

Critical Evaluation of Oil Palm Fresh Fruit Bunch Solid Wastes as Soil Amendments: Prospects and Challenges

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Abstract

Sustainable land use has been identified as one way of tackling challenges related to climate change, population expansion, food crisis and environmental pollution. Disposal of oil palm fresh fruit bunch (FFB) solid wastes is becoming a challenge with an increased demand and production of palm oil. Whilst this poses a challenge, it could be turned into an opportunity by utilising it as a resource and fully valorise it to meet soil and crop demands. This review presents the potentials of FFB solid wastes, which include empty fruit bunch (EFB), mesocarp fibre (MF), palm kernel shell (PKS), as soil ameliorants. The major findings are the following: 1) pyrolysis, gasification, combustion, and composting are processes that can enhance the value of FFB solid wastes. These processes lead to new products including biochar, ash, and compost, which are valuable resources that can be used for soil improvement. 2) The application of EFB mulch, ash from EFB, MF and PKS, biochar from EFB, and PKS, and compost of EFB, and MF led to improvement in soil physico-chemical properties, and growth and performance of sweet corn, mushroom, oil palm, sweet potato, cauliflower plant, banana, maize, cocoa, cassava, eggplants, and pepper. However, reports show that EFB compost and ash led to decrease in

29 growth and performance of okra. Therefore, the use of appropriate conversion
30 technology for FFB solid wastes as soil ameliorants can significantly improve
31 crop yield and soil properties, reduce environmental pollution, and more
32 importantly increase income of oil mill processors and savings for farmers.

33 **Keywords:** Empty fruit bunch, Palm kernel shell, Mesocarp fibre, Ash, biochar,
34 Soil

35

36 **1 Introduction**

37 Agricultural productivity and land conservation are important for the
38 sustainability of humanity. With an increasing demand for food due to increasing
39 population, an integrated sustainable approach needs to be adopted to ensure
40 that agricultural production does not impinge negatively on land resources. To
41 ensure there is continuous supply of food and fibre without depleting the land
42 resources, one approach to replenish nutrients can be through the application of
43 organic amendments. Lack of resources limit soil conservation practices and
44 therefore efforts are being made towards deriving greater values from available
45 organic materials. Organic amendments have gained interest due to the high
46 cost of inorganic fertilisers and the adverse effects of its continuous usage on
47 soil. However, inefficient use of organic amendments can pose significant
48 environmental challenges such as eutrophication of water bodies and leachate
49 affecting groundwater. Applying these amendments to the soil in an optimum
50 manner can result in an increase in soil organic matter, which improves soil
51 fertility and minimises soil degradation (Rickson et al., 2015).

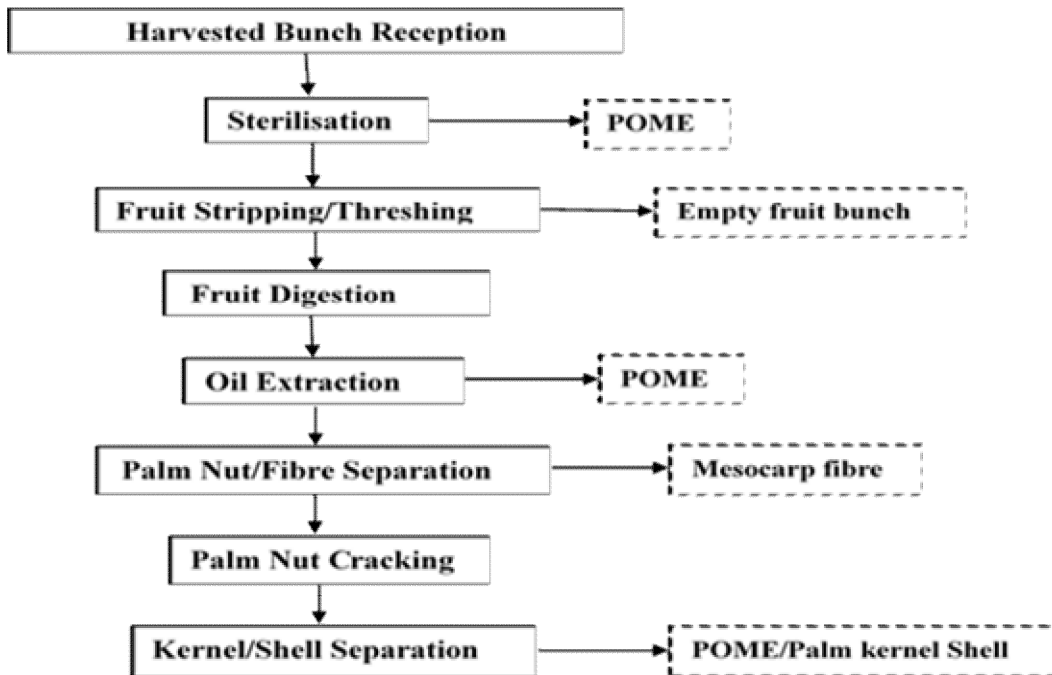
52 African oil palm (*Elaeis guineensis*) is believed to originate from West Africa and
53 today is widely grown in most parts of West and Central Africa, Southeast Asia,
54 and South America. Oil palm is a single stemmed tree and can grow to a height
55 of more than 30 metres (Ibitoye and Onje, 2013; Jagustyn et al., 2013). The fruit
56 bunch can weigh up to 25 kg and contain as much as 1000 fruits (Ibitoye and

57 Onje, 2013; Jagustyn et al., 2013). The oil palm tree is the major source of plant
58 oil in the tropical region.

59 Palm oil is produced by processing oil palm fresh fruit bunch (FFB), which leads
60 to the generation of FFB solid wastes. Notable FFB solid wastes are empty fruit
61 bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS) while palm oil
62 mill effluent is the liquid wastes (Figure 1). Other residues and/by-products
63 processed from FFB solid wastes are in the form of ash, biochar, and compost.
64 The major producers of palm oil are Indonesia, Malaysia, Thailand, Colombia
65 and Nigeria according to Index mundi (2017), contributing 92 % of global
66 production (Figure 2). An estimated 1.65 million hectares of oil palm is spread
67 over Nigeria (Olagunju, 2008), while there are over 4 million and 7 million
68 hectares of oil palm in Malaysia and Indonesia, respectively (Sulaiman et al.,
69 2011). Anyaoha et al. (2018) reported that the total FFB solid wastes produced
70 in 2014 was 75 million tonnes, and that the figure is equivalent to 23 million
71 tonnes of EFB, 21 million tonnes of MF, and 7.5 million tonnes of PKS.

72 The FFB solid wastes are used as fuel in palm oil mills to generate steam,
73 which enables the palm oil mills to be self-sufficient in energy (Yusoff, 2006);
74 however, more of the wastes are generated than required in the palm oil mills.
75 Therefore, proper utilisation of the FFB wastes remains a challenge for palm oil
76 millers and local authorities.

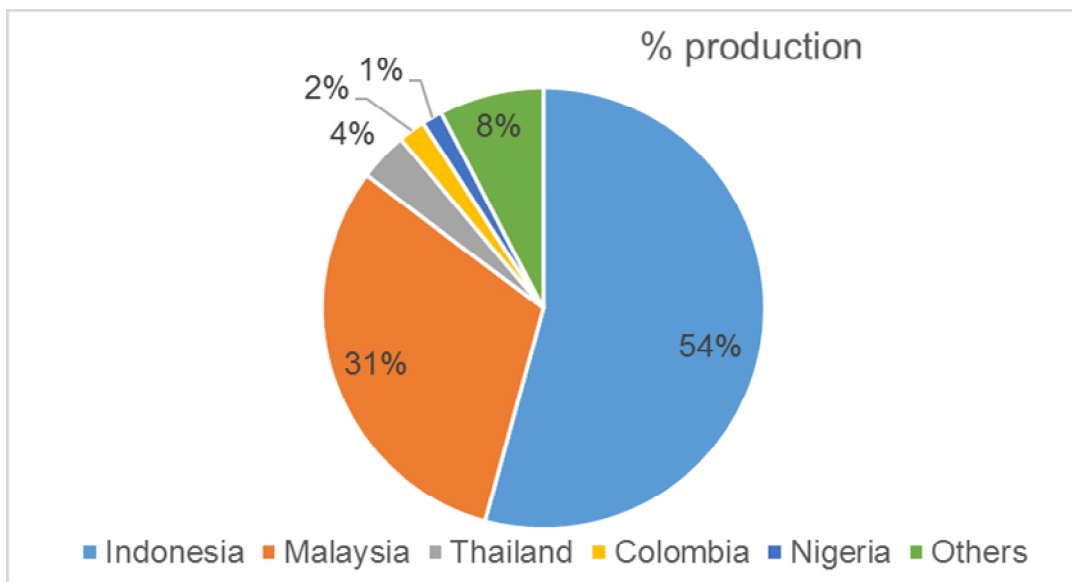
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79 **Figure 1** Flow chart of fresh fruit bunch processing showing points of
 80 **generation of wastes. Solid boxes are the process, while dashed boxes**
 81 **represent wastes. POME - palm oil mill effluent.**

