:N 44.5:1; final C:N 12.8:1)	>Inconsistent quality >Uncontrolled microorganism interactions.	>Open air composting better than closed system >Partially reacted POME (supplement) is proved can be used as microbial seedling.
[43]	Natural compost + decanter cake slurry (regular turning plant)	>51 days (Initial C:N 63.67; final C:N 18.65:1)	>No report on microbial composition	>Decanter cake slurry improved degradation of EFB.
[44]	Commercial microbial activators contain decomposer fungi (*Corynascus sp.*, *Scytalidum sp.*, *Chaetomium sp.*, *Scopulariopsis sp.*, *Streptomyces sp.*), alcoholic yeast (*Saccharomyces sp.*), and bacteria (*Bacillus sp.*, *Lactobacillus sp.*) + supplement (decanter sludege) compares with	>60 days; aerobic >90 days; anaerobic	>Used microorganism activator > Costly	>Replacement chicken manure to decanter sludge to improve odor problem.

Ref.	Method	Composting Period	Disadvantages	Advantages
	chicken manre. Method: Anaerobic & aerobic			
[45]	Commercial fungi (*Trichoderma virens*) + POME supplement	92 days	>Using only 1 microorganism as degradation agent	>Microbial approach >Cheap (only 1 microorganism)
[46]	Inhabiting bacteria + POME anaerobic sludge + open method Method: In-vessel composter	40 days (Initial C:N 58:1; final C:N 13.85:1)	>Costly	>Systematic composting plan
[47]	Commercial fungi (Trichoderma viride F26, Trichoderma reesei RUT C-30, Panus tigrinus M609RQY (IMI 398363) and Penicillium sp.,) + POME supplement Method: Tray and covered by aluminum foil.	60 days	>Usage of Penicillium sp. at the end-stage might contribute to antibiotic resistance.	>Used fungi for other enzymatic applications (such as used for ethanol, pulp, paper and etc.
[48]	Commercial fungi (Trichoderma virens, Trichoderma reesei and Aspergillus niger) + POME supplement	36 days	>Treated EFB with a chemical for lignin removal	>Used fungi for other enzymatic applications (such as used for ethanol, pulp, paper and etc.
[49]	Natural compost + POME	12 days (Initial C:N 45:1)	>Final C:N ratio is not measured	>Methane production is positively correlated to the degradation of the compost >Effect of different CN ratios towards the biodegradability of POME and EFB is investigated
[50]	Natural compost + Trichoderma Selective Medium isolate	28 days (Initial C:N 10.42:1; final C:N 2.79:1	>Identity of the fungi only up to genus level	>Microbial approach >Cheap (only 1 microorganism)

In 1995, Thambirajah *et al*. [36] composted EFB and EFB supplemented with either goat dung, chicken manure, or cow dung, which resulted in different C:N ratios after 60 days of composting. Significant reduction of the initial C:N ratios (52:1, 35:1, 48:1, 47:1) for the four compost to C:N ratios of 24:1, 14:1, 18:1 and 12:1, respectively, were observed. Both mesophilic and thermophilic bacteria showed consistent activity throughout the process, whereas fungal activity was completely suppressed during the peak heating phase (70°C). The finding demonstrated that the rate of cellulosic material utilization is positively correlated with the increase of nitrogen content in the compost [36].

The decomposition of EFB in oil palm plantations has been done by Hamdan and Mohammed Mohd Tayeb [37]. In the field study, the EFB was spread in the field as a mulch on top of a nylon net at a rate of 30, 60, and 90 mt/ha/year. Every 2 months before fresh EFB application, spots were selected to ensure a C/N ratio of 15, 30, and 60 was achieved.

Estimation of decomposition was made by calculating the remaining weight of EFB in the nylon net. After 10 months, the EFB was completely decomposed. The method requires a longer composting period, yet it is eco-friendly without the usage of supplementation.

One of the studies compared the effect between open and closed EFB composting systems [38]. In the study, mixtures of EFB, fermentation liquid waste (POME), and chicken manure were the raw composting materials. Aeration is ensured by the porous nature of the material itself and further improved by mechanical turning equipment. The composting process is faster in the open system compared to the closed system. To achieve the C:N ratio of 16, the closed system required 85 days, while the open system only required 50 days. However, the researchers did not report on the inhabiting microorganism during the composting process.

