

CRANFIELD UNIVERSITY

Kelechi Ezenwa Anyaoha

FRESH FRUIT BUNCH SOLID WASTES: PROCESSING,
CONVERSION AND UTILISATION NEXUS IN NIGERIA

School of Water, Energy and Environment

PhD

Academic Year: 2017- 2018

Supervisor: Dr Ruben Sakrabani, Dr Kumar Patchigolla and Prof.
Abdul Mouazen (Ghent University)

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the degree of Doctor of Philosophy

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ABSTRACT

The oil palm fresh fruit bunch (FFB) solid wastes, which include the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS) are generated during the production of palm oil. The utilisation of the ash resulting from combustion or gasification of the FFB solid wastes for soil improvement and crop yield especially cassava is a challenge in the management of the FFB solid wastes. This study is aimed at understanding the relationship between the processing of the FFB in Nigeria, thermal conversion of the FFB solid wastes, and the utilisation of the ash for soil improvement and cassava yield.

The industrial, small-scale, and traditional routes of the FFB processing in Nigeria were investigated to determine the losses associated with each. Secondly, the effects of the co-firing of the EFB with MF and PKS were investigated. Finally, ash from the FFB solid wastes was applied on soil at different levels (0, 40, 80, and 160 tonnes/ha) and feedstock compositions to determine the effects on soil nutrient contents and cassava tuber yield.

In the industrial route, 29, 18, 75, and 27 kg of CPO, PK, MF, and PKS were lost for every 1000 kg of the FFB processed more than in the small-scale and traditional routes, respectively. The use of 40 tonnes/ha, and 80 tonnes/ha treatments resulted in 427 % and 341 % more cassava tuber yield than the control plot, respectively. The ash of the EFB, MF and PKS feedstock resulted in more cassava tuber yield of approximately 6 tonnes/ha than that of only MF and PKS feedstock (3 tonnes/ha).

The thesis has demonstrated that the use of ash from the FFB solid wastes for agricultural purposes is related to the thermal conversion and the processing of the FFB. The feedstock of the equal mixture of EFB, MF and PKS is more valuable for the generation of ash useful as soil amendment and in cassava production providing evidence for the co-firing of the EFB, MF and PKS and improved efficiency of the FFB processing.

Keywords: Oil palm, empty fruit bunch, mesocarp fibre, palm kernel shell, soil, ash

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LIST OF ABBREVIATIONS

AR	As Received
BS	Bunch Stalk
CCE	Carbon Conversion Efficiency
CGE	Cold Gas Efficiency
C/N	Carbon/Nitrogen
CPO	Crude Palm Oil
CRD	Completely Randomized Design
DB	Dry Basis
EFB	Empty Fruit Bunch
EFS	Empty Fruit Spikelet
ER	Equivalence Ratio
FFB	Fresh Fruit Bunch
FFS	Fresh fruit spikelet
FTIR	Fourier Transform Infrared Spectroscopy
HHV	Higher Heating Value
I	Industrial
K/Ca	Potassium/Calcium
PK	Palm Kernel
PKC	Palm Kernel Cake
PKO	Palm Kernel Oil
PKS	Palm Kernel Shell
LHV	Lower Heating Value
MF	Mesocarp Fibre

POME	Palm Oil Mill Effluent
RCBD	Randomized Complete Block Design
S	Small-scale
T	Traditional
TWF	Total Weight of Fruits

1 Introduction

1.1 Background

The oil palm tree is a major source of plant oil in the tropical zones where it grows. The African oil palm (*Elaeis Guineensis*) is believed to originate from West Africa, and today is widely grown in most parts of West and Central Africa, Southeast Asia, and South America. Indonesia, Malaysia, Thailand, Colombia and Nigeria are the leading producers of palm oil in the world and account for over 90 % of global palm oil production (FAOSTAT, 2017). In 2014, an estimated 57 million tonnes of palm oil was produced globally (FAOSTAT, 2017), which led to the generation of 250 million tonnes of biomass worldwide from within the oil palm industry (4.4 tonnes of biomass for every 1 tonne of palm oil according to Krishnan et al. (2016)). The biomass from the oil palm industry is estimated to be 90 % of the total production while palm oil is about 10 % (Chang, 2014). The biomass includes leaves, fronds, trunks, empty fruit bunch (EFB), mesocarp fibre (MF), palm kernel shell (PKS), and palm oil mill effluent (POME) (Evbuomwan et al., 2013, and Madaki and Seng, 2013).

The oil palm produces more oil per hectare of land than any other known oil crop (Ohimain et al., 2013, and Evbuomwan et al., 2013), and the most important oil crop in the tropics in terms of return on investment and yield of other useful products. In Nigeria, the oil palm has continued to play a major role with regard to income generation for the oil palm plantation owners and processors, jobs creation for millions of people and raw materials for industries. Nigeria has always played a leading role in the production of palm oil and with export figure representing 43 % of global oil production (Thomas et al., 2011) but in more recent times Nigeria produces less than 3 % of the global consumption, although Nigeria still produces more than half of Africa's total palm oil production (Gourichon 2013).

1.1.1 Fresh Fruit Bunch Wastes

Palm oil is processed from the oil palm fruits. Oil palm fruits are produced in bunches known as fresh fruit bunch (FFB). The wastes generated during the processing of FFB are divided into both liquid and solid. The liquid waste is generally known as POME while the solid waste comprises of EFB, MF, and PKS. In Nigeria, palm oil production is carried out in three different scales/routes: large scale (industrial), small-scale, and the subsistence level (traditional). The large scale processing of FFB involves the reception and sterilisation of the FFB, threshing/stripping (removal of fruits from the sterilised FFB), digestion of the fruits, extraction of oil from the pulp, which is formed during fruit digestion, separation of MF and palm nut, cracking of the palm nut and separation of the PKS and palm kernel (Figure 1-1). The difference between the industrial, small scale and traditional routes of FFB processing is the sterilisation of the fruits. In small-scale and traditional routes, the FFB are left to ferment for more than 4 days to enable easy removal of the fruits and later the fruits are cooked directly in water. In industrial route, the FFB are sterilised on the day of harvest (Ohimain and Izah, 2014). In the small-scale route, the bunch are quartered and left for days to enable the manual removal of the fruits from the quartered bunch (Ohimain and Izah, 2014), while in traditional route the bunch are separated into the inner stalk known as bunch stalk (BS) and the outer fruit carrying spikelet (Nafu et al., 2015) known as fresh fruit spikelet. The solid wastes are fuels used in the boilers for the generation of steam and electricity in the palm oil mills, which results in the production of residue known as ash.

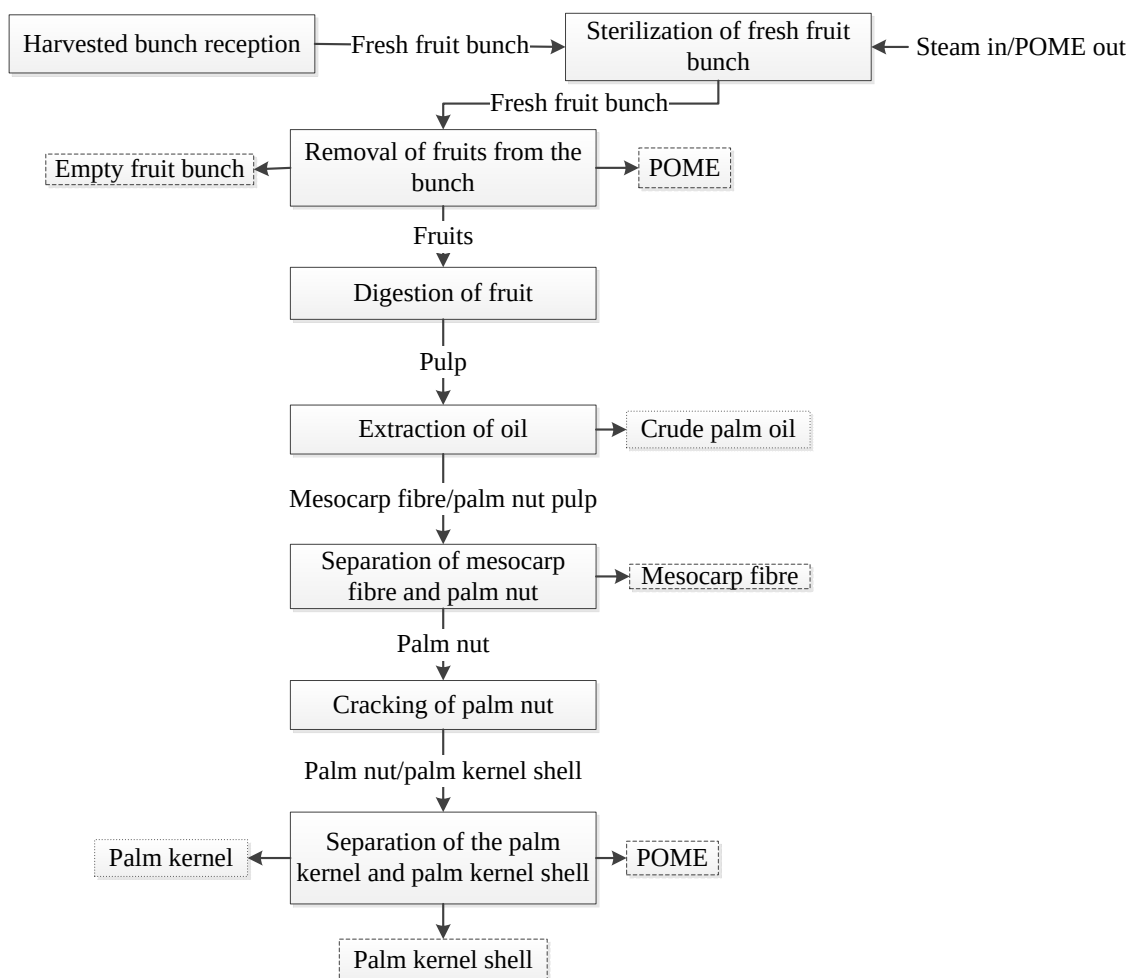


Figure 1-1 The flowchart of the industrial route of processing fresh fruit bunch, solid box - process, dashed box – waste, dotted box - product, POME – palm oil mill effluent.

1.1.2 Status of electricity generation in Nigeria

Energy is a major challenge facing Nigeria in the quest for socioeconomic development. The first public use of electricity in Nigeria was recorded in 1896 (Sadiq et al., 2015) and since then there has been significant efforts put towards balancing demand and supply of electrical power. About 60 % of the Nigerian population is not connected to the national electricity grid, while the connected 40 % face constant power disruptions around 60 % of the time (Sadiq et al., 2015). Nigeria's electricity challenges are responsible for high cost of production even with low cost of labour. Nigeria's electricity generation is dependent on petroleum, natural gas, and hydropower. The two most important regulations

(Electricity Distribution Network and Embedded Generation 2012) from the Nigeria Electricity Regulatory Commission empowers investors, communities, state and local governments to generate and distribute electricity for their exclusive consumption using facilities of existing electricity distribution companies or independent electricity distribution network operators, and also to invest in electricity distribution networks in areas without access to the grid or distribution network or areas poorly serviced (Sadiq et al., 2015).

The need for environmental protection has continued to raise awareness for development in cleaner and renewable energy sources. Biomass and other renewable energy sources are beginning to take centre stage in the paradigm shift. Biomass from agriculture offers a big opportunity for Nigeria in attaining sustainable levels of electricity production. Nigeria has 11 million hectares of woodland forest, 28.2 million hectares of arable land for agricultural production, and generates 30 million tonnes/yr of municipal solid wastes (Adebisi, 2013). The Energy Commission of Nigeria (2014) Draft National Renewable Energy and Energy Efficiency Policy on biomass include to effectively harness non-fuelwood biomass energy resources and integrate them with other energy resources, to promote the use of efficient biomass conversion technologies, and to enhance the demand side measures that support the use of biomass for the production of renewable energy. Table 1-1 is the projections for electricity supply and demand in Nigeria from Energy Commission of Nigeria (2014). Energy generation from biomass is expected to increase by 54.3 % while that of hydropower is expected to increase by 13.4 % between 2025 and 2030. Studies have shown that energy from FFB solid wastes can completely replace the use of fossil fuel within the oil palm processing industry (Ng et al., 2011; Niu et al., 2010 and Ohimain et al., 2013). Therefore, in Nigeria FFB solid wastes offer a huge opportunity in the quest for sustainable energy and the proper utilisation of the wastes and the ash is very important.

Table 1-1 Electricity supply and demand based on 7 % projections scenario, in kW adapted from Energy Commission of Nigeria, (2014).

Fuel projection/yr	2009 (Base year)	2020	2025	2030
Demand projection (000 kW)	4052	45.490	79.798	115.674
Supply projection by fuel (000 kW)				
Coal	0	6527	7545	10984
Electricity import	0	0	0	31948
Gas	3803	33711	61891	80560
Hydro	1950	6942	7427	8419
Nuclear	0	1500	2500	3500
Solar	0	3455	7000	25917
Wind	0	22	25	29
Biomass	0	16	35	54
Total supply	5753	52174	86422	161411

1.1.3 Problem Statement

Currently in Nigeria, PKS and MF are used as boiler fuel, while almost all the EFB produced in the palm oil mills are disposed of in the oil palm plantations leading to an increase in greenhouse emissions and therefore poorly utilised. This is common in most palm oil mills around the world due to the difficulty of using EFB as a boiler fuel. However, Elbersen et al. (2013) reported that EFB is 3.5 times more beneficiary when used as fuel than as mulch. The challenges of using EFB as fuel include its low bulk density (110 kg/m^3) (Sung et al., 2010), high moisture content (60 – 70 %) according to Aziz et al. (2017) compared to MF and PKS. These properties of EFB makes its transportation and handling difficult. To increase energy sources from the oil palm industry will require the use of EFB for energy production. The proper management of EFB, MF, and PKS will require proportional utilisation of the wastes, and the residue (ash) of the co-utilisation.

Most local farmers are limited by resources especially with regard to access and the use of organic fertilisers; however, the increasing use of farm lands requires that soil amendment be added to the soil to ensure increase and steady yield. The increase in the use of FFB solid wastes for energy purposes will lead to the generation of ash. One of the challenges faced by the palm oil industry is on how to use the ash produced for soil improvement and increase crop yield particularly cassava.