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83

84 **Figure 2** Global percentage of palm oil production (Source: Index Mundi,
 85 **2017).**

86 This paper aims to present a critical evaluation of the value of FFB solid waste
87 streams (EFB, MF, PKS, ash, biochar and compost) and their benefits for crop
88 performance and soil quality improvement, when used as organic amendments.
89 Specifically, the following will be reviewed: (i) the current progress on the soil
90 applications of FFB solid waste by-products (ash, biochar, and compost)
91 derived from thermal and biological conversions of EFB, MF, and PKS, and (ii)
92 the agronomical and environmental impacts of FFB solid waste streams
93 utilisation, providing bases for strategic development needs.

94

95 **2 Fresh fruit bunch solid waste streams**

96 There are variations in the physical and chemical characteristics of FFB solid
97 wastes. Apart from the potential differences due to geography and the soil
98 where the trees are grown, oil palm tree differs due to the thickness of the shells
99 (varieties), and on the quality of the FFB. Dura variety is known for its thick shell
100 and thin mesocarp, Pisifera variety is known to be shell-less, while Tenera
101 variety has a thicker mesocarp and thinner shell (Asadullah et al., 2014). In
102 Nigeria, most palm oil mills process a mixture of the three varieties. Higher
103 quality FFB produces relatively more fruits compared to the size of the EFB, a
104 tree can produce varying bunch (high and low-quality). These variations
105 influence the weight of EFB, PKS, and MF per FFB. Tables 1, 2 and 3
106 summarise the characteristics of EFB, MF and PKS, respectively.

107 **Table 1 Proximate and ultimate analysis and heating values of empty fruit bunch (EFB) from literature.**

Analysis	Literature	References
	db	
Proximate (wt.%)		
Volatile matter	67.59 – 83.86	Idris et al. (2015); Lahijani et al. (2013); Sulaiman and Abdullah (2011)
Fixed carbon	8.36 – 21.80	Idris et al. (2015); Lahijani et al. (2013); Lahijani and Zainal (2011)
Moisture content	5.18 – 8.31	Idris et al. (2015); Lahijani et al. (2013); Mohammed et al. (2012); Omar et al. (2011)
Ash	3.45 - 7.54	Idris et al. (2015); Lahijani et al. (2013); Mohammed et al. (2012); Omar et al. (2011)
Ultimate (wt.%)		
Carbon	43.52 – 49.07	Idris et al. (2015); Lahijani et al. (2013); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011)
Hydrogen	5.72 - 6.48	Idris et al. (2015); Lahijani et al. (2013); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011)
Nitrogen	0.25 – 1.65	Idris et al. (2015); Lahijani et al. (2013); Mohammed et al. (2012); Omar et al. (2011)
Sulphur	0.04 - 1.06	Idris et al. (2015); Lahijani et al. (2013); Mohammed et al. (2012); Omar et al. (2011)
Oxygen*	38.29 – 48.9	Idris et al. (2015); Lahijani et al. (2013); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011)
Lignocellulose (wt.%)		
Cellulose	13.75 – 59.70	Idris et al. (2015); Mohammed et al. (2012) Sulaiman and Abdullah (2011)
Hemicellulose	12.79 – 22.1 0	Idris et al. (2015); Mohammed et al. (2012) Sulaiman and Abdullah (2011)
Lignin	7.79 – 30.45	Idris et al. (2015); Mohammed et al. (2012) Sulaiman and Abdullah (2011)
HHV (kJ/kg)	15220 – 19350	Anyaoha et al. (2018); Idris et al. (2015); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011)
Bulk density (kg/m ³)	110 - 144	Anyaoha et al. (2018); Sung et al. (2010)

108 All in wt.% except where it is stated otherwise. db – dry basis, HHV – high heating value, *by difference

109

110 **Table 2 Proximate and ultimate analysis, and heating values of mesocarp fibre (MF) from literature.**

Analysis	Literature	
	db	References
Proximate (wt.%)		
Volatile matter	67 – 79	Khanday et al. (2016); Wilson et al. (2011)
Fixed carbon	9.3 – 28	Khanday et al. (2016); Wilson et al. (2011)
Moisture content	4.98 – 5	Khanday et al. (2016); Wilson et al. (2011)
Ash	1 - 11.8	Khanday et al. (2016); Wilson et al. (2011))
Ultimate (wt.%)		
Carbon	30.02 - 52.2	Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Hydrogen	3.81 – 11	Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Nitrogen	0.7 – 1	Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Sulphur	0.07 – 1	Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Oxygen**	23.35 – 42	Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Chlorine	0.06	Wilson et al. (2011)
Lignocellulose (wt.%)		
Cellulose	40	Khanday et al. (2016)
Hemicellulose	20	Khanday et al. (2016)
Lignin	30	Khanday et al. (2016)
HHV (kJ/kg)	19331 - 21980	Anyaoha et al. (2018); Harimi et al. (2005); Khanday et al. (2016); Wilson et al. (2011)
Bulk density (kg/m ³)	225	Anyaoha et al. (2018)

111 All in wt.% except where it is stated otherwise. db – dry basis, HHV – high heating value, *by difference

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114 **Table 3 Proximate and ultimate analysis, heating values of palm kernel shell (PKS) from literature.**

Analysis	Literature	
	db	References
Proximate (wt.%)		
Volatile matter	53.38 – 77.5	Jamaluddin et al. (2013); Wilson et al. (2011); Zainal et al. (2016)
Fixed carbon	18.84 – 20.3	Jamaluddin et al. (2013); Wilson et al. (2011); Zainal et al. (2016)
Moisture content	8.4 – 9.55	Wilson et al., (2011); Zainal et al., (2016)
Ash	0.87 - 4.6	Jamaluddin et al. (2013); Wilson et al. (2011); Zainal et al. (2016)
Ultimate (wt.%)		
Carbon	43.8– 60.9	Harimi et al. (2005); Wilson et al. (2011); Zainal et al. (2016)
Hydrogen	5.27 – 12.76	Harimi et al. (2005); Wilson et al. (2011); Zainal et al. (2016)
Nitrogen	0.36 – 0.66	Harimi et al. (2005); Wilson et al. (2011); Zainal et al. (2016)
Sulphur	0.03 – 0.19	Harimi et al. (2005); Wilson et al. (2011); Zainal et al. (2016)
Oxygen*	31.18 - 37.7	Harimi et al. (2005); Wilson et al. (2011)
Chlorine	0.05	(Wilson et al. (2011))
Lignocellulose (wt.%)		
Cellulose	27.7	Zainal et al. (2016)
Hemicellulose	21.6	Zainal et al. (2016)
Lignin	44	Zainal et al. (2016)
HHV (kJ/kg)	17930 – 20520	Anyaoha et al. (2018)Harimi et al. (2005); Wilson et al. (2011); Zainal et al. (2016)
Bulk density (kg/m ³)	715 - 780	Anyaoha et al. (2018); Arzola et al. (2012)

115 All in wt.% except where it is stated otherwise. db – dry basis, HHV – high heating value, *by difference

116 EFB is generated when the fruits are removed from the FFB. It can appear in
117 different forms depending on how the FFB is processed, which differs
118 particularly in Nigeria with the generation of empty fruit spikelet (EFS), and
119 bunch stalk (BS) separately by the subsistence (traditional processing) palm oil
120 millers (Anyaocha et al., 2018). The chaff is the additional part of the EFB. The
121 chaff is found at the base where each fruit is attached to the spikelet and tends
122 to separate itself from the spikelet when dry. The chaff comprises of about 0.9 –
123 2.4 % of FFB (Ohimain et al., 2013). The EFB is generated at the palm oil mills
124 with very high moisture content of up to 60 % (Tabi et al., 2008). Relative to MF,
125 and PKS, EFB has a very low bulk density, which makes its transportation
126 difficult (Tables 1, 2 and 3).