The composting of EFB from oil palms has been carried out under a wet tropical climate at Medan in Indonesia by Schuchardt *et al*. [39]. Fresh POME was added to replace moisture loss due to the high rate of water evaporation during the composting process and followed by homogeneously mixing and aerating the composting ingredients with a self-driving windrow turning machine. The C:N ratio of 50 was reduced to 15 after 12 weeks of the rotting process. In comparison to the results of Schuchardt *et al*. [39], another study done in the province of Izabal, Guatemala showed abundant rainfall significantly ($p<0.05$) slowed down the composting process, lengthening the active period phase to 20 weeks [40]. The temperature in Guatemala was lower, and the moisture level was higher compared to Indonesia, where the average air temperature was 23.1°C, and annual rainfall has been up to 3,600 mm in Guatemala. The slow composting could be due to the nonequilibrium temperature distribution from the slowdown of air circulation by high moisture level.

A new composting trial was carried out in 2007 where POME and EFB were mixed with the induced microorganisms to overcome a conventional composting process [41]. The composting process uses selected substrates, POME, and EFB plus wheat flour as a co-substrate in a tray bio-reactor. The process involved using fungi isolates from POME such as strains of *Penicillium* sp., *Phanerochaete chrysosporium, Trichoderma harzianum,* and *Aspergillus niger* (A 106, S 101). The resulting C:N ratio dropped to 17 from 63 after 2 months period. Inoculating the specific microorganism into EFB oil palm compost has also been done by Siddiqui *et al*. [42] using *T. harzianum*. Trichoderma-enriched EFB extracts showed significant ($p<0.05$) higher degradation compared to the uninoculated EFB sample.

Another study by Yahya *et al*. [43] successfully converted EFB with an initial C:N ratio 63.67:1 to final compost with C:N ratio of 18.65:1 in 51 days. Yahya and colleagues studied the interaction of EFB and decanter cake slurry (by adding POME) in a commercial composting plant with regular turning operation. The composting process of the EFB was boosted by the presence of decanter cake slurry. After 51 days, the C:N ratio of the mature compost with the decanter cake slurry was only 18.65:1, while without the presence of decanter cake slurry, the ratio stayed high at 28.96:1. Besides, Kananam *et al*. [44] found that the use of decanter sludge did not affect any biochemical conditions of EFB composting. The final composting product met the compost nutrient standard where the C:N ratio is 15:1 within 30 days. However, under anaerobic conditions, the composting process failed to complete on day 90th. The results highlighted the importance of aeration during the degradation process and the aerobic nature of the composting bacteria and fungi.

Trichoderma virens have been used solely as an activator to convert EFB and POME into compost [45]. Compost with supplementation of both *T. virens* and organic N (chicken manure) has a higher biodegradation rate than compost with EFB and POME alone. Besides, higher xylanase and cellulase activities from *T. virens* resulted in rapid degradation of both cellulose and hemicelluloses.

Using a newly developed method, Razali *et al*. [46] investigated the alteration of the lignocellulosic structure of EFB during composting in an in-vessel composter. A total of 40 days was required for the composting treatment to reduce the initial C:N ratio of 58:1 to 13.85:1. The peak of degradation occurred during the thermophilic phase, as shown by scanning electron microscopy analysis. As expected, the in-vessel composter significantly ($p<0.05$) improved the composting of EFB, yet the method is expensive thus impractical in the industrial field.

Chai *et al*. [28] suggested that the impropriate C/N ratio is the main reason that EFB is unable to be composted solely. They suggest that composting of EFB becomes more effective when using a co-composting method where other organic waste materials with a C/N ratio of less than 30 can be mixed with EFB as a nitrogen source in the co-composting. Based on their point of view, a mixing percentage of 50% to 60% of EFB is deemed an ideal ratio in EFB co-composting.

An effective composting process of EFB with POME, using a multi-enzymatic fungal system, had been developed by Mohammad *et al*. [47]. Four strains of filamentous fungi, namely *Trichoderma viride* F26, *Trichoderma reesei* RUT C-30, *Panus tigrinus* M609RQY (IMI 398363), and *Penicillium sp.*, were selected in this study. A higher decrement of C:N ratio was achieved in the fungal treated system, in which the reduction was almost double compared to the control after 60 days. In addition, high activity of ligninase enzyme and cellulase activity was found in the system. Yet, the presence of *Penicillium sp*. in the compost may create an antibiotic resistance problem.

Another study was done by Amira *et al*. [48], where EFB and POME were used as substrates for compost production using fungi. Activators such as *Trichoderma virens*, *Trichoderma reesei*, and *Aspergillus niger* were employed to enhance the biodegradation process. As previously mentioned, enhanced degradation of cellulose and hemicellulose within 36 days could be achieved with the incorporation of fungi due to higher xylanase and cellulase activity. *Trichoderma virens* yielded the highest xylanase activity compared to control. *Aspergillus niger*, on the other hand, has the highest number of activities of filter paper unit (FPU). The drawback of the study was the use of chemicals to remove lignin, which may pose a risk to plant health when used in fertilizer.