1.2 Research Questions

The problems discussed above have led to the following research questions:

- (a) What are the effects of FFB processing on the utilisation of the solid wastes for energy purposes?
- (b) Is there any synergy in the thermal conversion of the mixture of EFB, MF, and PKS?
- (c) What are the effects of the application of ash from FFB solid wastes on soil physico-chemical properties and cassava yield?

1.3 Aim and Objectives

Aim

This study is aimed at understanding the relationship between the processing of FFB, thermal conversion of FFB solid wastes, and the utilisation of thermal residue of EFB, MF, and PKS for soil improvement and cassava yield. It is hypothesized that the co-utilisation of EFB, MF, and PKS will increase the value of FFB solid wastes in terms of energy and the resultant ash on soil.

Objectives

A number of objectives have been established in order to achieve the stated aim above.

Objective 1. To assess the literature for a critical review of the prospects and challenges of the co-firing of the FFB solid wastes and the utilisation as soil ameliorants.

Objective 2. To evaluate the difference between industrial, small scale, and traditional routes of processing the FFB for an increased utilisation of the solid wastes for energy purposes.

Objective 3. To evaluate the effects of the co-firing on the thermal behaviour of the EFB, MF and PKS especially on the properties of the ash generated.

Objective 4. To assess the effects of ash from FFB solid wastes on improvement of selected soil properties and cassava yield.

The schematic representation of the project and the interconnections of the objectives is as shown in Figure 1-2.

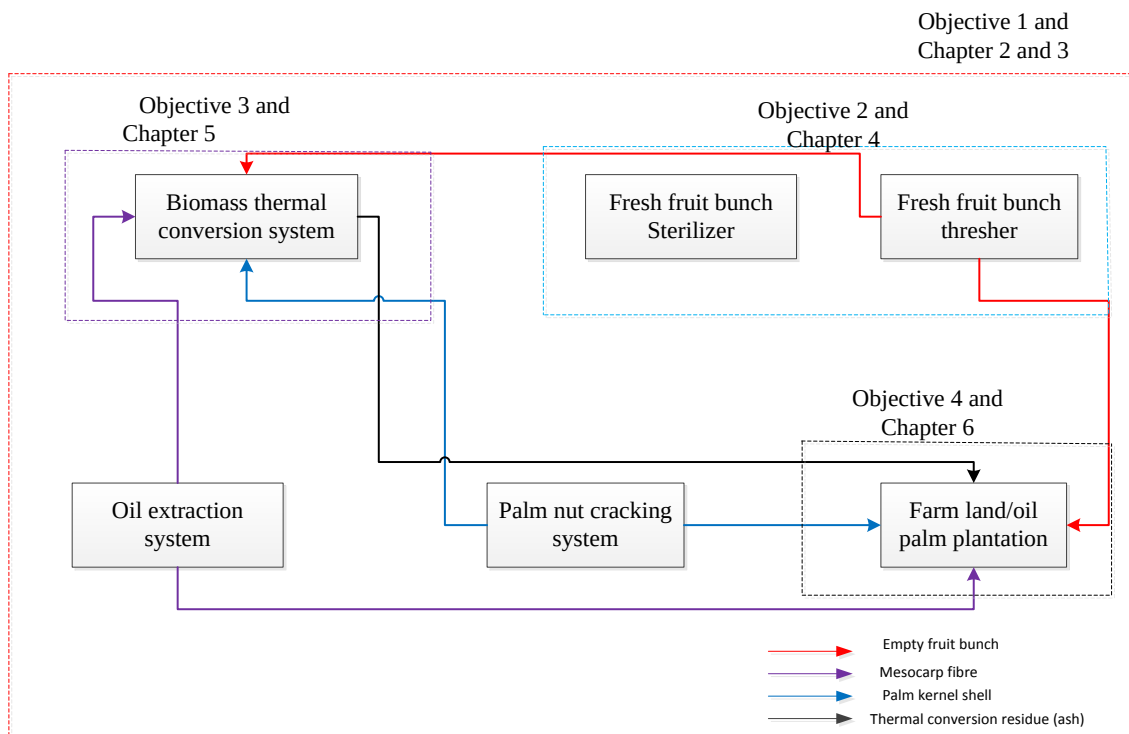


Figure 1-2 Schematic representation of the project and the interconnections of the objectives.

1.4 Thesis plan

The thesis is presented as journal papers in series of chapters. The primary author is Kelechi E. Anyaoha and each paper edited by Dr Ruben Sakrabani, Dr Kumar Patchigolla, and Prof. Abdul Mouazen (formally of Cranfield University, United Kingdom but now at Ghent University, Belgium). All experimental work was designed and implemented by Kelechi E. Anyaoha. The field trial using ash received assistance from Imo State Polytechnic Umuagwo, Imo State Nigeria where the field trial was located. The FFB solid wastes were sourced from Risonpalm (Siat Nig. Ltd), Rivers State and Ohaji, Imo State while the ash was collected from Risonpalm (Siat Nig. Ltd), Rivers State.

A literature review on the prospects and challenges of the oil palm FFB wastes as soil ameliorants was undertaken. Palm oil mills generate FFB wastes that are more than enough for internal use for both energy requirement and agronomic purposes. The availability of the wastes provides opportunities to fully valorise the wastes to meet soil and crop demands. This provided an insight into the widely-reported processes of the utilisation of FFB solid wastes including pyrolysis, gasification, combustion, and composting, which are processes that can enhance the value of EFB, MF, and PKS. These processes lead to valuable resources for soil use, which include biochar, ash, and compost. Although, EFB is used as mulch in most mills, it is only a means of disposal due to the inability of the mills to utilise it as fuel in the same as MF and PKS. The review provides evidence on the various processes leading to the valorisation of FFB wastes as resources for soil amelioration. Chapter 2 Paper 1: The paper “Critical Evaluation of Oil Palm Fresh Fruit Bunch Solid Wastes as Soil Amendments: Prospects and Challenges” by Kelechi E. Anyaoha, Ruben Sakrabani, Kumar Patchigolla, Abdul M. Mouazen has been submitted to *Resources, Conservation and Recycling*.

In line with the first review on valorising FFB as soil ameliorants, a second literature review was completed on the energy potentials of FFB wastes

especially with references to the co-firing of EFB, MF, and PKS in existing facilities. The chapter highlighted the available opportunities in the co-pyrolysis, co-gasification, and co-combustion of EFB, MF and PKS, respectively. This provides the background for the study on co-gasification and the use of the ash generated in line with outcomes of Chapter 2. Chapter 3 Paper 2: The paper “Critical evaluation of co-firing oil palm fresh fruit bunch solid biomass” by Kelechi E. Anyaoha, Kumar Patchigolla, Ruben Sakrabani, and Abdul M. Mouazen will be submitted to *Biomass and Bioenergy*.

The outcomes of chapter 2 and 3 led to an investigation into the challenges leading to the poor utilisation of FFB wastes. The difference between the three different processing routes of FFB in Nigeria were compared with regard to the losses associated with each. This led to a further insight on the loss of MF and PKS during the processing of FFB and the poor quality of EFB as an energy source. The biggest challenge in the use of EFB together with MF and PKS in the co-firing (Chapter 3) is due to the relative low bulk density, large particle size and high moisture content of EFB. Chapter 4 Paper 3 – published: Kelechi E. Anyaoha, Ruben Sakrabani, Kumar Patchigolla and Abdul M. Mouazen. Evaluating oil palm fresh fruit bunch processing in Nigeria (2018), *Waste Management & Research*, 0(0), 1–11.

The co-gasification of EFB, MF, and PKS mixtures were carried out and the effects on gasification parameters including carbon conversion efficiency, higher and lower heating values of the resultant syngas and residues’ properties and yield were investigated in Chapter 5. This provided evidence on the benefits of the co-firing and its effects on residue yield and properties, which was informed by the outcomes of Chapter 2, 3 and 4. Chapter 5 Paper 4: The paper “Co-gasification of Nigerian biomass in a pilot scale downdraft gasifier” by Kelechi E. Anyaoha, Ruben Sakrabani, Kumar Patchigolla and Abdul M. Mouazen will be submitted to the *Transactions of the ASABE (American Society of Agricultural and Biological Engineers)*.

The effects of ash from different sources on soil properties and on cassava yield were investigated in Chapter 6. The properties of ash from the co-firing of the

EFB, MF and PKS were compared with ash from the co-firing of MF and PKS. This demonstrates the effects of the co-firing of the EFB, MF, and PKS on the ash qualities, which is evident by the improvement on soil properties and cassava yield. Chapter 6 Paper 5: The paper “Variations in ash properties affecting soil and cassava yield in south East Nigeria” by Kelechi E. Anyaoha, Kumar Patchigolla, Ruben Sakrabani, and Abdul M. Mouazen will be submitted to *Soil Science Society of America Journal*.

The implementation of the overall work was discussed under Chapter 7 (Integrated discussion) by interconnecting the outcomes of the work.

Finally, the key conclusions and recommendations on the utilisation of FFB solid wastes were presented in Chapter 8. Table 1-2 is the summary of the thesis plan.

Table 1-2 Thesis Structure

Chapter	Objective	Title	Journal	Status
1		Introduction	-	-
2	1	Critical evaluation of oil palm fresh fruit bunch solid wastes as soil amendments: prospects and challenges	Resources, Conservation and Recycling	Submitted
3	1	Critical evaluation of co-firing oil palm fresh fruit bunch solid biomass	Biomass and Bioenergy	Completed
4	2	Evaluating oil palm fresh fruit bunch processing in Nigeria	Waste Management and Research	<i>Waste Management & Research</i> , 0(0), 1–11.
5	3	Co-gasification of Nigerian biomass in a pilot scale downdraft	Transactions of the ASABE	Completed

		gasifier		
6	4	Variations in ash properties affecting soil and cassava yield in south East Nigeria	Soil Science Society of America Journal	Completed
7	1,2,3,4	Integrated discussion: fresh fruit bunch processing, thermal conversion and utilisation nexus	--	--
8	--	Conclusions and Future Work	--	--

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2 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. The disposal of the 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 the 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 EFB, MF, and PKS. 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, EFB compost and ash led to decrease in growth and performance of okra. Therefore, the use of appropriate conversion technology for FFB solid wastes as soil ameliorants can significantly improve crop yield and soil properties, reduce environmental pollution, and more importantly increase income of oil mill processors and savings for farmers.

Keywords: Empty fruit bunch, Palm kernel shell, Mesocarp fibre, Ash, Soil

2.1 Introduction

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

The African oil palm (*Elaeis guineensis*) is believed to originate from West Africa and today is widely grown in most parts of West and Central Africa, Southeast Asia, and South America. The oil palm is a single stemmed tree and can grow to height of more than 30 metres (Jagustyn et al., 2013; Ibitoye and Onje, 2013). The improved breed of the oil palm starts to bear fruits after three years, while the semi-wild found in most parts of Africa can take more than 10

years. The oil palm produces fruits in bunches and can be harvested all year round although peak harvesting period occurs between November and June. The fruit bunch can weigh up to 25 kg and contain as much as 1000 fruits (Jagustyn et al., 2013; Ibitoye and Onje, 2013). The oil palm tree is the major source of plant oil in the tropical region. Palm oil has remained a major foreign exchange earner for many countries and is a source of employment for millions of people especially in West Africa and Southeast Asia. Palm oil is produced by processing the oil palm fresh fruit bunch (FFB), which leads to the generation of FFB solid wastes. Notable FFB solid wastes are the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS). The major producers of palm oil are Indonesia, Malaysia, Thailand, Colombia and Nigeria according to Index mundi (2017), contributing 92 % of global production (Figure 2-1). An estimated 1.65 million hectares of the oil palm is spread over Nigeria (Olagunju, 2008), while there are over 4 million and 7 million hectares of the oil palm in Malaysia and Indonesia, respectively (Sulaiman et al., 2011). In 2014, the global palm oil production was 57 million tonnes (FAOSTAT, 2017). The total FFB solid wastes was estimated at 75 million tonnes based on 1.3 kg of FFB solid wastes per 1 kg of palm oil produced (Sulaiman et al., 2011). The figure of 75 million tonnes given above is equivalent to 23 million tonnes of EFB, 21 million tonnes of MF, and 7.5 million tonnes of PKS if 30.6, 28.1, and 10 % for EFB, MF, and PKS, respectively are considered as fractions per FFB processed according to Ohimain et al. (2013). The solid waste streams of the FFB processing industry include EFB, MF, PKS, and ash (Figure 2-2). The liquid waste produced is palm oil mill effluent (POME). The other residues and/by-products processed from FFB solid wastes are in the form of biochar, and compost. The FFB solid wastes are used as fuel in palm oil mills to generate steam, which enables the palm oil mills to be self-sufficient in energy (Yusoff, 2006); however, more of the wastes are generated than required in the palm oil mills. Therefore, proper utilisation of FFB wastes remains a challenge for palm oil millers and local authorities.

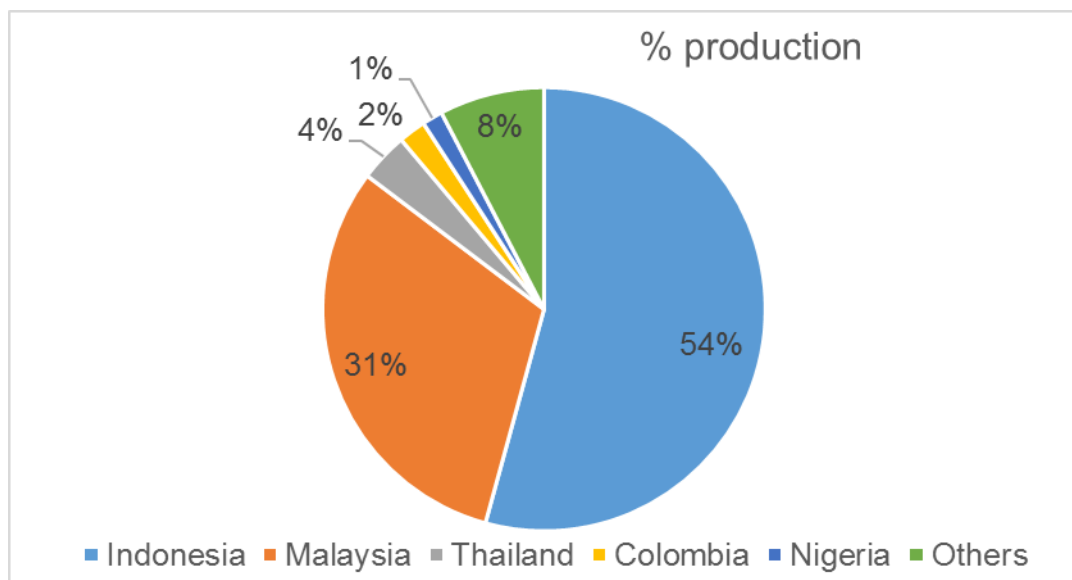


Figure 2-1 Global percentage of palm oil production (Source: Index Mundi, 2017).