127 The MF or palm press fibre results from the oil bearing mesocarp after the
128 extraction of oil and separation of the pulp (palm nut/mesocarp fibre mixture).
129 The oil is extracted by washing the pulp with steam or by pressing. The MF
130 makes up about 14 – 28.1 % of FFB (Ohimain et al., 2013; Omar et al., 2011;
131 Sulaiman and Abdullah, 2011).

132 The palm nut or the endocarp is the hard part of the oil palm fruit covering the
133 oil-bearing palm kernel. The palm nut when cracked takes varying shapes and
134 sizes because of the cracking force and the resulting product is called PKS.
135 When compared to EFB and MF, PKS has lower moisture content, and higher
136 lignin and bulk density (Tables 1, 2 and 3).

137 The availability of MF and PKS as better biomass fuels makes the application of
138 EFB to oil palm plantations the best option. The BS (82.6 %) of higher moisture
139 content than that of the EFS (57.5 %) according to Omar et al. (2011) limits the
140 use of EFB as fuel. The Conversion FFB solid waste streams into forms ready
141 for use as soil ameliorants is as important as the availability of the wastes.
142 Other than direct application, pyrolysis, gasification, combustion, and
143 composting are well-researched technologies of valorising FFB solid wastes.
144 These technologies lead to the production of ash, biochar, and compost, which
145 are important soil amendments that will be discussed in the following sections.

146 **2.1 Ash**

147 In palm oil mills, ash is generated in the form of fly ash, bottom ash, and slag
148 when FFB solid wastes are combusted especially MF and PKS. The estimated
149 global production of FFB solid wastes was 57 million tonnes in 2014, therefore
150 EFB, MF and PKS ash were 1.2 million tonnes, 1.1 million tonnes, and 0.1
151 million tonnes, respectively. The estimates are based on the ash contents of
152 EFB, MF, and PKS dry basis of 5.1, 5.5, and 1.7 wt.%, respectively as
153 determined according to British Standards Institute (2011). A significant
154 difference between the ash from the three solid biomass is the higher content of
155 alkali found in EFB (Abdullah and Sulaiman, 2013). Ash has been found to be
156 very useful in many ways but the specific increase in its agricultural use has
157 become of special interest due to the high nutrient content for soil amelioration
158 and crop improvement.

159 Gasification and combustion are important thermal conversion processes
160 leading to the generation of ash as residue. Gasification is a partial oxidation
161 process that is used to produce fuel gas (Puig-Arnavat et al., 2010). Most
162 palm oil mills rely on the combustion of MF and PKS for heat and power
163 generation, and therefore, the production of ash is an integral part of FFB
164 processing and valorisation of the wastes for soil use.

165 Most investigations on the gasification (Ogi et al., 2013) and combustion (Idris
166 et al., 2012) of FFB solid wastes focused on the fuel value with limited
167 consideration on the optimization of the residue yield for agricultural purposes
168 (for example soil amelioration, and consequently crop growth and yield), even
169 though the residue is an important part of the processes and can affect the
170 overall performance of the systems.

171 **2.2 Biochar**

172 Biochar is produced during pyrolysis after the moisture and volatiles have been
173 removed at an elevated temperature. Biochar remains an important output of
174 pyrolysis representing up to 35 % of PKS (palm shell), 29 % EFB, and 30 % MF

175 (Abnisa et al., 2013) of the wastes under pyrolysis. Expectedly, the highest
176 biochar yield of EFB was recorded at pyrolysis temperature of 300 °C and the
177 lowest at 700 °C (Sukiran et al., 2011) similar to figures by Claoston et al.
178 (2014) of 38 % at 350 °C and 21 % at 650 °C.

179 The mineral components retained in biochar during pyrolysis makes it a
180 valuable soil amendment (Lee et al., 2017a; Mašek et al., 2010; Xu et al.,
181 2017;). Zhao et al. (2013) reported that the biochar surface area, its carbon
182 recalcitrance, and high nutrient content determine its application.

183 Biochar prevents water contamination and soil erosion, and by its absorbing
184 characteristics due to large surface area, the ability of the soil to retain moisture
185 and nutrients increases (Abnisa et al., 2013). Biochar could ameliorate soil
186 quality, reduce fertiliser consumption, and sequester carbon (Lee et al., 2013).
187 The Brunauer–Emmett–Teller (BET) measures the surface area of the biochar.
188 Temperature and ash content have been reported to influence BET surface
189 area (Claoston et al., 2014; Nam et al., 2018; Shariff et al., 2014). Nam et al.
190 (2018) reported BET surface area for PKS of 100 m²/g at 550 °C, 155 m²/g at
191 650 °C, and 270 m²/g at 750 °C. Claoston et al. (2014) found that the
192 temperature of 650 °C led to the highest BET surface area of 28 m²/g compared
193 to temperatures of 500 °C (15 m²/g) and 350 °C (12 m²/g) for EFB of <2 mm
194 with the operation lasting for 2 h. Lee et al. (2017a) reported a BET value of 191
195 m²/g at 500 °C for PKS, 2.71 m²/g at 350 – 450 °C was reported for EFB
196 (Harsono et al., 2013), 0.13 m²/g at 550 °C for EFB (Shariff et al., 2014) while
197 Abdulrazzaq et al. (2015) reported a value of 12.2 m²/g at 300 – 350 °C for
198 EFB. The EFB ash contents of 5.29, 4.65, 3.28, 2.21, and 1.60 wt.% led to
199 increase in BET of approximately 0.13, 0.38, 9.25, 11.12, and 7.99 m²/g,
200 respectively. There was increase in BET as ash content reduces except with the
201 1.60 wt.% value.

202 Idris et al. (2014) reported 210, 186, and 145 % more Ca, K, and Ca in EFB
203 biochar than raw EFB making biochar a more valuable soil amendment.
204 Similarly, K increased with temperature (4 wt.% at 350 °C and 7 wt.% at 650 °C)

205 (Claoston et al., 2014). Compared to wood bark (4736 ppmw) and paddy straw
206 (1956 ppmw), Lee et al. (2013) demonstrated that PKS biochar (21,380 ppmw)
207 contains higher concentration of iron and tends to be more acidic with pH of 6.9
208 compared to 9.6 and 10.5 of wood bark and paddy straw, respectively. The low
209 pH was attributed to lower alkali and alkali earth metals in PKS. Kabir et al.
210 (2017) demonstrated that MF biochar contains significantly higher ash content
211 (27%) than that of palm frond (4%), while the K and Ca contents of MF are 22
212 % and 9 % compared to that of palm frond of 46 % and 16 %, respectively. The
213 pyrolysis was carried out in a slow heating bed-reactor of a temperature of 550
214 °C, heating rate of 10 °C/min, and a nitrogen flow rate of 200 ml/min. The K and
215 Ca contents of PKS biochar were 1.105 % and 5.25 % (Kim et al., 2010)
216 whereas Bazargan et al. (2014) reported values of 29.8 % and 41.4 %,
217 respectively.

218 Mašek et al. (2010) defined two biochar fractions as stable and non-stable,
219 which differentiate how long the biochar will sequester and demonstrated that
220 the yield of the stable fraction of biochar is not dependent on pyrolysis
221 temperature. The biochar adds to the carbon content of the soil and suppresses
222 the release of greenhouse gases from the soil. Biochar has a higher calorific
223 value than raw fuel (Bazargan et al., 2014). For example, raw MF and biochar
224 from the MF pyrolysis have calorific values of 18760, and 23540 kJ/kg,
225 respectively (Hooi et al., 2009). Harsono et al. (2013) investigated energy
226 balances, greenhouse gas emissions and economics of biochar production and
227 demonstrated that the production of biochar from slow pyrolysis of EFB is
228 economically feasible and technically viable. Xu et al. (2017) reported that the
229 properties of biochar are very important in its effectiveness. The biochar is
230 therefore a valuable fuel, which will lead to ash production either through
231 gasification or combustion (Kimble et al., 2008). Table 4 is the characteristics of
232 biochar from EFB, MF, and PKS (Abnisa et al., 2013; Nam et al. (2018).

233 **2.3 Compost**

234 Compost is produced from the decomposition of organic matter through the
235 process of composting. Important considerations in composting are degradation
236 rate and the quality of the final compost (Rupani et al., 2010). Composting
237 efficiency is measured by the carbon-nitrogen (C/N) ratio of the compost. The
238 C/N ratio is an important indicator in composting with 30:1 considered as an
239 optimum value, and can be achieved by the addition of other materials.