Nurliyana *et al*. [49] investigated the effect of different C:N ratios towards the co-digestion of POME and EFB in terms of the biodegradability of the substrates. The C:N ratios were adjusted to a specific value by using different EFB and POME loadings. The degradation rate of co-digestion of POME with EFB was evaluated through methane production and was found to be positively correlated to the degradation of organic substrates. The results demonstrated that the C:N ratio of 45 (EFB:POME; 76:24) has the highest biodegradability rate in POME and EFB.

In 2017, *Trichoderma sp.* from soil was selected for composting of EFB using Trichoderma Selective Medium [50]. The initial C:N ratio of 10.42:1 was observed to decrease to a final C:N ratio of 2.79:1. Although the composting method in the study was conducted using the microbial approach, fungi's identity is not specified to species level.

5. Issues and Challenges in EFB Composting

Although composing seems to offer a better solution for EFB waste, some barriers impede EFB waste composting. Broadly, the challenges that persist in the oil palm industries themselves include acceptance and participation, administrative, management, logistical, technological, marketing, and demand [53]. The application of composting technology is generally new for some oil palm mills. This renders delays for the implementation of such technology due to a shortage of experienced and skilled workers.

On the other hand, the development of the composting technology at the oil palm mill faces various issues. The issues in composting technology include source separation, composting process, contamination, quality of the end product (nutrient content and moisture), and effective composting technologies [54-59]. The composting process requires to prolong period, which is impractical for industrial purposes. The characteristics of EFB in nature make it difficult to be composted alone because microorganisms are difficult to grow on it as this organic waste is classified as carbon source material and has lower moisture and nitrogen contents [28-29]. EFB also had very low bulk density (66.98 kg/m^3), which the heat during composting may be difficult to retain if the open windrows method is used [28]. Due to EFB being a by-product from palm oil production, residual palm oil was found to range from 3 to 7% on a dry basis [60]. Residual oil in EFB will slow down the decomposition process and may attract pests and vermin.

As EFB possess some limitations to be composted alone, to reduce the composting period, selection of the most suitable enzymes or microorganisms for composting plant is crucial [61]. Besides, the pungent smell resulting from the composting process is one of the main issues in the industry [62].

6. Way Forward

As the palm oil industry will remain one of the key industries for national income generation and economic expansion, the generation of EFB as the most abundant solid waste in palm oil mills will not end. Therefore, the disposal issue of EFB is always a challenge in the palm oil industry [63]. Converting EFB to other value-added applications is a promising way to handle the disposal issue of EFB while creating some value-added applications from this readily available, abundant, biodegradable, and cheap organic waste material [64-65].

Therefore, it is proposed that the optimum condition for composting should be focused on the following criteria: the moisture level, C:N ratio, aeration, etc. As discussed in Section 4.0, when compared to conventional methods, current methods emphasize using certain strains of fungi to reduce the composting time, produce high-quality compost, solve environmental problems, and enhance economic benefits in the oil palm industry.

The government encouraged the practice of converting oil palm wastes such as EFB into value-added applications (e.g., bio-fertilizer) through the introduction of the National Agro-Food Policy (2011-2020) and the National Biomass Strategy 2020. Incentives such as Depreciation Accelerated Capital Allowance will be given to palm oil mills to procure machinery required for converting oil palm wastes into value-added products such as fertilizer, animal feed, and biogas. Apart from this, palm oil mills will also be entitled to income tax exemption (ranging from 30 to 100%) if they produce promoted products (e.g., palm-based bio-fertilizer) or engage in such activities.

However, additional efforts should be executed by the government. The government should formulate the Oil Palm Biomass Policy or Roadmap and proper management on the distribution of biomass amongst sectors (wood-based, bio-fuel, bio-fertilizer, or bio-based chemicals). In addition, setting up a biomass consortium or Biomass Collection center is also an important move. Apart from that, the government should establish certification and controls on the quality of products to ensure compliance with international standards by relevant parties. More funding should also be allocated to support pilot or demo plants study and support the industry by engaging the stakeholders.

Funding

This research was funded by MINISTRY OF HIGHER EDUCATION, MALAYSIA, grant number 5540158, Reference code: FRGS/1/2018/WAB07/UPM//1.

Acknowledgments

The authors would like to express their gratitude to all the lab officers from the Institute of Tropical Forestry and Forest Product, Universiti Putra Malaysia, for assisting with the project.

Conflicts of Interest

The authors declare no conflict of interest.

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