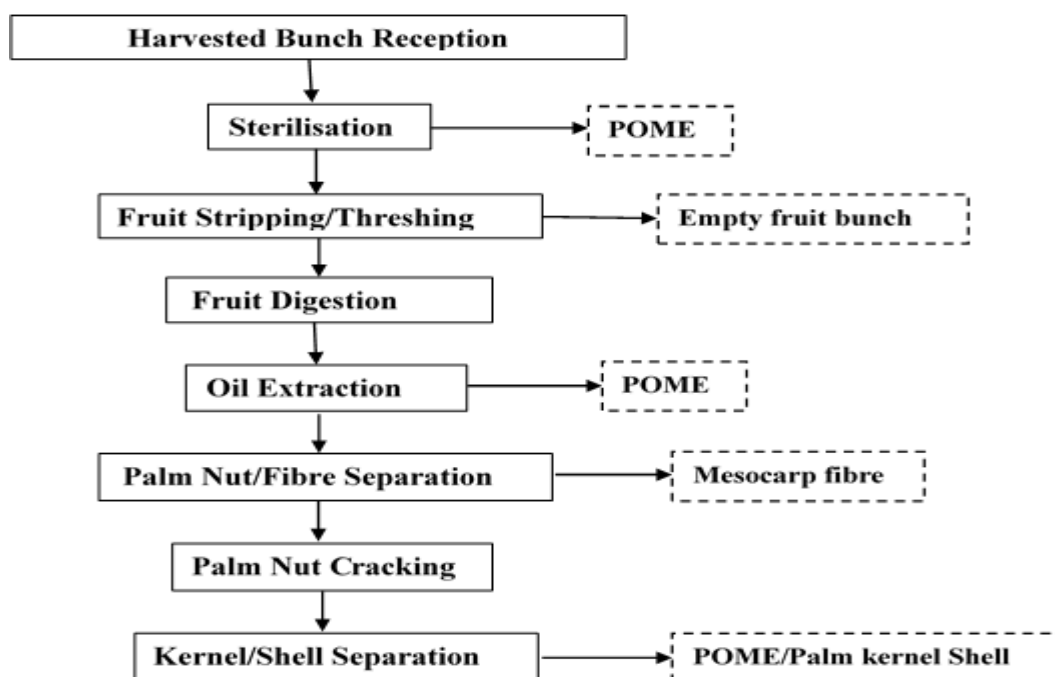


Figure 2-2 Flow chart of fresh fruit bunch processing showing points of generation of wastes. Solid boxes are the process, while dashed boxes represent wastes. POME - palm oil mill effluent.

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

2.2 Fresh fruit bunch solid waste streams

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

Table 2-1 Proximate and ultimate analyses and heating values of empty fruit bunch from literature and those analysed according to British Standards Institute (2011) from the materials sourced from a mill in South Eastern Nigeria.

Analysis	Our study		Literature	References
	ar	db	db	
Proximate (wt.%)				
Volatile matter	73.70	86.10	67.59 – 83.86	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Fixed carbon	7.50	8.80	8.36 – 21.80	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Moisture content	14.40	-	5.18 – 8.31	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Ash	4.40	5.10	3.45 - 7.54	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Ultimate (%)				
Carbon	37.50	43.80	43.52 – 49.07	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Hydrogen	5.00	5.80	5.72 - 6.48	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Nitrogen	0.40	0.50	0.25 – 1.65	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Sulphur	0.10	0.10	0.04 - 1.06	Mohammed et al. (2012); Idris et al. (2015); Omar et al. (2011);

Oxygen*	38.00	44.40	38.29 – 48.9	Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013) Omar et al. (2011); Idris et al. (2015); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011); Lahijani et al. (2013)
Lignocellulose (wt.%)				
Cellulose	-	-	13.75 – 59.70	Mohammed et al. (2012); Piarpuzán et al. (2011); Idris et al. (2015); Omar et al. (2011); Sulaiman and Abdullah (2011)
Hemicellulose	-	-	12.79 – 22.1 0	Mohammed et al. (2012); Idris et al. (2015); Piarpuzán et al. (2011); Omar et al. (2011); Sulaiman and Abdullah (2011)
Lignin	-	-	7.79 – 30.45	Mohammed et al. (2012); Idris et al. (2015); Piarpuzán et al. (2011); Omar et al. (2011); Sulaiman and Abdullah (2011)
HHV (kJ/kg)	15900	18580	15220 – 19350	Mohammed et al. (2012); Idris et al. (2015); Lahijani and Zainal (2011); Sulaiman and Abdullah (2011)
LHV (kJ/kg)	14500	17470	-	
Bulk density (kg/m³)			110	Sung et al. (2010)

All in wt.% except where it is stated otherwise, ar – as received, db – dry basis, HHV – high heating value, LHV – low heating value, *by difference

Table 2-2 Proximate and ultimate analyses, and heating values of mesocarp fibre from literature and those analysed according to British Standards Institute (2011) from the materials sourced from a mill in South Eastern Nigeria.

Analysis	Our study		Literature	References
	ar	db	db	
Proximate (wt.%)				
Volatile matter	75.9	86.4	67 – 79	Khanday et al. (2016); Wilson et al. (2011)
Fixed carbon	7.1	8.1	9.3 – 28	Khanday et al. (2016); Wilson et al. (2011)
Moisture content	12.1	-	4.98 – 5	Khanday et al. (2016); Wilson et al. (2011)
Ash	4.8	5.5	1 - 11.8	Khanday et al. (2016); Wilson et al. (2011))
Ultimate (%)				
Carbon	45.8	52.1	30.02 - 52.2	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)
Hydrogen	6.3	7.2	3.81 – 11	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)
Nitrogen	0.9	1	0.7 – 1	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)
Sulphur	0.2	0.2	0.07 – 1	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)
Oxygen**	29.5	33.6	23.35 – 42	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)

Chlorine	0.33	0.38	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)	19480	22170	19690 - 21980	Wilson et al. (2011); Harimi et al. (2005); Khanday et al. (2016)
LHV (kJ/kg)	17850	20840	-	

All in wt.% except where it is stated otherwise. ar – as received, db – dry basis, HHV – high heating value, LHV – low heating value, *by difference

Table 2-3 Proximate and ultimate analyses, heating values of palm kernel shell from literature and those analysed according to British Standards Institute (2011) from the materials sourced from a mill in South Eastern Nigeria.

Analysis	Our study		Literature	
	ar	db	db	References
Proximate (wt.%)				
Volatile matter	79.6	90.4	53.38 – 77.5	Jamaluddin et al. (2013); Zainal et al. (2016); Wilson et al. (2011)
Fixed carbon	7	7.9	18.84 – 20.3	Zainal et al. (2016); Jamaluddin et al. (2013); Wilson et al. (2011)
Moisture content	12	-	8.4 – 9.55	Zainal et al., (2016; Wilson et al., (2011)
Ash	1.5	1.7	0.87 - 4.6	Zainal et al. (2016); Jamaluddin et al. (2013); Wilson et al. (2011)
Ultimate (%)				
Carbon	46	52.3	43.8– 60.9	Zainal et al. (2016); Wilson et al. (2011); Harimi et al. (2005)
Hydrogen	5.1	5.8	5.27 – 12.76	Zainal et al. (2016); Wilson et al. (2011); Harimi et al. (2005)
Nitrogen	0.4	0.4	0.36 – 0.66	Zainal et al. (2016); Wilson et al. (2011); Harimi et al. (2005)
Sulphur	0.02	0.02	0.03 – 0.19	Zainal et al. (2016); Wilson et al. (2011); Harimi et al. (2005)
Oxygen*	35	39.8	31.18 - 37.7	Wilson et al. (2011); Harimi et al. (2005)
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)	18710	21260	17930 – 20520	Zainal et al. (2016; Wilson et al. (2011); Harimi et al. (2005)
LHV (kJ/kg)	17340	19980	-	
Bulk density (kg/m³)			780	Arzola et al. (2012)

All in wt.% except where it is stated otherwise. ar – as received, db – dry basis, HHV – high heating value, LHV – low heating value, *by difference

The EFB is generated when the fruits are removed from the FFB. It can appear in different forms depending on how the FFB is processed, which differs particularly in Nigeria with the generation of empty fruit spikelets (EFS), and bunch stalk (BS) separately by the subsistence (traditional processing) palm oil millers. The chaff is the additional part of the EFB. The chaff is found at the base where each fruit is attached to the spikelet and tends to separate itself from the spikelet when dry. The chaff comprises of about 0.9 – 2.4 % of FFB (Ohimain et al., 2013). However, in most cases the chaff is attached to the EFB or EFS, and therefore is considered as part of the EFB. Among the other two solid wastes from FFB processing, EFB has the lowest value of lignin content (Sulaiman and Abdullah, 2011; Idris et al., 2010). The EFB is generated at the palm oil mills with very high moisture content of up to 60 % (Tabi et al., 2008; Yusoff, 2006). The high moisture content of EFB is due to sterilisation of the material. Relative to MF, and PKS, EFB has a very low bulk density, which makes its transportation difficult (Tables 2-1, 2-2 and 2-3, respectively).

The MF or palm press fibre results from the oil bearing mesocarp after extraction of oil and drying of the pulp. The oil is extracted by washing the pulp with steam or by pressing. The MF dries out quickly and can be fed into the boilers soon after generation. The MF makes up about 14 – 28.1 % of FFB (Husain et al., 2002; Omar et al., 2011; Sulaiman and Abdullah, 2011; Ohimain et al., 2013).

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

The EFB is generated at a higher volume. The availability of MF and PKS as better biomass fuels makes the application of EFB to the oil palm plantations the best option. The BS (82.6 %) with its higher moisture content than the EFS (57.5 %) according to Omar et al. (2011) limits the use of EFB as fuel. The chaff is used as both fuel and manure (Ohimain et al. 2013).

The MF is preferably used as fuel in palm oil mills. The ash generated after its combustion is a source of minerals including potassium, calcium and magnesium for plants and soil. The MF is used in soil stabilisation, compaction, for landscaping and horticulture (Ohimain et al., 2013). Since MF is used more consistently as a fuel, combustion is the widely-used conversion technology. When MF used in landscaping, horticulture and soil stabilisation, it does not require further treatment. During peak production periods in some palm oil mills, there is usually more MF available than required as fuel, dumping the waste in the plantation becomes the only option especially with the lack of capacity to export the heat and electricity to local areas.

The palm kernel shell (PKS) is used locally in Nigeria as a cooking fuel, on local roads or open premises of residential houses and in oil mill plantations. When used on roads and premises of residential houses, it presents a cost-effective means of soil erosion prevention. In palm oil mills, the shells are used as a combustion fuel resulting in the production of ash. However, Okoroigwe et al. (2014) reported that during combustion, the PKS generate excess smoke (due to poor combustion) especially when used without other fuels, hence the use of MF in combination with PKS in the palm oil mills.

The Conversion of the FFB solid waste streams into forms ready for use as soil ameliorants is as important as the availability of the wastes. The other than direct application, pyrolysis, gasification, combustion, and composting are well-researched technologies of valorising FFB solid wastes. These technologies lead to the production of ash, biochar, and compost, which are important soil amendments that will be discussed in the following sections.

2.2.1 Ash

In palm oil mills, ash is generated in the form of fly ash, bottom ash, and slag when FFB solid wastes are combusted. The estimated global production of 57 million tonnes in 2014, EFB ash, MF ash, and PKS ash were 1.2 million tonnes, 1.1 million tonnes, and 0.1 million tonnes, respectively. These estimates are based on the ash contents of EFB, MF, and PKS dry basis of 5.1, 5.5, and 1.7

wt.%, respectively as determined by the authors (British Standards Institute, (2011)). A significant difference between the ash from the three solid biomass is the higher content of alkali found in EFB (Abdullah and Sulaiman, 2013). Ash has been found to be very useful in many ways but the specific increase in its agricultural use has become a special interest due to the high nutrient content for soil amelioration and crop improvement.

Gasification and combustion are important thermal conversion processes leading to the generation of ash as residue. Gasification is a partial oxidation process that is used to produce fuel gas (Puig-Arnavat et al., 2010). According to Esfahani et al. (2012), the fuel gas yield depends on feedstock origin, gasifier design, operating temperature, static bed design, fluidizing velocity, equivalence ratio and gasifying agent. Ogi et al. (2013) investigated the gasification of EFB using steam (H_2O) and the combination of steam and oxygen as gasifying agents and demonstrated that the gasification rate increased up to 90 % with the addition of oxygen to steam.

Combustion is considered to be the most important means of using biomass to produce energy globally. Combustion occurs in four stages: drying, devolatilisation, and char combustion (Venturini et al., 2010; Werther et al., 2000; Williams et al., 2001; Zhou et al., 2005). Most palm oil mills rely on MF and PKS for heat and power generation, and therefore, the production of ash is an integral part of FFB processing and valorisation of the wastes for soil use. Idris et al. (2012) investigated the combustion of EFB, MF, and PKS via thermogravimetric analysis (TGA) with the emphasis on ignition temperature of the fuels. Parshetti et al. (2014) carried out TGA–FTIR investigation of combustion characteristics of hydrothermally carbonised EFB and concluded that the hydrothermally carbonised EFB produced better combustion characteristics than raw EFB because of the increased carbon content.

Most investigations on gasification (Ogi et al., 2013), and combustion (Parshetti et al., 2014 and Idris et al., 2012) focused on the fuel value of the FFB solid wastes with limited consideration on optimizing the residue yield for agricultural purposes (for example soil amelioration, and consequently crop growth and

yield), even though the residue is an important part of the processes and can affect the overall performance of the systems.