240 The effective utilisation of FFB as organic amendment requires suitable
241 treatments including composting to convert it into a more suitable material for
242 soil application. Mohammad et al. (2012) reported that most of the EFB
243 generated are returned to the oil palm plantations. Since compost is a better
244 source of quality nutrients than the fresh material, in this context composting is
245 an important part of valorising EFB. Chopping EFB, its composting and
246 incorporation into the soil will enable quick release of nutrient to the soil
247 (Budianta et al., 2010).

248 Bakar et al. (2011) stated that composting offers an alternative of using EFB as
249 either fuel or mulch, but it brings additional operational costs and may require
250 advance technology for higher efficiency and quality. Siddiquee et al. (2017)
251 used two *Trichoderma* strains (strain SICCI and strain 11B) in composting EFB
252 and demonstrated variations in the properties of the composts produced by the
253 fungi and on their effects on soil properties. Compost from strain SICCI led to
254 the highest K content of 6.7 % after 8 weeks followed by that of strain 11B (5.9
255 %) and the control (soil without compost) had the lowest K content of 5.8 %.
256 *Trichoderma* species increases composting rate, and function as a biological
257 control agent (Shafawati and Siddiquee, 2013).

258 Vermicomposting is the use of different species of worms in composting
259 operation to produce a nutrient rich material known as vermicompost suitable as
260 soil amendment. Vermicompost is more fragmented and porous material, with
261 less contaminants and high nutrient content (Rupani et al., 2010) compared to
262 the raw material. An important advantage of vermicomposting technology over

263 other technologies is the production of earthworm biomass, which is a good
264 source of protein for animal feeds. Sabrina et al. (2009) reported that *Eisenia*
265 *fetida*, *Eisenia andrei*, *Lumbricus rubellus* or *Peryonix excavatus* are mostly
266 used in commercial vermicomposting. The earthworms prepare the biomass for
267 microbial activities by fragmentation and conditioning, which leads to reduction
268 in the C/N ratio, and increased surface area (Singh et al., 2011).

269 Sabrina et al. (2009) demonstrated that EFB compost is toxic to *Pontoscolex*
270 *corethrurus*, and *Amyntas rodericensis*, since only *Eisenia fetida* survived in
271 EFB compost during vermincomposting operation using EFB with cow dung as
272 supplement. Sabrina et al. (2009) reported that particle size affects the nutrient
273 content of EFB vermicompost. The EFB of particle size more than 0.05 m led to
274 significantly higher ($p < 0.05$) C/N ratio, K, and Mg than fine particle size of less
275 than 0.002 m. The pH of the coarse EFB vermicompost was also significantly
276 higher ($p < 0.05$) than the fine particles. However, the total nitrogen content of
277 the EFB fine particles was significantly higher ($p < 0.05$) than the coarse particles
278 (1.8, and 1.6 %, respectively). Nahrul Hayawin et al. (2010) investigated
279 vermicomposting of EFB using African Nightcrawler (*Eudrilus euginae*) for 84
280 days, demonstrating increases in total P and K from 0.023 % to 0.025 %, and
281 0.063 % to 0.069 % for raw EFB and EFB vermicompost, respectively. Similarly,
282 total Cu, Zn, Fe and Mn in the final product (Cu – 2.18, Zn – 2.82, Fe – 1.62 and
283 Mn – 16.78 mg/kg) were higher than in the original material (Cu – 9.59, Zn –
284 10.56, Fe – 9.29 and Mn - 18.75 mg/kg).

285

286 **Table 4 Characteristics of biochar from empty fruit bunch, mesocarp fibre, and palm kernel shell from literature.**

Analysis	PKS char	Reference	EFB char*	MF char**
Proximate (wt.%)				
Volatiles	18 - 35	Abnisa et al. (2013); Nam et al. (2018)	7.20 - 40.10	52
Ash	2 - 3	Abnisa et al. (2013); Nam et al. (2018)	12.80 - 19.86	4.30
Fixed carbon	72.50- 61	Abnisa et al. (2013); Nam et al. (2018)	41.70 - 72.94	30.60
Ultimate (wt.%)				
Carbon	64 - 79.40	Abnisa et al. (2013); Nam et al. (2018)	64.93 - 67.09	67.70
Hydrogen	3.18 - 5	Abnisa et al. (2013); Nam et al. (2018)	2.02 - 2.55	2.43
Nitrogen	0.82 - 1	Abnisa et al. (2013); Nam et al. (2018)	1.12 - 6.83	0.65
Oxygen***	16.61- 30	Abnisa et al. (2013); Nam et al. (2018)	23.90 - 31.41	29.23
HHV (kJ/kg)	28850	Abnisa et al. (2013)	21340	29.06

299 *Abnisa et al. (2013) at 500 °C and Shariff et al. (2014) at 550 °C, **Abnisa et al. (2013), Nam et al. (2018) at 550 °C,
 300 ***by difference, HHV – high heating value, MF – mesocarp fibre, PKS – palm kernel shell, EFB – empty fruit bunch

301 Table 5 shows the characteristics of vermicomposted EFB, non-vermicomposted
 302 (naturally composted) EFB, and non-composted (fresh) EFB treated with Gafsa rock
 303 phosphate (Sabrina et al., 2011). The nutrient contents of the EFB increased in the
 304 order of vermicompost>non-vermicompost>fresh. This could be attributed to
 305 concentration of nutrients due to reduction in volume, the availability of nutrients due
 306 to breakdown of the EFB by the worms in the vermicomposting and composting
 307 processes. Razali et al. (2012) investigated the in-vessel composting of EFB,
 308 reporting improvement in the C/N ratio from 77:1 to 13.8:1. Another important aspect
 309 of EFB valorisation is the separation into its component parts of EFS and BS.
 310 Zaharah and Lim (2000) reported that BS decomposed faster than EFS, which was
 311 because of relatively lower C/N ratio of 73.2 and 96.2 and lignin of 28.1 % and 29.1
 312 %, respectively.

313 **Table 5 The characteristics of vermicomposted, non-vermicomposted**
 314 **(naturally composted), and non-composted (fresh) empty fruit bunch (EFB)**
 315 **treated with Gafsa rock phosphate (Source: Sabrina et al., 2011).**

Parameter	Empty fruit bunch		
	Vermicompost	Composted	Fresh
Organic C (%)	23.96	23.88	52.27
Total N (%)	1.67	1.54	0.70
pH 1:10 in water	8.46	8.54	7.28
Total P (%)	1.48	0.95	0.20
Total K (%)	5.28	4.23	3.16
Humic acid (g/g soil)	0.08	0.04	nd

316 nd - not detected

317 **2.3.1 Co-composting**

318 Addition of supplements to enhance the C/N ratio in EFB composting is also called
 319 co-composting. Co-composting therefore is the use of more than one feedstock in
 320 composting. Decanter cake slurry can be collected separately from POME in palm oil
 321 mills. Yahya et al. (2010) reported that decanter cake slurry enhanced the formation
 322 of POME + EFB compost. Lower C/N ratio of 18.65 against 28.96 from compost of

323 no decanter cake slurry indicated mature compost. Nutongkaew et al. (2014)
324 obtained 3.26 wt.% N, 0.9 wt.% P and 2.0 wt.% K when POME was co-composted
325 with EFB and decanter cake. Notably, POME, EFB, FFB solid wastes ash, and
326 decanter cake slurry are oil mill wastes that can be co-composted, or anyone added
327 to aid the composting process (especially ash and POME to EFB) with the potentials
328 of increasing the value of the products as soil amendments. Lim et al. (2015)
329 demonstrated the effects of *Eudrilus eugeniae* in vermicomposting of EFB
330 supplemented with cow dung. The EFB vermicomposted without cow dung did not
331 encourage the productivity of earthworms. This was because of high C/N ratio. The
332 EFB and cow dung of the ratio 2:1 showed the best quality vermicompost with higher
333 increases in Ca (373 %), P (391 %), K (154 %), and Mg (371 %), which was a
334 demonstration of the lowest C/N ratio it had. Rupani et al. (2013) investigated the
335 effects of epigeic earthworms, *Lumbricus rubellus* on vermicomposting of MF treated
336 with POME, cow dung, and lawn clipping for 50 days. There was significant
337 decrease in the C/N ratio due to the addition of lawn clipping, cow dung, and POME
338 at the ratio of 15:15:50, respectively compared to using only MF. Baharuddin et al.
339 (2009) investigated the partial treatment of POME on EFB co-composting and
340 reported reductions in the C/N ratio. The initial C/N values of EFB and POME were
341 56.5 and 13.5; the values were 15.7 after 45 days and 12.8 after 60 days. Similarly,
342 Hock et al. (2009) investigated windrow co-composting of MF and POME anaerobic
343 sludge and demonstrated reduction in the C/N ratio from the values of 56.9 of raw
344 MF and 8.3 for that of POME anaerobic sludge to the final matured compost of 12.6
345 after 50 days.