2.2.2 Biochar

Biochar is produced during pyrolysis after the moisture and volatiles have been taken out at an elevated temperature. The mineral components retained in biochar during pyrolysis makes it a valuable soil amendment (Lee et al., 2017; Mašek et al., 2010; Xu et al., 2017;). Zhao et al. (2013) reported that the biochar surface area, its carbon recalcitrance, and high nutrient content determine its application.

Biochar remains an important output of pyrolysis representing up to 35 % of PKS (palm shell), 29 % EFB, and 30 % MF yields (Abnisa et al., 2013) of the wastes under pyrolysis. Expectedly, the highest biochar yield of EFB was recorded at the pyrolysis temperature of 300 °C and the lowest at 700 °C (Sukiran et al., 2011) similar to Claoston et al. (2014) of 38 % at 350 °C and 21 % at 650 °C.

Biochar prevents water contamination and soil erosion, and by absorbing moisture and nutrients increases the ability of the soil to retain the moisture and nutrient (Abnisa et al., 2013). Biochar could ameliorate soil quality, reduce fertiliser consumption, and sequester carbon (Lee et al., 2013). Surface area influences ability of biochar to absorb and retain nutrient and moisture and therefore are important biochar parameters for soil amelioration. The surface area of the biochar is measured by the Brunauer–Emmett–Teller (BET). Optimizing the pyrolysis parameters is also an important factor in terms of producing the best quality of biochar to absorb moisture and nutrients. Temperature and ash content have been reported to influence BET surface area (Claoston et al., 2014; Nam et al., 2018; Shariff et al., 2014). Nam et al. (2018) reported BET surface area for PKS of 100 m²/g at 550 °C, 155 m²/g at 650 °C, and 270 m²/g at 750 °C. The temperature of 650 °C led to the highest BET surface area of 28 m²/g compared to temperatures of 500 °C (15 m²/g) and 350 °C (12 m²/g) for EFB of <2 mm with the operation lasting for 2 h (Claoston

et al., 2014). Other reports on BET surface area include 191 m²/g at 500 °C for PKS (Lee et al., 2017), 2.71 m²/g at 350 – 450 °C for EFB (Harsono et al., 2013), 0.13 m²/g at 550 °C for EFB (Shariff et al., 2014) and 12.2 m²/g at 300 – 350 °C for EFB (Abdulrazzaq et al., 2015).

Idris et al. (2014) reported 210, 186, and 145 % more phosphorus, potassium, and calcium in EFB biochar than raw EFB, respectively making biochar a more valuable soil amendment. Similarly, potassium increased with the temperature (4 wt.% at 350 °C and 7 wt.% 650 °C) (Claoston et al., 2014). Compare to wood bark (4736 ppmw) and paddy straw (1956 ppmw), Lee et al. (2013) demonstrated that PKS biochar (21,380 ppmw) contains higher concentration of iron and tends to be more acidic with pH of 6.9 compared to 9.6 and 10.5 of wood bark and paddy straw, respectively. The low pH was attributed to lower alkali and alkali earth metals in PKS. Kabir et al. (2017) demonstrated that MF biochar contains significantly higher ash content (27%) than that of palm frond (4%), while the potassium and calcium contents of MF are 22 % and 9 % compared to that of palm frond of 46 % and 16 %, respectively. The pyrolysis was carried out in a slow heating bed-reactor of temperature of 550 °C, heating rate of 10 °C/min, and nitrogen flow rate of 200 ml/min. Conversely, the potassium and calcium contents of PKS biochar were 11050 ppm and 52500 ppm, respectively (Kim et al., 2010), while Bazargan et al. (2014) reported values of 29.8 % and 41.4 % for potassium and calcium, respectively.

Mašek et al. (2010) defined two biochar fractions as stable and non-stable fractions, which differentiate how long the biochar will sequester and demonstrated that the yield of stable fraction of biochar is not dependent on pyrolysis temperature. The biochar adds to the carbon content of the soil and suppresses the release of greenhouse gases from the soil. Biochar has a higher calorific value than raw fuel (Bazargan et al., 2014). For example, raw MF and biochar from the MF pyrolysis have calorific values of 18760, and 23540 kJ/kg, respectively (Hooi et al., 2009). Harsono et al. (2013) investigated energy balances, greenhouse gas emissions and economics of biochar production and demonstrated that the production of biochar from slow pyrolysis of EFB is

economically feasible and technically viable. Xu et al. (2017) reported that the properties of biochar are very important in its effectiveness. The biochar is therefore a valuable fuel, which will lead to ash production either through gasification or combustion (Kimble et al., 2008). Table 2-4 is characteristics of biochar from EFB, MF, and PKS (Abnisa et al., 2013; Nam et al. (2018).

2.2.3 Compost

Compost is produced from the decomposition of organic matter through the process of composting. The objectives of composting are to produce compost with nutrient qualities better than the original materials, and to make wastes less harmful. Although, compositing requires more space and time, it results in a more valuable product. Important considerations in composting are degradation rate and the quality of the final compost (Rupani et al., 2010). The composting efficiency is measured by the carbon-nitrogen (C/N) ratio of the compost. The C/N ratio is an important indicator in composting with 30:1 considered as an optimum value, and can be achieved by the addition of other materials (Rupani et al., 2010). The process control parameters in composting are initial C/N ratio of the composting material, amount of bulking agent for controlling porosity, the pile size, moisture content and turning frequency (Yeoh et al., 2011).

Vermicomposting is the use of different species of worms in composting operation to produce a nutrient rich material known as vermicompost suitable as soil amendment. Rupani et al. (2010) reported that vermicompost is more fragmented and porous material, with less contaminants and high nutrient content from the raw material. An important advantage of vermicomposting technology over other technologies is the production of earthworm biomass, which is a good source of protein for animal feeds (Rupani et al., 2010). Sabrina et al. (2009) reported that *Eisenia fetida*, *Eisenia andrei*, *Lumbricus rubellus* or *Peryonix excavates* are mostly used in commercial vermicomposting. The earthworms prepare the biomass for microbial activities by fragmentation and conditioning, which leads to reduction in the C/N ratio, and increased surface area (Singh et al., 2011).

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

Bakar et al. (2011) stated that composting offers an alternative of using EFB to either fuel or mulch, but it brings additional operational costs and may require advance technology for higher efficiency and quality. Siddiquee et al. (2017) used two *Trichoderma* strains (strain SICCI and strain 11B) in composting EFB and demonstrated variations in the properties of the composts produced by the fungi and on their effects on soil properties. The compost from strain SICCI led to the highest potassium content of 6.7 % after 8 weeks followed by that of strain 11B (5.9 %) and the control (soil without compost) had the lowest potassium content of 5.8 %. Carron et al. (2015) investigated the effects of decomposing EFB on soil properties at different time intervals. Expectedly, Carron et al. (2015) demonstrated that the soil total nitrogen, phosphorus, potassium, magnesium, calcium and organic carbon of the decomposing EFB decreased with time with highest values recorded after 1 month, and the values were higher than the original EFB. Sabrina et al. (2009) demonstrated that EFB compost is toxic to *Pontoscolex corethrurus*, and *Amyntas rodericensis*, since only *Eisenia fetida* survived in EFB compost during vermincomposting operation using EFB with cow dung as supplement. Therefore, the use of *Pontoscolex corethrurus*, and *Amyntas rodericensis* in vermicomposting will be less effective compared to other worms. Sabrina et al. (2009) reported that particle size affects the nutrient content of EFB vermicompost. EFB of particle size more than 0.05 m led to significantly higher ($p < 0.05$) C/N ratio, potassium, and magnesium than fine particle size of less than 0.002 m. The pH of the coarse EFB vermicompost was also significantly higher ($p < 0.05$) than the fine particles.

However, the total nitrogen content of the EFB fine particles was significantly higher ($p < 0.05$) than the coarse particles (1.8 and 1.6 %, respectively).

Table 2-5 shows the characteristics of vermicomposted EFB, non-vermicomposted (naturally composted) EFB, and non-composted (fresh) EFB treated with gafsa rock phosphate (Sabrina et al., 2011). The nutrient contents of the EFB increased in the order of vermicompost > non-vermicompost > fresh (Table 2-5). This could be attributed to concentration of nutrients due to reduction in volume, the availability of nutrients due to breakdown of the EFB by the worms in the vermicomposting and composting processes. Lim et al. (2015) demonstrated the effects of *Eudrilus eugeniae* (earthworm) in vermicomposting of EFB supplemented with cow dung. EFB vermicomposted without cow dung did not encourage the productivity of the earthworms. This was because of high C/N ratio. EFB and cow dung of the ratio 2:1 showed the best quality vermicompost with higher increases in calcium (373 %), phosphorus (391 %), potassium (154 %), and magnesium (371 %), which was a demonstration of the lowest C/N ratio it had. Addition of supplements to enhance the C/N in EFB composting is also called co-composting. Decanter cake slurry can be collected separately from POME in palm oil mills. Yahya et al. (2010) reported that decanter cake slurry enhanced the formation of POME + EFB compost. The lower C/N ratio of 18.65 against 28.96 from compost of no decanter cake slurry indicated mature compost. Nutongkaew et al. (2014) obtained 3.26 wt.% N, 0.9 wt.% P and 2.0 wt.% K when POME was co-composted with EFB and decanter cake. Notably, POME, EFB, FFB wastes ash, and decanter cake slurry are oil mill wastes that can be co-composted, or one or more added to aid the process (especially ash and POME to EFB) with the potentials of increasing value of the products as soil amendments. Another important aspect of EFB valorisation is the separation into its component parts of EFS and BS. Zaharah and Lim (2000) reported that BS decomposed faster than EFS, which was because of relatively lower C/N ratio of 73.2 and 96.2 and lignin of 28.1 % and 29.1 %, respectively.

Table 2-4 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

*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, ***by difference, HHV – high heating value, MF – mesocarp fibre, PKS – palm kernel shell, EFB – empty fruit bunch

Table 2-5 The characteristics of vermicomposted, non-vermicomposted (naturally composted), and non-composted (fresh) empty fruit bunch treated with Gafsa rock phosphate (Source: Sabrina et al., 2011).

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

Nd - not detected

According to Yeoh et al. (2011) the higher porosity, water holding capacity, and nutrient holding capacity of EFB make it more suitable for composting compared to MF and PKS. However, Nahrul Hayawin et al. (2010) investigated vermicomposting of MF using African Nightcrawler (*Eudrilus euginae*) for 84 days. Expectedly, total phosphorus and total potassium was higher in the MF vermicompost than the original MF. Similarly, total copper, zinc, iron and manganese in the final product (Cu - 5.3, Zn - 5.7, Fe - 6.7, Mn - 25.3 mg/kg) were higher than in the original material (Cu - 2.9, Zn - 4.0, Fe - 1.3, Mn - 18.9 mg/kg). Thambirajah and Kuthubutheen (1989) compared to composting only MF, MF supplemented with poultry deep-litter and urea, and MF supplemented with poultry broiler floor-litter and urea. The authors found that the C/N ratio reduced from 40, 33 and 26 to 26, 17, and 16, respectively after 8 weeks. Rupani et al. (2013) investigated the effects of epigeic earthworms, *Lumbricus rubellus* on vermicomposting of MF treated with POME, cow dung, and lawn clipping for 50 days. There was significant decrease in the C/N ratio due to the addition of lawn clipping, cow dung, and POME at the ratio of 15:15:50, respectively compared to only the MF. Razali et al. (2012) investigated the in-vessel composting of MF with improvement in the C/N ratio from 77:1 to 13.8:1.

There were limited reports on PKS composting; however, the particulate nature of PKS makes it a potential bulking material for EFB, and MF composting.

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

EFB can be used as either fuel, mulch or as industrial material for example Ecomat (mat or carpet compressed from EFB). 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. Apart from moisture conservation, weed suppression, and erosion control effects, the decayed mulching materials increased soil nutrients and therefore increased pineapple yield (personal communication). When EFB is used as fuel by the process of incineration or combustion, or gasification, the ash generated is useful as soil amendment, and to recover degraded soil. When used in pyrolysis, the biochar can be further combusted or used as gasification feedstock or directly used on soil as amendment. In some places, EFB is incinerated as a method of disposal. It is preferably used as mulch and to add 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.

EFB is used as a source of soil nutrient for the nearby oil palm plantations (Yeoh et al., 2011), and as a result increases organic matter content of soil. EFB is usually left to decompose on plantations and orchards helping to return organic matter to soil, control weeds and erosion as well as retain moisture (Figure 2-3). Similarly, until recently excess PKS has been deposited in the farms as a means of disposal in Nigeria. EFB fibre and MF are used in erosion control, soil stabilisation/compaction, landscaping and horticulture, as compost and organic fertiliser (Ohimain et al., 2013 and Embrandiri et al., 2012). The 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). Mulching is used to protect the soil against raindrop impact (increase aggregate stability), runoff erosion and moisture loss, in addition to its impact in controlling weeds. Mulching has significant effects on soil moisture content at field capacity, total porosity, aggregate stability, and organic matter content (Mulumba and Lal, 2008; Jordán et al., 2010).

Sung et al. (2010) used Ecomat and EFB as mulching materials and compared their effects on soil water content, demonstrating the soil mulched with EFB had 27 % more water than the soil mulched with Ecomat, and 38 % more water than the control (without any mulch). The soil under Ecomat mulches had only 8 % more water than bare soil. Sung et al. (2010) concluded that in terms of water conservation, one layer of EFB is equivalent to five layers of Ecomat.

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

Soil nutrient is very essential in plant growth and metabolism. Crop growth and yield depends on equilibrium between nutrient supply from either amendments or soil metabolism, and demand by crops. Local farmers in Nigeria use ash from the combustion of FFB solid wastes as a replacement for lime. Ash can improve soil nutrient quality, act as lime replacement, and stimulate microbial activities

(Awodun et al., 2007). Conversely, Ojeniyi et al. (2010) demonstrated an increase in soil organic matter by 0.16 and 0.06 % more than the control due to the addition of EFB ash on a field experiment at Benin and Ekiadolor in southern Nigeria, respectively. Awodun et al. (2007) reported significant increases in soil organic matter up to 51 %, due to application of EFB ash at levels of 0, 2, 4, 6, and 8 tonnes/ha. Budianta et al. (2010) demonstrated that the application of EFB at the rate of 40 Mg/ha/yr for 2 years increased significantly exchangeable magnesium by 100 % compared to control (without EFB application), which is a positive improvement.