346 Thambirajah and Kuthubutheen (1989) compared treatments of MF composting, MF
347 supplemented with poultry deep-litter and urea, and MF supplemented with poultry
348 broiler floor-litter and urea. These authors found that the C/N ratio reduced from 40,
349 33 and 26 to 26, 17, and 16, respectively after 8 weeks.

350 According to Yeoh et al. (2011) the higher porosity, water holding capacity, and
351 nutrient holding capacity of EFB make it more suitable for composting compared to
352 MF and PKS. There were limited reports on MF and PKS composting; however, the
353 particulate nature of PKS makes it a potential bulking material for EFB, and MF
354 composting.

3 Improving soil physical and chemical properties by the addition of fresh fruit bunch solid waste streams

The PKS can be directly used as mulch without any form of treatment (Embrandiri et al., 2012). The dusty part of PKS with high MF is used locally in Nigeria as mulch in pineapple orchards (personal communication). Apart from moisture conservation, weed suppression, and erosion control effects, the decayed mulching materials increased soil nutrients (personal communication). When EFB is used in pyrolysis, the biochar can be further combusted or used as gasification feedstock or directly used on soil as amendment. The EFB is preferably used as mulch and as organic fertiliser to the soil (Lin, 2009; Moradi et al., 2012; Ohimain et al., 2013; Rosenani and Hoe, 1996; Sulaiman and Abdullah, 2011). These are true for MF and PKS except that most palm oil mills use MF and PKS preferably as fuels for the boilers to generate steam for heating and electricity. This is because it costs more energy to use EFB for energy compared to MF and PKS with lower moisture content and higher bulk densities. Similarly, until recently excess PKS has been deposited in the farms as a means of disposal in Nigeria. The EFB fibre and MF are used in erosion control, soil stabilisation, compaction reduction, landscaping and horticulture, as compost and organic fertiliser (Embrandiri et al., 2012 and Ohimain et al., 2013).

3.1 Effects of empty fruit bunch on soil physico-chemical properties

The EFB is being used as a source of soil nutrients for the nearby oil palm plantations (Yeoh et al., 2011), and as a result increases organic matter content of soil. The EFB is usually left to decompose on plantations and orchards helping to return organic matter to the soil, control weeds and erosion as well as retain moisture (Figure 3). Labour cost, high weight and volume to nutrient content ratio, and pest attraction are the limiting factors associated with the use of EFB as mulch and organic fertiliser (Sulaiman and Abdullah, 2011; Yusoff, 2006).

Sung et al. (2010) used Ecomat (mat or carpet compressed from EFB) and EFB as mulching materials and compared their effects on soil water content, demonstrating that the soil mulched with EFB had 27 % more water than the soil mulched with

385 Ecomat, and 38 % more water than the control (without any mulch). The soil under
386 Ecomat mulches had only 8 % more water than bare soil. Sung et al. (2010)
387 concluded that in terms of water conservation, one layer of EFB is equivalent to five
388 layers of Ecomat. Carron et al. (2015) investigated the effects of decomposing EFB
389 on soil properties at different time intervals. Expectedly, Carron et al. (2015)
390 demonstrated that the soil total N, P, K, Mg, Ca and organic C of the decomposing
391 EFB decreased with time with highest values recorded after 1 month, and the values
392 were higher than the original EFB.

393 The EFB mulching affected the water retention curve by increasing significantly the
394 amount of water held at field capacity (Moradi et al., 2015). The average daily soil
395 water content was 0.2961 m due to EFB addition and was 0.2468 m due to pruned
396 palm fronds addition. There was significant increase at depth of 0 – 0.15 m of the
397 aggregate stability, available soil water content, and soil water concentration at field
398 capacity using EFB and therefore significantly increased the relative proportion of
399 soil mesopores (2.0×10^{-7} – 3.0×10^{-5} m) by 5 % more than the silt pit. Additionally,
400 EFB led to the highest amount of organic matter into the soil than pruned palm frond,
401 Ecomat, and silt pit (Moradi et al., 2015). The high organic matter led to the changes
402 in available water content of 13, 10, 10, 9 % v/v due to EFB, pruned palm frond,
403 Ecomat, and silt pit, respectively.

404 Rosenani and Hoe (1996) investigated the decomposition of single and double
405 layered EFB and have shown that 71 % of double layered EFB decayed within 15
406 weeks while 68 % of single layered EFB decayed within the same period. This was
407 attributed to high microbial activity within the double layered. Similarly, the single
408 layered EFB increased the soil total nitrogen from 0.23 % to 0.27 % while the
409 doubled layered increased to 0.28 %.

410 When compared to chemical fertiliser, EFB application at the rate of 0.3
411 tonne/palm/yr significantly increased ($P = 0.01$) the soil pH by 2, and cation
412 exchangeable capacity by 5.5 cmol (+)/kg more than chemical fertilizer in the 0.2 –
413 0.4 m soil layer (Bakar et al., 2011). Budianta et al. (2010) demonstrated that the
414 application of EFB at the rate of 40 Mg/ha/yr for 3 years ($pH = 5.85$) resulted in a
415 significant difference ($p < 0.05$) in pH at soil depth of 0 – 0.2 m against the control (pH

416 = 4.74). The soil pH, exchangeable K, Mg and Ca, organic C, and total N were 0.8,
417 0.3 cmol (+)/kg, 3.2 cmol (+)/kg, 9.2 cmol (+)/kg, 1.2 %, and 0.2 % more than the
418 control due to application of EFB at the rate of 37.5 tonnes/ha/yr, respectively (Chiew
419 and Rahman, 2002). There was significant effect due to EFB application on soil
420 organic C, with 38.1 % higher than that using silt pit and pruned oil palm fronds, and
421 36.4 % higher than Ecomat at depth of 0 – 0.15 m, and exchangeable Mg and Ca
422 (Moradi et al., 2012). Moradi et al. (2012) also reported an increase in soil
423 exchangeable K up to 70 % higher than silt pit, pruned oil palm fronds and Ecomat.
424 Budianta et al. (2010) demonstrated that the application of EFB at the rate of 40
425 Mg/ha/yr for 2 years increased significantly exchangeable Mg by 100 % compared to
426 the control (without EFB application). There was no significant effect on soil organic
427 C, and cation exchangeable capacity, N and P at 0 – 0.2 m depth after a year using
428 40 Mg/ha/yr of EFB (Budianta et al., 2010).

429 The PKS is used locally in Nigeria as a cooking fuel, on local roads or open premises
430 of residential houses and in oil mill plantations. When used on roads and premises of
431 residential houses, PKS presents a cost-effective means of soil erosion prevention.
432 There were limited reports on the use of MF and PKS to improve soil physico-
433 chemical properties, however Hock et al. (2009) report that co-composting using
434 excess MF (not used for energy purposes) and POME led to a material of higher
435 nutrients content suitable for soil use.

436 **3.2 Effects of ash and biochar from fresh fruit bunch** 437 **wastes on soil physico-chemical properties**

438 Soil nutrient is very essential in plant growth and metabolism. Crop growth and yield
439 depends on equilibrium between nutrient supply from either amendments or soil
440 metabolism, and demand by crops. Local farmers in Nigeria use ash from the
441 combustion of FFB solid wastes as a replacement for lime. Ash can improve soil
442 nutrient quality, act as lime replacement, and stimulate microbial activities (Awodun
443 et al., 2007). Conversely, Ojeniyi et al. (2010) demonstrated an increase in soil
444 organic matter by 0.16 and 0.06 % more than the control due to the addition of EFB
445 ash on a field experiment at Benin and Ekiadolor in southern Nigeria, respectively.
446 Awodun et al. (2007) reported significant increases in soil organic matter up to 51 %,

447 due to application of EFB ash at levels of 0, 2, 4, 6, and 8 tonnes/ha. The ash from
448 the combustion of MF and PKS is returned to plantations as soil amendment
449 (Elbersen et al., 2013), which is a positive development.