Figure 2-3 Empty fruit bunch and ash dumped into an oil palm plantation. This is the poor practice in Nigeria due to enormous amount of the wastes generated with no other form of disposal.

Rosenani and Hoe (1996) investigated the decomposition of single and double layered EFB and have shown that 71 % of double layered EFB decayed within 15 weeks while 68 % of single layered EFB decayed within the same period. This was attributed to high microbial activity within the double layered. Similarly,

the single layered EFB increased the soil total nitrogen from 0.2 % to 0.3 % while the doubled layered increased to 0.3 %.

When compared to chemical fertiliser, EFB application at the rate of 300 kg/palm/yr significantly increased the soil pH by 2, the total nitrogen content, and cation exchangeable capacity by 5.1 cmol (+)/kg in the 0 – 0.40 m soil layer (Bakar et al., 2011). Budianta et al. (2010) demonstrated that the application of EFB at the rate of 40 Mg/ha/yr for 3 years (pH = 5.85) resulted in a significant difference ($p < 0.05$) in pH at soil depth of 0 – 0.2 m against control (pH = 4.74). The soil pH, exchangeable K, Mg and Ca, organic C, and total N were 0.8, 0.3 cmol (+)/kg, 3.2 cmol (+)/kg, 9.2 cmol (+)/kg, 1.2 %, and 0.2 % more than the control due to the application of EFB at the rate of 37.5 tonnes/ha/yr, respectively (Chiew and Rahman, 2002). Moradi et al. (2012) reported significant effects due to EFB application on soil organic carbon, with 38.1 % higher than that using silt pits and pruned oil palm fronds, and 36.4 % higher than Ecomat at depth of 0 – 0.15 m, and exchangeable magnesium and calcium. The authors reported an increase in soil exchangeable potassium up to 70 % higher than silt pits, pruned oil palm fronds and Ecomat (Moradi et al., 2012).

The high nutrient content in EFB ash has led to much interest in its effects on soil properties (Table 2-6). Awodun et al. (2007) reported an increase in soil nitrogen (48 %), phosphorus (51 %), potassium (61 %), calcium (43 %), magnesium (68 %) due to application of EFB ash with the levels of 0, 2, 4, 6, and 8 tonnes/ha. Some literature reports on properties of EFB ash are shown in Table 2-6. Ojeniyi et al. (2010) investigated the effects of 4 tonnes/ha EFB ash, and 0.3 tonne/ha nitrogen-phosphorus-potassium (NPK) (15-15-15) fertiliser, and their mixture at different levels, and demonstrated that using only the EFB ash at 4 tonnes/ha recorded the highest potassium and pH values in the soil. Similarly, Awodun et al. (2007) reported an increase in soil organic matter due to application of EFB ash as the application level increased from 0, 2, 4, 6, and 8 tonnes/ha. The 8 tonnes/ha EFB treatment recorded the highest organic matter of 3.4 % while control led to the lowest value of 1.8 % at Akure site in

Nigeria. Similar results were obtained for soil exchangeable potassium with the 8 tonnes/ha treatment 0.37 cmol/kg more than the control. Adjei-Nsiah and Obeng (2013) demonstrated that significantly ($p < 0.05$) more soil pH (0.7), available P (6.29 ppm) and exchangeable K (0.34 cmol/kg), Ca (0.76 cmol/kg) and Mg (1.06 cmol/kg) than the control due to the application of 4 tonnes/ha EFB ash. Budianta et al. (2010) reported no significant effect on soil organic carbon, and cation exchangeable capacity, nitrogen and phosphorus at 0 – 0.2 m depth after a year using 40 Mg/ha/yr of EFB.

Table 2-6 Characteristics of empty fruit bunch 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 Carbon	0.55 – 1.92 %	Adjei-Nsiah and Obeng (2013) Gbaraneh and Chu (2016)
	0.17 %	Akanbi et al. (2014)
Total Nitrogen	0.08 - 0.19 %	Adjei-Nsiah and Obeng (2013) Gbaraneh and Chu (2016); Ojeniyi et al. (2009)
	0.02 %	Akanbi et al. (2014)
Total Phosphorus	0.26 - 0.18 %	Gbaraneh and Chu (2016)
Total Potassium	27.10 - 28.30 %	Gbaraneh and Chu (2016)
	2.65	Akanbi et al. (2014)
Total Calcium	6.59 – 8.10 %	Gbaraneh and Chu (2016)
Total Magnesium	3.10 – 3.33 %	Gbaraneh and Chu (2016)
C/N ratio	10.10 -10.90	Gbaraneh and Chu (2016)
Exchangeable Potassium	582.77 cmol/kg	Adjei-Nsiah and Obeng (2013)
Exchangeable Calcium	0.85 - 34.93 cmol/kg	Adjei-Nsiah and Obeng (2013); Akanbi et al. (2014) Ojeniyi et al. (2009)
Exchangeable Magnesium	1.80 - 29.08 cmol/kg	Adjei-Nsiah and Obeng (2013) Akanbi et al. (2014) Ojeniyi et al. (2009)
Available Phosphorus	1.90 (mg/kg)	Ojeniyi et al. (2009)
	0.20 (g/kg)	Akanbi et al. (2014)

2.4 Crop response to fresh fruit bunch waste streams

The availability of nutrients is the major factors affecting crop yield including oil palm. Land slope under intensive rainfall conditions limits crop productivity due to increased loss of nutrient from soil erosion (Moradi et al., 2012). Therefore, mulching has proven to be an effective method of controlling erosion and increasing crop growth and yield. Laying EFB on top of the soil has been an effective means of utilising the waste for crop growth. Moradi et al. (2012) found 0.08 and 0.07 % more oil palm leaf P compared to the control (oil palm fronds) and silt pit after 6 months of application of EFB at the rate of 1000 kg/treatment plot/yr, respectively. Comparing EFB and oil palm fronds, Moradi et al. (2012) reported that EFB decomposed at a faster rate than oil palm fronds and therefore released significantly higher amounts of potassium and calcium after 6 months. The decomposition rate influences nutrient releases and hence crop yield. Chiew and Rahman (2002) reported an increase of the oil palm FFB yield (21, 30, and 34 tonnes/ha/yr), bunch number (990, 1197, and 1256) and average bunch weight yield (21, 25, and 27 kg) due to the control, and the application of 37.5 and 75 tonnes/ha/yr EFB bunch, respectively. Ravooof (1988) demonstrated that EFB single layer mulch can be used to grow sweet potato on sandy soil without fertiliser. Bakar et al. (2011) compared the effects of chemical fertiliser, and EFB at rates of 150, and 300 kg/palm/yr as mulch in the oil palm plantation for 10 years and concluded that there was no significant difference between the application of only the EFB at the rate of 150 kg/palm/yr and chemical fertilizer, however the 300 kg/palm/yr rate was 9 % higher. Similarly, EFB at the rate of 150 kg/palm/yr increased significantly ($p = 0.01$) soil organic carbon in the top soil. According to Sridhar and AdeOluwa (2009) at 6 tonnes/ha EFB can return half the nutrients originally harvested in FFB on decomposition. Chiew and Rahman (2002) reported the application of EFB as mulch in an oil palm plantation of plinthaquic paleudult soil at the levels of 35.5 tonnes/ha/yr in a single layer and 75 tonnes/ha/yr in two layers, which rased the nitrogen content of the oil palm leaf significantly to 2.7 and 2.9 %, respectively while the control was 2.6. The EFB, and MF (especially from the local oil palm FFB processors) attract insects due to the high oil content and

have been used as a biological means of protecting eggplants (*Solanum aethiopicum*), and pepper tree (*Piper guineense*) against other destructive pests (personal communication).

Haya et al. (2017) demonstrated that the potassium contents of orange-fleshed sweet potato storage root increased significantly ($p < 0.05$) due to the application of EFB compost + 30 ppm hexaconazole (growth regulator) by 107 % more than the control. The use of only the EFB compost led to significant increase ($p < 0.05$) in potassium contents of the sweet potato leaf, stem and root by 0.58, 0.68, and 0.37 % more than the control. These were due to the EFB compost providing the soil the ability to retain potassium long enough for the plant to absorb it compared to the control (inorganic fertiliser). However, the use of 100 % EFB compost was found to be responsible to stunted growth in okra (Siddiqui et al. 2009), and a decrease in germination of okra seeds as EFB compost level increased against chicken manure. The EFB compost level of 25, 50, 75 and 100 % resulted in 81.4, 49.72, 48.14 and 9.9 % germination, respectively. From Siddiqui et al. (2009), EFB compost is obviously not suitable for okra growth and productivity. Bakar et al. (2011) reported that 150 kg/palm/yr of EFB could replace chemical fertiliser in terms of FFB yield.

Asiah et al. (2004) demonstrated that EFB could be used as growing medium for hybrid cauliflower plant although, when compared to coconut coir dust resulted in lower total dry matter yield (0.006 kg/plant) and total nitrogen uptake (more than 300 mg N/plant) 42 days after transplanting. Tabi et al. (2008) demonstrated that 100 % EFB as substrate for the cultivation of *pleurotus ostreatus* (mushroom) could not produce *pleurotus ostreatus* fruit bodies, whereas 100 % MF produced 4.6 % biological efficiency (the yield of fresh fruit bodies per 100 g dry substrate (Tabi et al., 2008). The 50 % MF and 50 % rubber tree sawdust produced the highest biological efficiency of 11.3 %, which is the same value produced by 100 % rubber tree sawdust used commercially as substrate for *pleurotus ostreatus* cultivation according to Tabi et al. (2008). Tabi et al. (2008) concluded that the low content of nitrogen in EFB was responsible for the inability of the mycelium to grow. The MF can be used to

grow *pleurotus ostreatus* or in combination with rubber tree sawdust. Hoe (2014) used MF as a growing media for banana tissue culture seedlings and demonstrated that the height of the banana seedling increased significantly (Tukey's HSD 5 %) by 0.0746, 0.1292, and 0.1824 m due to the use of only the MF more than the control (soil) after weeks 5, 6 and 7, respectively.

The essential plant nutrients found in fly ash encourage plant growth and increase crop yield and metabolism (Masto et al., 2013; Gupta et al., 2002). Awodun et al. (2007) reported an increase in maize leaf Ca of up to 13 % due to 6 and 8 tonnes/ha of EFB ash, which was higher than the control when the oil palm bunch (EFB) ash (levels of 0, 2, 4, 6, and 8 tonnes/ha) was applied at two different sites. Awodun et al. (2007) also reported significant increase in maize cob and grain yield except at 8 tonnes/ha of the ash with highest yield at 6 tonnes/ha of 0.053 kg/plant maize cob and 0.046 kg/plant maize grain.

Akanbi et al. (2014) investigated the effects of 1, 2, 3, 4 and 5 tonnes/ha levels of EFB and cocoa pod husk ash, respectively and 10 kg of the NPK (20:10:10) fertiliser on growth and dry matter yield of cocoa (*Theobroma cacao*). The authors demonstrated that EFB ash at the level of 4 tonnes/ha significantly ($p < 0.05$) increased the height and root length of cocoa seedlings more than the NPK (20:10:10) fertiliser by 0.0476 and 0.2 m, respectively. Ojeniyi et al. (2009) investigated the effects of 1.25, 2.50, 3.75, and 5.00 tonnes/ha EFB ash, and 0.6 tonne/ha NPK (15:15:15) fertiliser against no amendment application on cassava performance. The 2.5 tonnes/ha EFB ash led to significant higher ($p < 0.05$) tuber yield of sweet cassava and more than the NPK (15:15:15) fertiliser by 83 %. Gbaraneh and Chu (2016) compared the effects of 10 tonnes/ha EFB ash, 10 tonnes/ha poultry manure, and mixtures of the ash and poultry manure, 0.2 tonne/ha NPK (20:10:10) fertiliser and the mixtures of the amendments on soil nutrient status and performance of okra. All the treatments increased okra pod length, weight and total yield against the control, the 10 tonnes/ha EFB treatment was only greater than the control by 5, 0.0053 kg, and 1.96 tonnes/ha, respectively in the second year. The 5 tonnes/ha EFB ash + 0.1 tonne/ha NPK increased the okra pod length, weight and total yield more than

the 10 tonnes/ha EFB treatment. This is in line with Siddiqui et al. (2009) report on okra performance using EFB compost as stated above. Adjei-Nsiah and Obeng (2013) demonstrated significant increase ($p < 0.05$) in mean leaf phosphorus and potassium of eggplants, okra, and pepper of 0.1, 0.1 and 0.08 % and 0.09, 0.1, 0.08 % more than the control due to the application of 2, 4, and 6 tonnes/ha EFB treatments, respectively.

2.5 Prospects and challenges

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

The combustion or gasification of FFB wastes increases fouling and corrosion of the thermal facilities due to high alkali metals contents in the biomass, which reduces the heat transfer capacity of the heat exchangers while slagging increases cost of maintenance. Haryati et al. (2016) reported that the lower nitrogen content of PKS biochar relative to the feedstock is an added advantage in terms of low level of fuel NO_x during combustion. EFB is either returned to the plantation or incinerated due to the inability of the palm oil mills to utilise it properly. When burnt, it generates undesirable air pollution including release of particulate matter and dark smoke. When it is returned to the plantations, it takes weeks before the heaps are turned leading to poor decomposition and emission of methane. According to Elbersen et al. (2013), poor decomposition of EFB contributes to greenhouse gas emissions by the release of methane and nitrogen oxide up to 0.23 tonne carbon dioxide equivalent per tonne FFB, which can be reduced to 0.05 tonne carbon dioxide equivalent/tonne EFB by a well-

controlled composting facility. Krishnan et al. (2016) supported Elbersen et al. (2013) by demonstrating that EFB and POME co-composting can reduce greenhouse gas emissions by 76 %. This was achieved by avoiding open dumping of EFB and pond treatment of POME. The capture and burning of released biogas from decomposition of EFB in a flare would reduce greenhouse gas emissions by 95 % (Elbersen et al., 2013). Sabrina et al. (2012) demonstrated that extractible phenols from field decomposed EFB decreased with increasing age of the EFB compost. Similar types of phenols were found in fresh field decomposed and composted EFB, which had no harmful effect on earthworm population (Sabrina et al., 2012). Sabrina et al. (2012) concluded that vermicomposting could degrade toxic compounds as no phenols were found in vermicomposted EFB.