450



451

452 **Figure 1 Empty fruit bunch and ash dumped into an oil palm plantation. This is**
453 **the poor practice in Nigeria due to enormous amount of the wastes generated**
454 **with no other form of disposal.**

455 The high nutrient content in EFB ash increases its positive effects on soil fertility
456 (Table 6). Awodun et al. (2007) reported an increase in soil N (48 %), P (51 %), K
457 (61 %), Ca (43 %), Mg (68 %) due to application of EFB ash with the levels of 0, 2, 4,
458 6 and 8 tonnes/ha. Some literature reports on properties of EFB ash are shown in
459 Table 6. Ojeniyi et al. (2010) investigated the effects of 4 tonnes/ha EFB ash, and
460 0.3 tonne/ha nitrogen-phosphorus-potassium (NPK) (15-15-15) fertiliser, and their
461 mixture at different levels, and demonstrated that EFB ash at 4 tonnes/ha recorded
462 the highest K and pH values in the soil. Similarly, Awodun et al. (2007) reported an
463 increase in soil organic matter due to application of EFB ash as the application level

464 increased from 0, 2, 4, 6 and 8 tonnes/ha. The 8 tonnes/ha EFB ash level recorded
 465 the highest organic matter content of 3.4 % while the control led to the lowest value
 466 of 1.8 % in Nigeria. Similar result was obtained for the soil exchangeable K with the 8
 467 tonnes/ha ash level, which was 0.37 cmol/kg more than the control. Adjei-Nsiah and
 468 Obeng (2013) demonstrated that significantly ($p < 0.05$) more soil pH (0.7), available
 469 P (6.29 ppm) and exchangeable K (0.34 cmol/kg), Ca (0.76 cmol/kg) and Mg (1.06
 470 cmol/kg) than the control due to the application of 4 tonnes/ha EFB ash.

471 **Table 6 Characteristics of empty fruit bunch (EFB) ash from literature.**

Parameter	Empty fruit bunch ash	References
pH (H₂O)	7.50 - 10.89	Adjei-Nsiah and Obeng (2013); Akanbi et al. (2014)
Organic C	0.55 – 1.92 %	Adjei-Nsiah and Obeng (2013) Gbaraneh and Chu (2016)
	0.17 %	Akanbi et al. (2014)
Total N	0.08 -0.19 %	Adjei-Nsiah and Obeng (2013); Gbaraneh and Chu (2016); Ojeniyi et al. (2009)
	0.02 %	Akanbi et al. (2014)
Total P	0.26 -0.18 %	Gbaraneh and Chu (2016)
Total K	27.10 - 28.30 %	Gbaraneh and Chu (2016)
	2.65 %	Akanbi et al. (2014)
Total Ca	6.59 – 8.10 %	Gbaraneh and Chu (2016)
Total Mg	3.10 – 3.33 %	Gbaraneh and Chu (2016)
C/N ratio	10.10 -10.9	Gbaraneh and Chu (2016)
Exchangeable K	582.77 cmol/kg	Adjei-Nsiah and Obeng (2013)
Exchangeable Ca	0.85 - 34.93 cmol/kg	Adjei-Nsiah and Obeng (2013); Akanbi et al. (2014); Ojeniyi et al. (2009)
Exchangeable Mg	1.80 - 29.08 cmol/kg	Adjei-Nsiah and Obeng (2013); Akanbi et al. (2014); Ojeniyi et al. (2009)
Available P	0.19 %	Ojeniyi et al. (2009)
	0.02 %	Akanbi et al. (2014)

472

473 Biochar can help to mitigate climate change through stable carbon storage and the
474 reduction of GHG emissions when added to the soil (Kong et al., 2014). Abdulrazzaq
475 et al. (2015) investigated the use of EFB biochar on soil properties and concluded
476 that EFB biochar is more suitable for soil fertility improvement compared to rice husk
477 biochar. There was a significant difference in the hydraulic conductivity, mean
478 porosity and drained upper limit of soil due to the EFB biochar compared with the
479 control (soil without any biochar). The hydraulic conductivity, mean porosity, and
480 drained upper limit of soil of the 30 tonnes/ha EFB biochar treatment were 0.75
481 cm/h, 5 %, and 0.07 % more than the control. The micropore area and pore volume
482 of the biochar led to improvement in the soil porosity. High drained upper limit
483 enhances the soil aeration potential. Bakar et al. (2015) reported that the soil
484 available P, and exchangeable Ca increased by 41, and 37 % more than the control,
485 respectively using 40 tonnes/ha EFB biochar in a pot study on the effects of EFB
486 biochar on the growth performance of rice. Lee et al. (2017b) reported that the
487 application of 20 Mg/ha EFB biochar increased soil exchangeable Ca, K and Mg,
488 and cation exchange capacity significantly by 45.45, 343.4 and 72.73, and 3.14 %
489 more than the control (no biochar), respectively. Conversely, the soil exchangeable
490 Al significantly decreased by 34.17 %.

491 **4 Crop response to fresh fruit bunch waste streams**

492 The availability of soil nutrients is the major factors affecting crop yield including oil
493 palm. Land slope under intensive rainfall conditions limits crop productivity due to
494 increased loss of nutrient from soil erosion (Moradi et al., 2012). Therefore, mulching
495 has proven to be an effective method of controlling erosion and increasing crop
496 growth and yield. Laying EFB on top of the soil has been an effective means of
497 utilising the waste for crop growth. The oil palm leaf P was 0.08 and 0.07 % more
498 compared to the control (oil palm fronds) and silt pit after 6 months of application of
499 EFB at the rate of 1 tonne/treatment plot/yr, respectively. Comparing EFB and oil
500 palm fronds, EFB decomposed at a faster rate than oil palm fronds and therefore
501 released significantly higher amounts of K and Ca after 6 months (Moradi et al.,
502 2012). The decomposition rate influences nutrient release and hence crop yield.
503 There was an increase in oil palm FFB yield (21, 30 and 34 tonnes/ha/yr), bunch
504 number (990, 1197, and 1256) and average bunch weight yield (21, 25 and 27 kg)

505 due to the control, and the application of 37.5 and 75 tonnes/ha/yr EFB mulch,
506 respectively (Chiew and Rahman, 2002). Similarly, the N content of the oil palm leaf
507 increased significantly to 2.7 and 2.9 %, respectively while the control was 2.6 %.
508 Ravooof (1988) demonstrated that EFB single layer mulch can be used to grow sweet
509 potato on a sandy soil without fertiliser. Bakar et al. (2011) compared the effects of
510 chemical fertiliser, and EFB at rates of 0.15 and 0.3 tonne/palm/yr as mulch in oil
511 palm plantation for 10 years and concluded that there was no significant difference
512 between the application of EFB at the rate of 0.15 tonne/palm/yr and chemical
513 fertilizer, however the 0.3 tonne/palm/yr rate was 9 % higher. Similarly, EFB at the
514 rate of 0.15 tonne/palm/yr increased significantly ($p = 0.01$) soil organic C in the top
515 soil. According to Sridhar and AdeOluwa (2009), adding EFB at 6 tonnes/ha can
516 return half the nutrients originally harvested in the FFB on decomposition.

517 Asiah et al. (2004) demonstrated that EFB could be used as growing medium for
518 hybrid cauliflower plant although, when compared to coconut coir dust resulted in
519 lower total dry matter yield (0.006 g/plant) and total nitrogen uptake (more than 300
520 mg N/plant) 42 days after transplanting. Tabi et al. (2008) demonstrated that 100 %
521 EFB as substrate for the cultivation of *pleurotus ostreatus* (mushroom) could not
522 produce *pleurotus ostreatus* fruit bodies, whereas 100 % MF produced 4.6 %
523 biological efficiency (the yield of fresh fruit bodies per 100 g dry substrate. The 50 %
524 MF and 50 % rubber tree sawdust produced the highest biological efficiency of 11.3
525 %, which is the same value produced by 100 % rubber tree sawdust used
526 commercially as substrate for *pleurotus ostreatus* cultivation (Tabi et al. 2008). The
527 low content of nitrogen in EFB was responsible for the inability of the mycelium to
528 grow. The MF can be used to grow *pleurotus ostreatus* or in combination with rubber
529 tree sawdust. Hoe (2014) used MF as a growing media for banana tissue culture
530 seedlings and demonstrated that the height of the banana seedling increased
531 significantly (Tukey's HSD 5 %) by 0.0746, 0.1292, and 0.1824 m due to the use of
532 MF more than the control (only soil) after weeks 5, 6 and 7, respectively.

533 There were limited reports on the application of raw PKS on soil for crop
534 improvement, however as stated above the dusty part of PKS with high MF is used
535 locally in Nigeria as mulch in pineapple orchards (personal communication). The
536 effects on pineapple growth and yield have not been documented.