The challenges of poor ash management affect humans, animals and plants as well as occupy valuable space. Most palm oil mills dispose the ash from combustion of MF and PKS by returning it to the plantation the same way EFB is disposed. When the fly ash is used as soil amendment, the dust has been reported to stick to the leaves and fruits of vegetables leading to chemical and physical injuries (Gupta et al., 2002). The deposition can reduce or completely prevent transpiration and photosynthesis, as well as affect food quality of the leaves and fruits. According to Gupta et al. (2002) fly ash on leaves can absorb more heat and increase the leaf temperature leading to higher transpiration. Another challenge of applying ash on soil is heavy metal contamination. This could also lead to heavy metal poisoning of the plant roots and shoot (Singh et al., 2008). There are limited reports on the heavy metal contamination of ash from the FFB solid wastes. However, Ohimain et al. (2012) investigated the heavy metal content of POME from different locations and reported wide range in the concentrations of chromium (Cr) (0.6053 – 1.6683 mg/l), copper (Cu) (0.6143 – 1.6093mg/l), and cadmium (Cd) (0.0040 – 0.0231mg/l). This may be due to the different processing equipment and conditions.

Austria, Germany, Denmark, Sweden, and Finland are few of the countries in Europe with regulations/recommendations on the use of ash for agricultural

purposes. The considerations for the regulations include heavy metals and organic compounds contents, and the application per year per hectare (Van Eijk et al., 2012). In Austria, 2 % by weight of ash to the weight of compost material is the maximum allowable biomass ash addition. In Sweden, only biomass ash is allowed for agriculture and forestry applications whereas in Finland there is a distinction between ash used in agriculture, horticulture and landscape (agroash) and that used in forestry (forest ash) (Van Eijk et al., 2012). The use of biomass ash to increase tree growth is not allowed in Finnish rules but it is allowed to maintain forest in Swedish rules. In Finland, Lithuania and Sweden, there are recommendations on the concentrations of calcium, magnesium, potassium and phosphorus to meet the soil requirements. In Denmark no more than 90 kg phosphorus/ha is allowed every three years whereas it is recommended in Canada for the plant available nitrogen, potassium, and phosphorus be determined as a guide on the ash application level (Hanman et al., 2016). There is limited information on regulation of the use of ash from the FFB solid wastes on soil in Nigeria.

The Processing of EFB to enhance its value will generate employment and therefore reduce social unrest in areas where unemployment is a major challenge. This is true with the production of Ecomat from EFB, which is used as a landscaping mulching material in urban area (Sung et al., 2010). Elbersen et al. (2013) reported that the value of the EFB returned to the field was estimated to be up to \$3.3 per tonne due to the benefit from replacing fertiliser, the costs for transport and spreading. However, the economic benefit of using EFB as a fuel for power generation is 3.5 times the benefit of using EFB as a mulch (Elbersen et al., 2013).

The best value from the FFB solid wastes is achievable if a proper waste management system is part of the design of the palm oil mills, or a separate facility designed to match the capacity of the palm oil mills. Figure 2-4 is a flow chart describing the different routes to utilisation of FFB solid waste streams as soil ameliorants, which can be considered in designing palm oil mills. EFB, MF and PKS, and their by-products in different forms can add nutrients to the soil,

used as mulching materials, in erosion control and soil liming, and in carbon sequestration. The biochar generated from pyrolysis can be used in either combustion or gasification, which is potentially effective in reducing environmental challenges of thermal conversion of the raw biomass. Similarly, the ash produced can be used to aid composting. As suggested by the model, the wastes can be used simultaneously or separately. The simultaneous utilisation may provide opportunity for improvements and reduce the needless disposal of any of the wastes.

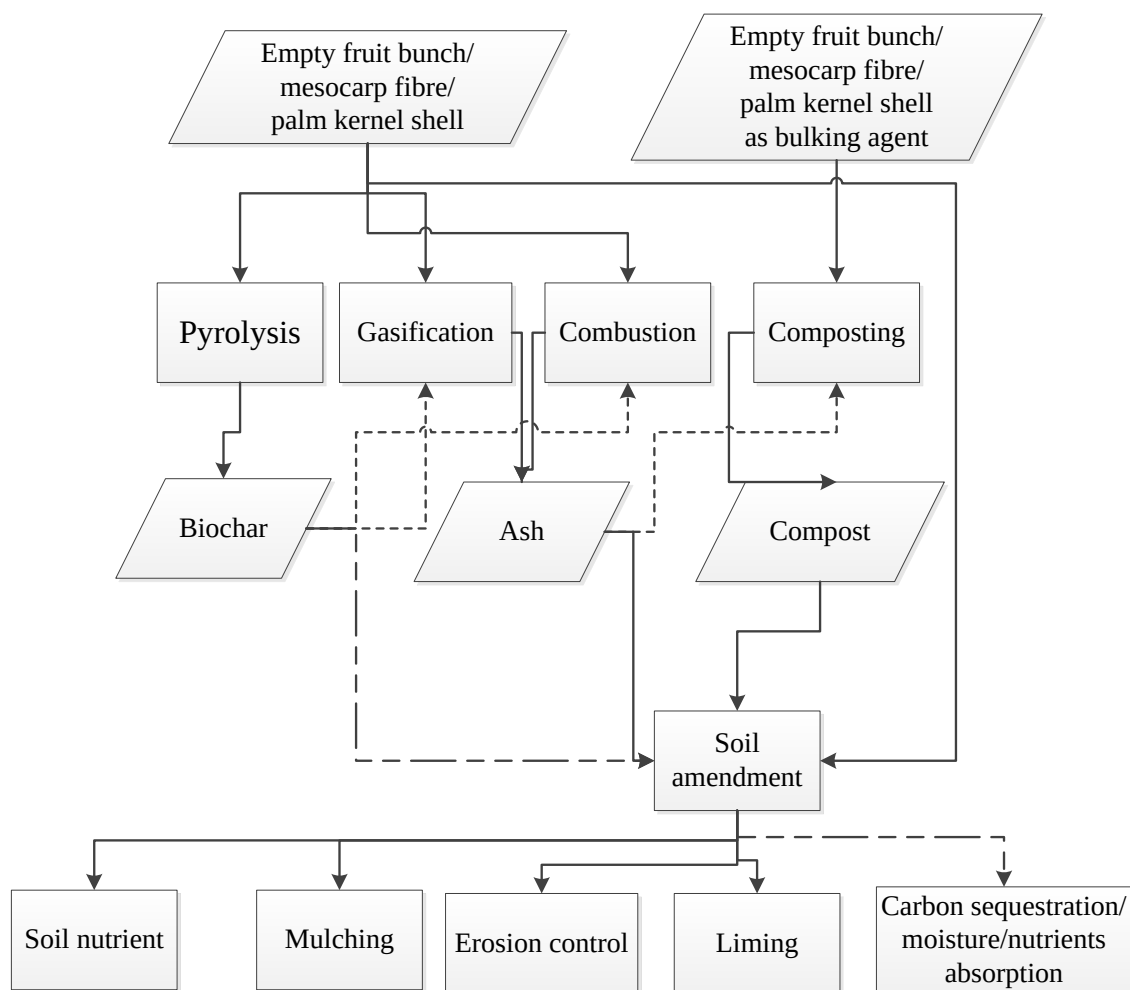


Figure 2-4 Flow chart for fresh fruit bunch solid wastes valorisation as soil ameliorant.

2.6 Conclusions

The EFB, MF, and PKS are used as boiler fuels and the ash generated used as soil amendments. The challenges of the FFB solid wastes use as fuel for the generation of ash and biochar include low bulk density, high moisture content, and high alkali content. Bulk density limits the transportation of the raw biomass especially EFB and their residue to areas in high demand, and any economic benefits accruable. It forces the palm oil mills to deposit the wastes including ash within the palm oil mills, adding pressure to the limited land space and leading to greenhouse gas emissions. These have led to alternatives means of increasing the value of the wastes, which also leads to valuable soil ameliorants. The processes include pyrolysis (biochar), gasification (ash or biochar), combustion (ash), and composting (compost). There is need to include in the design of palm oil mills other facilities to manage the wastes especially EFB (which is almost more than MF, and PKS put together per FFB processed), including composting facilities. A well-balanced utilisation of the FFB solid wastes will reduce the negative impacts of disposal of the wastes, including greenhouse gas emissions, pest breeding, pressure on land resources, and waste of potential soil ameliorants and the attendant economic losses. Co-utilisation (pyrolysis, gasification, combustion, and composting) of the EFB, MF, and PKS provide a suitable option in effective management of the wastes.

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3 Critical evaluation of co-firing oil palm fresh fruit bunch solid biomass

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Abstract

The increasing need for biomass utilisation especially for heat and electricity generation encourages the use of the oil palm fresh fruit bunch (FFB) solid wastes. FFB solid wastes consist of the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS) are generated from processing of the oil palm fruits. Co-combustion of biomass is a sustained tradition in rural areas where different biomass materials are used together for cooking or heating. In most palm oil mills, co-combustion of FFB solid wastes are currently being carried out because of the availability of EFB, MF, and PKS in large quantities. This chapter presents overview of results reported in the literature on pyrolysis, gasification, and combustion of EFB, MF, and PKS. It also presents opportunities in co-pyrolysis, co-gasification, and co-combustion of these fuel mixtures. Some of the benefits of the co-firing of the EFB, MF, and PKS are improvements in fuel gas, bio-oil and biochar yields and qualities, and synergies in reducing tar yield. Therefore, there is need for a sustained research on simultaneous use of EFB, MF, and PKS in pyrolysis, gasification, and combustion with a focus on efficiency of each of the process, on quality and quantity of each of the respective products. More importantly, on how the

challenges including tar formation, agglomeration, and emissions can be controlled through co-firing.

Keywords: Empty fruit bunch, Palm kernel shell, Mesocarp fibre, Co-firing

3.1 Introduction

Energy resources in the world can be divided into fossil fuel (81 %), nuclear fuel (6 %), hydropower (0.5 %), and others (2.3 %) according to Danjuma et al. (2013). Renewable energy accounts for 10 – 20 % of world energy supply (Danjuma et al., 2013). Biomass is an important renewable energy and provides 14 % of the global energy need and 35 % of energy need of developing countries (Demirbas, 2004) and by 2050 these renewables could provide 17 % of electricity in the world (Idris et al., 2010). According to Fuwape and Akindele (1997), only the wood and charcoal supply 90 % of energy need of 1500 million people in the developing world. As more awareness is being raised with respect to the impact of greenhouse gas on the environment, more people will rely on biomass for heating and cooking in future (Danjuma et al., 2013).

Biomass from the same source can appear in different forms introducing heterogeneity in the material, which is a major challenge in biomass conversion and utilisation (García et al., 2013). The oil palm fruits are harvested in bunches known as fresh fruit bunch (FFB). FFB wastes include all the wastes generated during the production of palm oil from FFB. The solid wastes include the empty fruit bunch (EFB), palm kernel shell (PKS), mesocarp fibre (MF), and chaff (which is usually part of EFB).

The palm nut is a part of the FFB, which yields the palm kernel (PK) and PKS when cracked. PKS takes varying shapes and sizes during the cracking process. MF comes from the oil-bearing mesocarp following the extraction of oil. It is widely used as fuel and consists of about 14 – 28.1 % of FFB (Husain et al., 2002; Omar et al., 2011; Sulaiman and Abdullah, 2011; Ohimain et al., 2013). When the fruits are detached from the FFB, the waste is EFB. About 23, 21, and 7.5 million tonnes of EFB, MF, and PKS, respectively were produced worldwide in 2014 (FAOSTAT, 2017).

In palm oil mills, the PKS is used as fuel, although it generates lots of smoke especially due to poor combustion (Okoroigwe et al., 2014). The use of PKS in the production of bio-oil and biochar during pyrolysis have been reported (Bazargan et al., 2014; Tan et al., 2008;). MF and PKS (Figure 3-1) are preferably used in palm oil mills for heat and power production (Husain et al., 2002) mainly due to lower moisture content and high bulk density relative to EFB. Due to the high moisture content of EFB (Figure 3-1) of about 60 % (Abdullah et al., 2011), it is preferably added to the soil as mulch and organic fertiliser (Sulaiman and Abdullah, 2011). The reduction of the moisture content of EFB will require more energy compared to MF and PKS and therefore increases cost. The higher moisture content of the BS (82.6 %), which is more than that of the EFS (57.5 %) (Omar et al., 2011) limits the use of the EFB as source of energy. The incineration of the EFB leads to air pollution and wastage of heat, however, the ash is used as a fertiliser (Al-Kayiem and Yunus, 2013).

3.1.1 Scope of the review

Co-combustion of biomass is a sustained tradition in rural areas where different biomass materials are used together for cooking or heating. This tradition is also being practiced in modern thermal conversion facilities (Colechin and Malmgren, 2005; Woods et al., 2006; Koppejan and Loo, 2012; McGlynn et al., 2014; International Energy Agency, 2009). The need to reduce the rate of carbon dioxide emissions from coal combustion necessitated the co-combustion of coal and biomass. There seems to be a growing interest beyond carbon emissions in co-combustion of coal and biomass. Notably, this offers opportunity for the use of biomass hitherto not utilised without the need to design an entirely new system. Idris et al. (2010) investigated the thermal behaviour of EFB, MF, PKS and coal and their blends during pyrolysis and concluded there was lack of interaction between biomass and coal blends. Idris et al. (2012) demonstrated that the ignition and burn out temperatures of biomass and coal blends were improved in comparison to only the coal, while the apparent activation energy value was reduced during the combustion of PKS, MF, EFB and coal blends, respectively. The co-firing of biomass with coal

produces residues that may not be very useful as agricultural amendments, especially ash that contains a high content of heavy metals, which applies more to coal ash (Singh et al., 2010). This is usually not the case when only the biomass is combusted. Although the co-firing of coal and biomass has continued to gain attention, ash agglomeration and the utilisation of the resultant residues are challenging issues.