537 **4.1 Crop response to empty fruit bunch compost**

538 Haya et al. (2017) demonstrated that the K content of orange-fleshed sweet potato
539 storage root increased significantly ($p<0.05$) due to the application of EFB compost +
540 30 ppm hexaconazole (growth regulator) by 107 % more than the control. The EFB
541 compost led to a significant increase ($p<0.05$) in the K contents of the sweet potato
542 leaf, stem and root by 0.58, 0.68, and 0.37 % more than the control, respectively.
543 These were due to the EFB compost providing the soil the ability to retain K long
544 enough for the plant to absorb it compared to the control (inorganic fertiliser).
545 However, the use of 100 % EFB compost was found to be responsible to stunted
546 growth in okra (Siddiqui et al. 2009), and a decrease in germination of okra seeds as
547 EFB compost level increased against chicken manure. The EFB compost level of 25,
548 50, 75 and 100 % resulted in 81.4, 49.72, 48.14 and 9.9 % germination, respectively.

549 **4.2 Crop response to empty fruit bunch ash**

550 Awodun et al. (2007) reported an increase in maize leaf Ca of up to 13 % due to 6
551 and 8 tonnes/ha of EFB ash, which was higher than the control when EFB ash
552 (levels of 0, 2, 4, 6 and 8 tonnes/ha) was applied at two different sites. Awodun et al.
553 (2007) also reported significant increase in maize cob and grain yield except at 8
554 tonnes/ha ash level with the highest yield of 0.053 kg/plant of maize cob and 0.046
555 kg/plant of maize grain obtained at 6 tonnes/ha.

556 Akanbi et al. (2014) investigated the effects of 1, 2, 3, 4 and 5 tonnes/ha levels of
557 EFB and cocoa pod husk ash, respectively and 10 kg of the NPK (20:10:10) fertiliser
558 on the growth and dry matter yield of cocoa (*Theobroma cacao*). These authors
559 demonstrated that EFB ash at the level of 4 tonnes/ha significantly ($p<0.05$)
560 increased the height and root length of cocoa seedlings more than the NPK
561 (20:10:10) fertiliser by 0.0476 and 0.2 m, respectively. Ojeniyi et al. (2009)
562 investigated the effects of 1.25, 2.50, 3.75 and 5.00 tonnes/ha EFB ash, and 0.6
563 tonne/ha NPK (15:15:15) fertiliser against no amendment application on cassava
564 performance. The 2.5 tonnes/ha EFB ash led to significantly higher ($p<0.05$) sweet
565 cassava tuber yield, which exceeded the NPK (15:15:15) fertiliser by 83 %.
566 Gbaraneh and Chu (2016) compared the effects of 10 tonnes/ha EFB ash, 10
567 tonnes/ha poultry manure, 0.2 tonne/ha NPK (20:10:10) fertiliser and the mixtures of

568 the amendments on soil nutrient status and performance of okra. All the treatments
569 increased okra pod length, weight and total yield against the control, the 10
570 tonnes/ha EFB ash level was only greater than the control by 5 mm, 0.0053 kg, and
571 1.96 tonnes/ha, respectively in the second year. The 5 tonnes/ha EFB ash + 0.1
572 tonne/ha NPK increased the okra pod length, weight and total yield more than the 10
573 tonnes/ha EFB ash level. This is in line with Siddiqui et al. (2009) report on okra
574 performance using EFB compost as stated above. Adjei-Nsiah and Obeng (2013)
575 demonstrated significant increase ($p < 0.05$) in the mean leaf P and K of eggplants,
576 okra, and pepper of 0.1, 0.1 and 0.08 % and 0.09, 0.1, 0.08 % more than the control
577 due to the application of 2, 4 and 6 tonnes/ha EFB ash levels, respectively.

578 Recent reports on the use of ash from FFB solid wastes focused on EFB ash;
579 however, MF and PKS are mostly used in palm oil mill combustors (boilers), with the
580 generation of ash as residue. Reports above have shown that EFB ash is important
581 to crop yield and therefore there is a need to consider the use of EFB together with
582 MF and PKS in boilers to increase the quality of the ash produced for soil properties
583 and crop improvement.

584 **4.3 Crop response to fresh fruit solid wastes biochar**

585 Nam et al. (2018) investigated the use of PKS biochar at three levels of 10 g, 20 g
586 and 30 g for the cultivation of mushroom (*Pleurotus ostreatus*) by adding rice bran
587 and sawdust as sources of nutrient while Ca carbonate was used to balance the pH.
588 The 20 g level led to the highest yield of 500 g mushroom, which was 50 % more
589 than the control. The biochar retained more nutrient and water for the growth of the
590 mushroom compare with the treatment without biochar. Similarly, the mean shoot dry
591 weight of the sweet corn was 220 g per plot due to the EFB biochar application,
592 while that of the control (without biochar) was 50 g per plot (Abdulrazzaq et al.,
593 2015). Bakar et al. (2015) reported that the maximum height of rice, number of
594 panicles/hill, weight of 1000 grains, and total biomass/hill were 22.20, 163, 52.53,
595 and 318.60 % more than the control, respectively using 40 tonnes/ha EFB biochar in
596 a pot study on the effects of EFB biochar on the growth performance of rice.
597 Additionally, the P, K Ca, and Mg concentrations in the rice plant significantly
598 increase by 221.14, 601.27, 336.55, and 293.60 % more than the control,

599 respectively due to the 40 tonnes/ha EFB biochar application. The application of 10
600 Mg/ha EFB biochar resulted in 77.4 % significant increase in the total dry matter
601 weight of maize compared to the control (Lee et al., 2017b). Similarly, the K, P, and
602 Mg uptake by the maize aboveground biomass increased significantly by 246, 97,
603 and 83.9 % more than the control, respectively due to the application of 20 Mg/ha
604 EFB biochar.

605 **5 Prospects and challenges**

606 The incineration of EFB leads to emission of particulates including tar and soot
607 droplets (Tabi et al., 2008) and the wastage of heat. The dumping of EFB takes up
608 large space (Mohammad et al., 2012). The earlier means of disposing EFB, PKS,
609 MF, and the ash was dumping in the farms or roadside especially in Nigeria. Over
610 the years, these wastes have attracted interest due to the impacts on soil properties,
611 soil nutrient availability, crop yield, and soil erosion. Tabi et al. (2008) concluded that
612 a new usage of the FFB solid wastes should be looked into to minimise any pollution.
613 It has been reported above that PKS is used as fuel, Haryati et al. (2016) stated that
614 the left over PKS when disposed add pressure to the land.

615 The combustion or gasification of the FFB solid wastes increases fouling and
616 corrosion of the thermal facilities due to the high content of alkali metals in the
617 biomass, which reduces the heat transfer capacity of the heat exchangers. The low
618 melting point of these metals leads to slagging, which increases cost of
619 maintenance. Haryati et al. (2016) reported that the lower nitrogen content of PKS
620 biochar relative to the feedstock is an added advantage in terms of low level of fuel
621 NO_x during combustion. When EFB is burnt, it generates undesirable air pollution.
622 When it is returned to the plantations, it takes weeks before the heaps are turned
623 leading to poor decomposition and emission of methane. According to Elbersen et al.
624 (2013), poor decomposition of EFB contributes to greenhouse gas emissions by the
625 release of methane and nitrogen oxide up to 0.23 tonne carbon dioxide equivalent
626 per tonne of EFB, which can be reduced to 0.05 tonne carbon dioxide
627 equivalent/tonne of EFB by a well-controlled compositing facility. Krishnan et al.
628 (2016) supported Elbersen et al. (2013) by demonstrating that the EFB and POME
629 co-composting can reduce greenhouse gas emissions by 76 %. This was achieved

630 by avoiding open dumping of EFB and pond treatment of POME. The capture and
631 burning of the released biogas from the decomposition of EFB in a flare would
632 reduce the greenhouse gas emissions by 95 % (Elbersen et al., 2013). Sabrina et al.
633 (2012) demonstrated that extractible phenols from field decomposed EFB decreased
634 with increasing age of the EFB compost. Similar types of phenols were found in fresh
635 field decomposed and composted EFB, which had no harmful effect on earthworm
636 population. Sabrina et al. (2012) concluded that vermicomposting could degrade
637 toxic compounds as no phenols were found in vermicomposted EFB.

638 The processing of the EFB to enhance its value will generate employment and
639 therefore reduce social unrest in areas where unemployment is a major challenge.
640 This is true with the production of Ecomat from EFB, which is used as a landscaping
641 and mulching material in urban area (Sung et al., 2010). Elbersen et al. (2013)
642 reported that the value of EFB returned to the field was estimated to be up to \$3.3
643 per tonne due to the benefit from replacing fertiliser, the costs for transport and
644 spreading. However, the economic benefit of using EFB as a fuel for power
645 generation is 3.5 times the benefit of using EFB as a mulch (Elbersen et al., 2013).
646 Harsono et al. (2013) reported that the cost of transporting raw EFB to the palm oil
647 plantation is 81 % more than the cost of transporting the EFB biochar, leading to a
648 savings of 21,384 US\$/yr. Bakar et al. (2011) reported that 0.15 tonne/palm/yr of
649 EFB could replace chemical fertiliser in terms of FFB yield.

650 **5.1 Environmental risk of ash application**

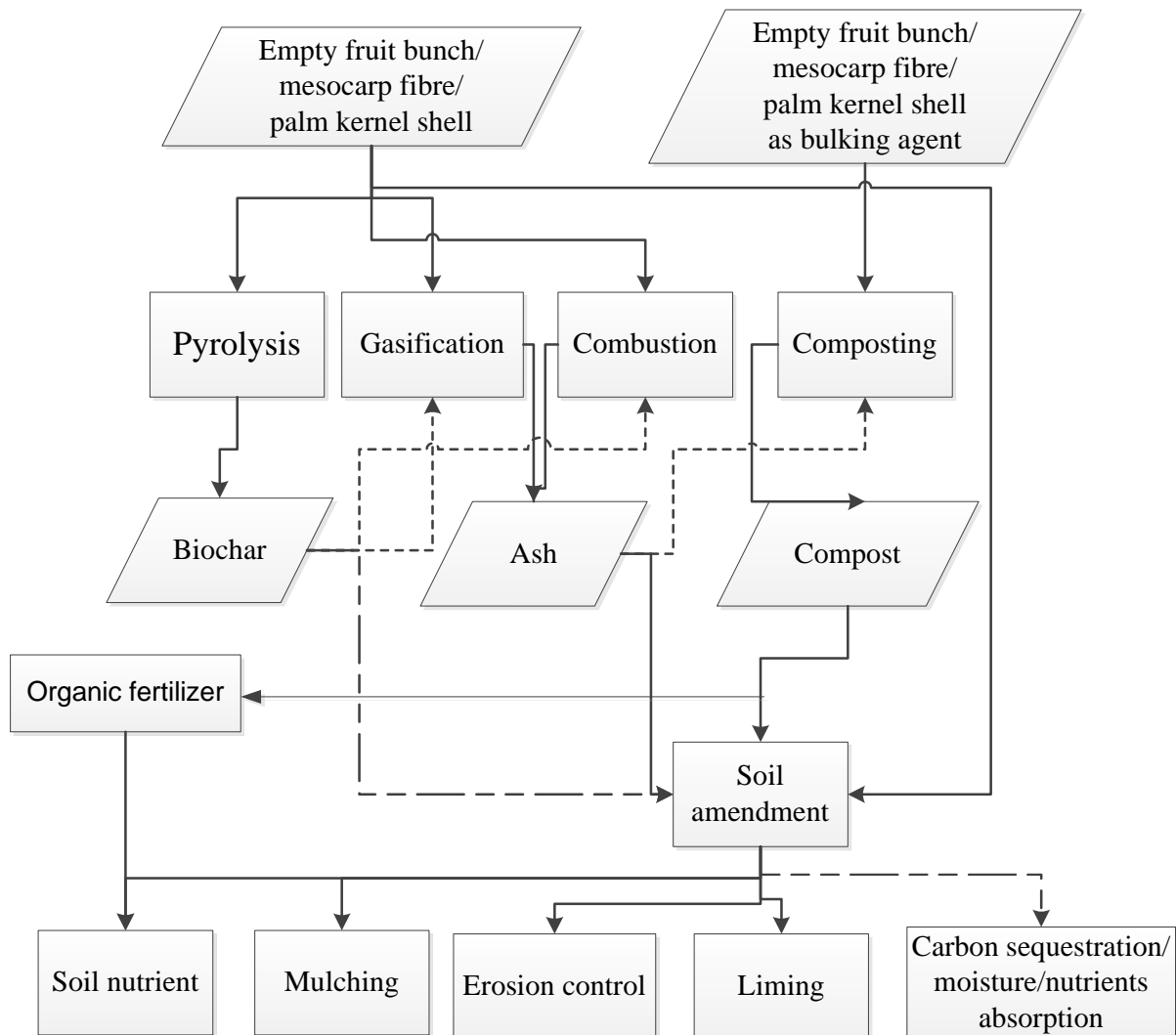
651 The challenges of poor ash management affect humans, animals, soil and plants as
652 well as occupy valuable space. Most palm oil mills dispose the ash from combustion
653 of MF and PKS by returning it to the plantation or landfills (Alsubari et al., 2018) the
654 same way the EFB is disposed. The ash from MF and PKS are used on roads
655 leading to palm oil mills (Vijaya et al., 2008). The environmental implication of this
656 form of disposal has not been fully documented. The combustion of EFB for ash
657 generation has been reported, although the practice has been prohibited in Malaysia
658 (Elbersen et al., 2013; Moradi et al., 2014).

659 Few of the countries in Europe with regulations/recommendations on the use of ash
660 for agricultural purposes are Austria, United Kingdom, Germany, Denmark, Sweden,

661 and Finland. The considerations for the regulations include heavy metals and
662 organic compounds content and application per year per hectare. Only ash from
663 clean biomass fuels is allowed for agriculture or forestry applications in Sweden (Van
664 Eijk et al., 2012) and for sustenance purposes only (Hanman et al., 2016). In Austria,
665 2 % weight base is the maximum biomass ash allowed in composting (Van Eijk et
666 al., 2012). In Finland ash application is allowed for restoration purposes only and not
667 to increase tree growth whereas in Denmark, Finland, Lithuania, Sweden and the
668 United Kingdom ash application is recommended to prevent negative impacts due to
669 the harvesting of forest biomass (Hanman et al., 2016).

670 **5.2 Outlook for fresh fruit bunch solid wastes valorisation**

671 The best value from FFB wastes is achievable if a proper waste management
672 system is part of the design of the palm oil mills, or a separate facility designed to
673 match the capacity of the palm oil mills. Figure 4 is a flow chart describing the
674 different routes to the utilisation of FFB solid waste streams as soil ameliorants,
675 which can be considered in designing palm oil mills. The EFB, MF and PKS, and
676 their by-products in different forms can add nutrients to the soil, used as mulching
677 materials, in erosion control, soil liming, and in carbon sequestration. The biochar
678 generated from pyrolysis can be used in either combustion or gasification, which is
679 potentially effective in reducing environmental challenges of thermal conversion of
680 the raw biomass. Similarly, the ash produced can be used to aid composting. As
681 suggested by the model, the wastes can be used simultaneously or separately. The
682 simultaneous utilisation may provide opportunity for improvements and reduce the
683 needless disposal of any of the wastes.



685

686 **Figure 1 Flow chart for fresh fruit bunch solid wastes valorisation as soil**
 687 **ameliorant.**

688 **6 Conclusions**

689 The EFB, MF, and PKS are used as boiler fuels and the generated ash used as soil
 690 amendments. The challenges of FFB solid wastes use as fuel for the generation of
 691 ash and biochar include low bulk density, high moisture content, and high alkali
 692 content. Low bulk density limits the transportation of the raw biomass especially EFB
 693 and their residue to areas in high demand. It forces the palm oil mills to deposit the
 694 wastes including ash within the palm oil mills, adding pressure to the limited land
 695 space and leading to greenhouse gas emissions. These have led to alternative

696 means of increasing the value of the wastes, which also leads to valuable soil
697 ameliorants. The processes include pyrolysis (biochar), gasification (ash),
698 combustion (ash), and composting (compost). There is a need to include in the
699 design of palm oil mills other facilities to manage the wastes especially EFB. A well-
700 balanced utilisation of the FFB solid wastes will reduce the negative impacts of
701 disposal of the wastes, including greenhouse gas emissions, pest breeding, pressure
702 on land resources, and the waste of potential soil ameliorants and the attendant
703 economic losses. Co-utilisation (pyrolysis, gasification, combustion, and composting)
704 of the EFB, MF and PKS a suitable option in effective management of the wastes.

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