The increase in palm oil production influences FFB solid wastes generation. FFB solid wastes offer a unique opportunity with the need for more energy from renewable and environmental friendly sources. Uemura et al. (2013) demonstrated that high level of energy consumption during biomass collection remains a major drawback in the use of biomass for energy compared to fossil fuel; this is not the case with EFB, MF and PKS as their cost of production is part of the cost of producing palm oil. The reports on FFB solid wastes have focused mainly on MF or PKS as energy resources (Asadullah et al., 2014; Esfahani et al., 2012), and EFB as soil amendment (Chiew and Rahman, 2002), although EFB is more than 3 times greater than PKS and 1.1 times greater than MF yields (Ohimain et al., 2013). However, there has been more interest in recent times on energy use of EFB due to its abundance (Nasrin et al., 2010; Uemura et al., 2013). This paper aims to present a critical review on: (i) evaluating the use of EFB, MF, and PKS in torrefaction, pyrolysis, gasification and combustion, and (ii) assessing the potentials and challenges of the co-firing of EFB, MF, and PKS.

3.2 Thermal conversion of fresh fruit bunch solid wastes

Combustion, gasification and pyrolysis are the three main thermochemical processes through which FFB solid wastes can be utilised. For any biomass, the proportion of its chemical composition is critical in its thermochemical conversion process (Gani and Naruse, 2007) if energy use is considered. Materials with similar compositions of lignocellulose will behave similarly during the thermal conversion processes and therefore the compositions of biomass are important in selecting its conversion technology.



Figure 3-1 Fresh fruit solid bunch wastes (A) empty fruit bunch, (B) mesocarp fibre, and (C) palm kernel shell.

3.2.1 Torrefaction

Torrefaction is an important conversion process that changes the biomass properties to obtain a better overall fuel quality for other conversion processes mainly combustion and gasification applications (Ghiasi et al., 2014; Swanson et al., 2010). Li et al. (2012) stated that torrefaction brings biomass physical and chemical properties closer to that of coal. Torrefaction results in hygroscopic energy densified products (Asadullah et al., 2014), good grindability, uniformity

in fuel quality and higher flowability (Li et al., 2012). The products of the PKS torrefaction according to Asadullah et al. (2014) include liquid (bio-oil) and gas (non-condensable gas), which increased as the temperature increased while biochar yield decreased. Asadullah et al. (2014) optimized the effects of temperature, residence time, and nitrogen gas flow-rate on the bio-oil yield during the torrefaction of PKS, and found an optimum of 73 % yield of bio-oil of calorific value 24500 kJ/kg at the temperature of 300 °C, the residence time of 20 min, with the nitrogen gas flow-rate of 300 ml/min in a 316 stainless steel of inner diameter of 0.006 m and height of 0.05 m.

Uemura et al. (2011) reported the torrefaction of each of EFB, MF, and PKS at temperatures of 220, 250 and 300 °C, respectively. Uemura et al. (2013) investigated the effects of torrefaction of EFB at oxygen concentrations of 0, 3, 9 and 15 %, particle sizes of 3.75×10^{-4} , 0.0015, 0.003 and 0.006 m, and temperatures of 220, 250 and 300 °C on the mass and energy yields. Chin et al. (2013) investigated the torrefaction of EFB at temperatures of 200, 250 and 300 °C for 15, 20, and 45 minutes, respectively. Following these three studies on EFB torrefaction mentioned above, there was a mass loss as temperatures increased, which is the same as that reported by Asadullah et al. (2014). The calorific values of EFB and MF increased with the processing temperature while the calorific value of dried PKS sample was more than samples torrefied at 220 and 250 °C and there was inconsistency on ash yield (Uemura et al., 2011). There was an increase in extractives (resin compounds, fatty acids, sterols, etc.) with time at 200 °C while the extractives decreased beyond 200 °C (Chin et al., 2013). The EFB particle size had no effect on mass yield but the mass yield decreased with increase in oxygen concentrations (Uemura et al., 2013), while the energy yield decreased with increasing oxygen concentrations. Na et al. (2013) reported an increase in energy value of torrefied MF by 5-19 %. Conversely, Ehrig et al. (2013) acknowledged the high cost of producing torrefied pellets because of the additional facilities but added that this could be compensated by reduced transportation cost.

3.2.2 Pyrolysis

Pyrolysis is the thermal conversion of organic materials in the absence of oxygen (Braga et al., 2014; Di Blasi, 2009; Sikarwar et al., 2017). Pyrolysis is usually the first stage during combustion or gasification, and can be classified as a pre-treatment technology (Uslu et al., 2008). However, pyrolysis is an independent process targeted at specific products. Bio-oils, gas, and biochar are the important products of pyrolysis (Demirbas and Arin, 2010; Lopez-Gonzalez et al., 2014; Quan et al., 2014; Tan et al., 2017).

Pyrolysis has been classified with regards to bio-oil/biochar yields and operating conditions. Fast pyrolysis takes place at temperature of 500 °C with the aim of producing more bio-oil than biochar, while slow pyrolysis takes place at the temperature of 400 °C for more biochar yield than bio-oil (Harsono et al., 2013). Khodier et al. (2009) reported three types of pyrolysis with regards to heating rate and operating temperature, which are conventional, flash, and fast pyrolysis. The heating rate and operating temperature for conventional pyrolysis range from 0.1 to 1 °C/s, and 300 to 700 °C, respectively. The heating rate for flash pyrolysis is ≥ 1000 °C/s. The high heating rate in flash pyrolysis leads to the generation of more bio-oil than biochar. The heating rate for fast pyrolysis range from 10 to 200 °C and 500 to 800 °C, respectively (Khodier et al., 2009).

The main product of pyrolysis is bio-oil, which can be used as fuel or a chemical feedstock (Abnisa et al., 2013). The main product of pyrolysis is bio-oil, which can be used as fuel or a chemical feedstock (Abnisa et al., 2013). The high calorific value of the non-condensable gas from pyrolysis which is about 13 wt.% of the biomass used according to Abnisa et al. (2013) makes it a valuable energy product. The biochar can be used in gasification for the production of hydrogen-rich gas, in the production of chemicals and activated carbon, or mixed with other biomass (Abnisa et al., 2013) or biochar from other biomass in boilers.

Abdullah et al. (2010) investigated fast pyrolysis of EFB and concluded that burning the biochar, which is a major output and contains nearly all the

minerals, would allow recovery of the ash useful as soil amendment. Sulaiman and Abdullah (2011) investigated the effects of temperature, residence time, nitrogen flow rate and combined impact of ash content and particle size on the bio-oil yield during EFB pyrolysis. Abdullah (2011) concluded that the liquid product was separated into two phases/layers, which could make its utilisation a challenge. Misson et al. (2009) successfully carried out pyrolysis of pre-treated EFB using three types of catalysts. The authors concluded that EFB lignin pre-treated with consecutive addition of NaOH and H₂O₂, and Ca(OH)₂ and H₂O₂ decomposed 100 % and 44 %, respectively. Shariff et al. (2014) demonstrated that the feedstock with the lowest ash content produced the lowest biochar yield of 23 wt.% during slow pyrolysis of EFB. Sembiring et al. (2015) optimized the effects of the reaction temperature and time on the EFB fast pyrolysis and obtained the highest bio-oil yield of 27 %, non-condensable gases yield of 23 % and 50 % biochar yield at a temperature of 500 °C and particle size of 70 mesh. Alias et al. (2014) investigated the effects of particle sizes and heating rate at a maximum temperature of 700 °C using nitrogen gas at the rate of 150 ml/min on EFB pyrolysis. The particle size of between 2.5×10^{-4} and 3×10^{-4} m led to biochar yield that is 10 % more than the particle size of less than 2.5×10^{-4} m and the decomposition rate was 1 mg/s at the highest heating rate of 80 °C/min.

Hooi et al. (2009) investigated pyrolysis of MF at temperatures between 450 and 800 °C at a heating rate of 10 °C/min and concluded that as the temperature increased, biochar and bio-oil yields decreased, but the non-condensable gases increased. A biochar of 70 % fixed carbon with energy content of 27000 kJ/kg was obtained at a temperature of 600 °C. Kabir et al. (2017) investigated the pyrolysis of MF and produced a maximum 48 wt.% bio-oil, high heating values of the bio-oil and biochar of 23000 kJ/kg and 24840 kJ/kg at a temperature of 550 °C, respectively.

Abnisa et al. (2011) demonstrated that the optimal conditions for 46 wt.% maximum bio-oil yield of PKS pyrolysis were temperature of 500 °C, nitrogen flow rate of 2 l/min, particle size of 0.002 m and reaction time of 60 min. The reactor is 0.127 m in length and diameter of 0.0025 m of a 304 steel tube. Kim

et al. (2010) demonstrated that high reaction temperatures led to higher product gas with heating value of 4000-8000 kJ/kg during the pyrolysis of PKS in a 304 steel tube with inner diameter of 0.11 m and height of 0.39 m and capacity of 1 kg/h. The authors further demonstrated that maximum bio-oil yield (48.7 wt.%) of PKS pyrolysis was obtained at a temperature of 490 °C, while that of biochar was at a temperature of 435 °C. The authors concluded that the smaller the feed size the higher the bio-oil yield, while the higher feed rate led to increase in bio-oil yield and decrease in the yield of non-condensable gases. Lee et al. (2017) compared the properties of biochar produced from EFB, PKS, and palm oil sludge. Unlike palm oil mill sludge, which is also derived from palm oil mills, the high heating values, fixed carbon, and moisture content of the char produced from EFB, and PKS increased more than the raw biomass. From the thermogravimetry analysis, Lee et al. (2017) concluded that the biochar produced from EFB, and PKS are of significant potentials especially as soil amendment, in pollution control and energy production due to the ability of the biochar to absorb moisture and nutrient in the soil, gases and its high calorific value.

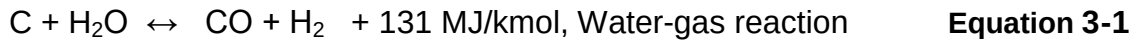
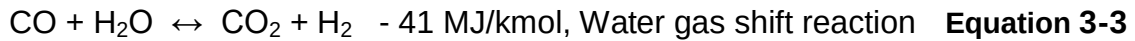
Yang et al. (2006) demonstrated that the maximum bio-oil yield of PKS was at a temperature of 500 °C. The MF and EFB maximum rate of gases evolving (H₂, CO, CO₂, and CH₄) occurred at approximately the same temperature ranges at 250 – 300, 300 – 350, 450 – 500, and 650 – 700 °C for CO, CO₂, CH₄, and H₂, respectively. The maximum rate of gases evolving for the PKS occurred at slightly different temperature range; 300, 400, 450, and 700 °C for CO, CO₂, CH₄, and H₂, respectively. Abnisa et al. (2013) demonstrated that PKS pyrolysis led to the highest biochar and bio-oil yields compared to the EFB and MF, while MF showed the highest yield of non-condensable gases. The operating parameters were temperature of 500 °C, nitrogen flow rate of 2 l/min and 60 min reaction rate in a 310 stainless steel reactor of length 0.127 m and internal diameter of 0.0025 m. The authors attributed the high biochar yield of PKS to its high lignin content.

The optimisation of each of EFB, MF, and PKS pyrolysis has been effectively experimented, which resulted in valuable energy materials in the form of biochar and bio-oil. The biochar, which can further be used in gasification and combustion makes co-firing easier in terms of grindability and mixing.

3.2.3 Gasification

Gasification is a partial oxidation to produce combustible gas (Kumar et al., 2010; Simonyan and Fasina, 2013; Swanson et al., 2010), which consists of a combination of CO, H₂, CO₂, N₂, H₂O and CH₄ (Rajvanshi, 1986). The gas produced during gasification can be used as chemical feedstock, in internal combustion engines or can also be burnt to produce heat for steam production, domestic or industrial heating. Gasification technology is still under developed and limited by capacity (Filho & Badr, 2004; Zevenhoven-onderwater et al., 2001) and requires a lot of cleaning, however offers more flexibility because the products can be used in various ways and can be transported (Chmielniak & Sciazko, 2003; Di Blasi, 2009). The other outputs of biomass gasification include ash, unburnt carbon (char), and slag, which depends on gasification temperature and efficiency. Gasification processes include entrained flow, fluidized bed and fixed bed. The characteristics of entrained flow are high temperature gasification of 1200 – 1600 °C, finely divided fuel, oxygen/steam as oxidant and the production of medium calorific fuel gas. The fluidized bed gasification is characterised by its flexible design and fuel preparation, medium temperature of 800 – 1000 °C, and air, steam/oxygen oxidant. The fixed bed gasification is known for flexible designs, low temperature gasification, low calorific gas yield and suitable for smaller and larger fuel particles. Rajvanshi (1986) identified updraft, and downdraft as two main types of gasification. The differentiating factor being the direction of air. In updraft gasifier, the air passes from the bottom to the top of the gasifier, while in downdraft the air passes from the top to the bottom. Gasification involves initial pyrolysis at low temperature leading to the release of volatile matter and char production, tar cracking at higher temperature reactions, and char gasification enhanced by Boudouard

reaction (Moghadam et al., 2014). The main reactions that take place in gasification can be represented as follows (Shahbaz et al., 2017):



The gasification efficiency is measured by the gas yield, syngas calorific values, carbon conversion efficiency, and cold gas efficiency. The gasifying agents include air, steam, oxygen-steam, air-steam, oxygen-enriched air and oxygen-air-steam (Lahijani and Zainal, 2011).

Gasification produces minimum air pollution, allows for efficient conversion of biomass to heat and there is control over combustion rate (Esfahani et al., 2012). Erlich and Fransson (2011) studied gasification of EFB pellets in a downdraft gasifier, which resulted in a poor syngas with high contents of non-combustible compounds. Esfahani et al. (2012) studied the gasification of PKS as a hydrogen feedstock in fluidized bed reactor and concluded that the temperature and equivalence ratio significantly influenced the gas yield up to 90 wt.% conversion and there was no recorded effect due to particle size and feeding rate.

Lahijani and Zainal (2011) investigated the gasification of EFB, which resulted in the maximum heating value of 5370 kJ/Nm³, dry gas yield of

2.04 Nm³/kg, carbon conversion efficiency of 93 % and cold gas efficiency of 7 % at a very high temperature of 1050 °C and equivalence ratio of 0.25. This was done in bubbling fluidized bed gasifier of height 1.05 m and internal diameter of bed zone of 0.15 m. Nor-Azemi et al. (2015) demonstrated that Ni-loaded MF produced higher concentration of CH₄, CO and H₂ compared to raw MF at the temperature range of 750 - 950 °C. The authors further stated that loading Ni to MF reduces CO₂ concentration in the syngas and a lower tar yield of 0.35 %.

There are reports on co-gasification of FFB solid wastes with other fuels, which provide evidence on the benefits of co-firing. Moghadam et al. (2014) investigated the co-gasification of polyethylene and PKS using reaction temperature, steam to feedstock ratio, and the ratio of PKS and polyethylene as sources of variation. Moghadam et al. (2014) demonstrated that the blending of PKS and polyethylene enriched total syngas production to a maximum value of 87.73 vol.%.

3.2.4 Combustion

Amongst pyrolysis, combustion and gasification, combustion is the most important means of using biomass to produce the world's large portion of bio-energy, whether as gaseous, liquid or solid fuel (Demirbas, 2007; Nussbaumer, 2003; Strzalka et al., 2013). Through combustion, solid biomass is converted into heat to produce steam, which is passed through a steam turbine to generate electricity or used for heating purpose. The outputs of biomass combustion include heat, which is the primary product, gaseous products (CO₂, steam, NO_x, SO_x and other gaseous pollutants), unburnt carbon (char), ash and slag depending on temperature of combustion and combustion efficiency.

The main combustion systems are grate furnace, pulverized fuel systems and fluidized bed combustors (Oberberger 1998; Yang et al. 2004). The grate furnace comprises of the inclined, traveling, chain, and vibrating types. The fuel is fed onto the grate by gravity. The moisture removal,

ignition, combustion, ash removal and cooling take place as the fuel bed moves. The primary air supply is sectioned so that there will be control over the flow rate and pressure at each section. The secondary air is supplied above the grate. The temperature above the bed and freeboard is between 800 and 1000 °C. The recirculation of the flue gas to cool the grate is an efficient way of controlling the temperature when burning low quality fuel (Strzalka et al. 2013). Few of the advantages of the grate furnace are: low investment and operating costs, suited for biomass with high moisture content, varying particles sizes, and high ash content (Sirisomboon et al. 2010; Singh 2014; Strzalka et al. 2013). It also has less fly ash load in flue gas.

In pulverized-fuel systems, pulverized fuels are blown with the combustion air into the furnace through burner nozzles into the combustion chamber where the existing condition is enough to ignite the fuel-air mixture. The mixture injection method describes the type of system, which can be wall-fired, tangential-fired and down-fired systems. Few advantages of the pulverized systems are: different types of fuel with varying characteristics can be used; quick response to changes in load and high pre-heat temperature. The pulverized firing system makes use of the whole volume of the furnace and ensure that the fuel burn completely to achieve higher efficiency, however a usual circumstance exist whereby the air velocity elutriates the light biomass before it has the chance to burn completely. It leads to drop in temperature and unstable process. In order to reduce sulphur dioxide, it uses desulphurisation unit unlike fluidized systems, which makes use of limestone to reduce sulphur dioxide.

The fluidized bed combustion technology is among the widely used technologies for biomass combustion. It is of two main types – bubbling fluidized bed combustors and circulating fluidized bed combustors (Singh 2014; Obernberger 1998). The fluidized bed combustion operate bed temperature of between 750 and 950 °C (Obernberger 1998) lower than that of grate and pulverized systems. This slows down the formation of NO_x

and enables the use of fuels with lower ash melting temperature. The other advantages are fuel flexibility, accepts fuels with varying particle size, no moving part in the combustion chamber, excellent solid-gas mixing and temperature homogeneity (Sirisomboon et al. 2010; Obernberger 1998). Few disadvantages include; it does not function well in condition of partial load, has high investment and operation costs, higher dust load in the flue gas leading to erosion of exchanger tubes (Obernberger 1998;). There is higher loss of bed material in circulating fluidized bed combustors and higher investment cost in preparing smaller fuel particles for both. The combustion efficiency and emission performance of biomass fired fluidized bed combustors are influenced by fuel properties, design features and operating conditions (Sirisomboon et al. 2010).

Idris et al. (2012) demonstrated that EFB has an ignition temperature of 249 °C lower than that of MF (256 °C) and PKS (266 °C) via thermogravimetric analysis and concluded it was due to the higher volatile matter as recorded by the study. There were differences in volatiles matter contents of EFB, MF, and PKS from other studies (Abnisa et al., 2013; Husain et al., 2002), which could be due to differences in the sources of the FFB solid wastes. Idris et al. (2012) also demonstrated that EFB is more reactive compared to the other two biomass. Parshetti et al. (2014) carried out Thermogravimetric analysis-Fourier transform infrared investigation of combustion characteristics of hydrothermally carbonised EFB and concluded that it showed better combustion characteristics than raw EFB because of increased carbon content. Ninduangdee and Kuprianov (2015) investigated the combustion of PKS in a fluidized-bed combustor and demonstrated that excess air of 40 % and 60 % are best with alumina and dolomite as bed materials, respectively.

The melting of ash – a challenge to furnace maintenance, is a function of temperature. The increase in the bed temperature not only increases efficiency, but also agglomeration especially in biomass with high contents of alkali metals. Since the rate of agglomeration increases with the temperature (Ma et al., 2007;

Werther et al., 2000), to balance the high temperature requirement and agglomeration, biomass with high ash melting point must be used or the system must be operated at lower temperature.

3.3 Properties of fresh fruit bunch solid wastes

The Reduction of moisture is the first stage in any thermal conversion process since moisture inhibits heat flow especially biomass with the inherent high moisture content and the potential to absorb moisture. The continual combustion or other forms of thermal conversion requires that moisture is driven off completely, which takes place at specific temperature depending on fuel (Aghamohammadi et al., 2011). Moni et al. (2016) reported that 10 - 20 % moisture is optimum for biomass during combustion. The sterilised EFB directly from the mill has a moisture content of 60 % on a wet basis (Abdullah et al. 2011), and according to Moni et al. (2014), at the moisture content of 30 % and above the biomass need to be dried before combustion. Therefore, the high moisture content of EFB is a limiting factor in its thermal conversion within the oil palm mills.

The effect of fuel size is important as it influences the design of the conversion systems. Modern systems are designed for fuels of smaller particle sizes enabling shorter conversion time and an efficient heat transfer. The small sized fuels tend to lose moisture faster, which shortens the entire process time. Bulk density is also an important factor in terms of energy per unit weight. EFB has a much lower bulk density of 110 kg/m³ (Sung et al., 2010), 133 kg/m³ and 275 kg/m³ (for MF) as received (Moni et al., 2016) compared to PKS bulk density of 780 kg/m³ (Arzola et al., 2012), and 697 kg/m³ as received (Moni et al., 2016). The tough and wood-like structure of PKS according to Moni et al. (2016) is responsible for its high bulk density. The fibrous nature and loose structure of EFB and MF (Moni et al., 2016) may pose challenges in terms of grindability unless when torrefied. Table 3-1 is the proximate and ultimate analysis of EFB, MF, and PKS measured as part of this review according to British Standards Institute (2011a), (2011b), (2011c). There are differences in the compositions of EFB, MF, and PKS shown in Table 3-1. These variations will affect the

performance of the process including the release of moisture and flowability of the wastes. For example, the lower heating value of EFB is due to its higher moisture content (Suheri and Kuprianov, 2015b). Moni et al. (2016) demonstrated considerable reduction in bulk densities from 133, 275, and 679 kg/m³ as received to 100, 193, and 565 kg/m³ at 0 % moisture content for EFB, MF and PKS, respectively. The other important characteristics of FFB solid wastes are high content of volatile matter and high ash content. Ash according to Abdullah et al. (2011) leads to reduction in bio-oil yield during fast pyrolysis. High content of volatile matter makes biomass easier to ignite and burn (Werther et al., 2000). High combustion efficiency is expected for low release of CO₂, hydrocarbons, and polycyclic aromatic hydrocarbon.

Alkali and alkali earth metals including potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), heavy metals including zinc (Zn), molybdenum (Mo), lead (Pb), cadmium (Cd), and phosphorus (P), sulphur (S), chlorine (Cl), aluminum (Al), iron (Fe), manganese (Mn) are some of the inherent and entrained elements in FFB solid wastes. Inherent elements are bound in the carbon structure while entrained elements are introduced into the biomass during and after harvest (Sahu et al., 2014). The elements introduced during, and after harvest are usually not removed prior to utilisation of the biomass and therefore will influence the thermal conversion process depending on quantity and the area where the materials are sourced.

3.4 Co-firing and blending of fresh fruit bunch solid wastes

Solids are very difficult to mix compared to liquids or gases. Non-homogeneity is a challenge when two or more solid fuels are to be blended. Solid fuel particle size will potentially affect synergic reactions between fuels, while bulk density will affect volume ratio. Non-homogeneity affects reactions between the fuels or encourage pockets of reaction.

When the objective of co-firing the FFB solid wastes is only to increase one biomass against the other, blending will aim to ensure the ratio is maintained during the thermal conversion process. However, this may not be the case when synergic reaction is considered, which will require that the fuels are

evenly mixed to create the needed contact between particles. Fuels can either be pre-mixed before co-firing or co-fired as they are mixed together.

Table 3-1 Proximate and ultimate analyses, high heating value and low heating value of empty fruit bunch, mesocarp fibre and palm kernel shell sourced from palm oil mills in South Eastern Nigeria.

Parameter	EFB		MF		PKS	
	db	ar	db	ar	db	Ar
Proximate analysis						
Moisture		14.4		12.1		12
Fixed carbon	8.8	7.5	8.1	7.1	7.6	7
Ash	5.1	4.4	5.5	4.8	1.7	1.5
Volatile matter	86.1	73.7	86.4	75.9	90.4	79.6
Ultimate analysis						
C	43.8	37.5	52.1	45.8	52.3	46
H	5.8	5	7.2	6.3	5.8	5.1
N	0.5	0.4	1.0	0.9	0.4	0.4
Cl	0.33	0.28	0.38	0.33	0.03	0.03
S	0.1	0.1	0.2	0.2	0.02	0.02
O*	44.4	38	33.6	29.5	39.8	35
HHV (kJ/kg)	18581	15903	22171	19484	21260	18711
LHV (kJ/kg)	17466	14499	20841	17846	19984	17336
Lignocellulose**						
Cellulose	51.2	na	23.7	na	27.7	na
Hemicellulose	22.5	na	30.5	na	21.6	na
Lignin	21.3	na	27.3	na	44	na

All in % w/w except where it is stated otherwise. ar - as received basis, db - dry basis, na -not available. HHV - high heating value, LHV - low heating value, EFB - empty fruit bunch, MF - mesocarp fibre, PKS - palm kernel shell, *by difference, **(Abnisa et al., 2013)

Decisions on how the fuels are mixed are crucial for an effective co-firing operation. According to Tillman et al. (2012), blending of solid fuels is aimed at

producing a homogenous mixture of two or more solids. The blending of fuels is because of regulations against SO₂, NO_x, particulates, trace metals including mercury and arsenic, fossil CO₂ emissions especially in coal-biomass co-firing, however the benefits goes well beyond the legal restrictions (Tillman et al., 2012). It is designed to modify the chemical characteristics of the mixture, achieve economic benefits through mitigating problems such as slagging, fouling, corrosion, and formation of pollutants (including NO_x, SO_x, and hazardous air pollutants). It provides opportunity to reduce ash content and particulates emissions. For example, PKS has more Ca and Si than K, while EFB has more K than Ca and Si (Suheri and Kuprianov, 2015a). The content of K influences agglomeration, and therefore the co-firing of EFB and PKS will potentially be influenced by the differences in K contents. Blending also provides the means for increasing the usable fuel.

Moni et al. (2014) used volatile matter content, moisture content, calorific value, annual production, supply availability, drying requirement and densification requirement to rank the favourability of co-gasification of biomass with another. Drying requirement and need for densification are the factors that could be changed considerably. Moni et al. (2014) ranked PKS ahead of MF and EFB in terms of less drying requirement and need for densification. Suheri and Kuprianov (2015b) investigated the co-combustion of EFB as secondary fuel and PKS as primary fuel in a fluidized-bed combustor. The authors used fuel staging by injecting the PKS into the expanded fluidized bed and EFB by the upper feeder onto the bed. Suheri and Kuprianov (2015a) demonstrated that the combustor could be operated at combustion efficiency of about 99 % with 35 % reduction in NO_x emissions when compared to firing only the PKS.

Difficulties in feeding fuel of varying physical properties (particle size, angle of repose, etc.) might result in designing different handling and conveying system to suit the different fuels leading to high investment cost (Veijonen et al., 2003). Uniformity of particles is another potential factor affecting the FFB solid wastes blending and co-firing. According to Tillman (2000), smaller fuel particles release more volatiles and more rapidly, while higher

temperatures leads to the release of volatiles from a greater proportion of the combustible fraction, and lower temperatures lead to increase in char formation.

Briquetting and pelletisation are two most important densification process necessary in solid fuel blending and co-firing, which influences effectiveness in co-firing particularly the EFB with either MF or PKS. Densification increases the bulk density, and calorific values of the pellets or briquettes. The major difference between briquetting and pelletisation is the particle size of the finished product. Briquettes typically have diameter of between 0.01 to 0.04 m, while pellets have diameter of 0.0048 to 0.019 m (Kaliyan and Morey, 2009). Notably, the high bulk density and calorific value improves the fuel marketability, handling, storage, and transportation. The process leads to reduction in the moisture content of the product and therefore its thermal conversion efficiency. Most importantly, it reduces the cost associated with storage, handling, and transportation. Densification processes involve particle size and moisture content reduction, addition of binder and mixing. Some of the properties of densified products are moisture content, bulk density, durability, angle of repose, compression resistance, impact resistance, and water resistance (Kaliyan and Vance, 2009). Moisture content affects thermal conversion efficiency of fuels, storability, calorific value, losses, and self-ignition. Durability is a measure of quality of the densified products, which affect its disintegration or losses during transportation. Hardness or compression resistance is the maximum crushing load a densified product can withstand before breaking. Pellets or briquettes may be exposed to rain or high humidity, therefore the ability of the product to resist high moisture environment or condition is also a measure of its quality (Kaliyan and Vance, 2009). Many authors have investigated the factors affecting the quality of densified materials (Ahn et al., 2014; Arzola et al., 2012; Tooyserkani et al., 2012). The factors are the particle size and distribution, moisture content, steam conditioning of feedstock, and machine parameters including, the pressure, die diameter and length, speed, gap between roller and die and temperature of operation. Arzola et al. (2012) observed that increase in process pressure has positive effect on

durability of PKS pellets of up to 99 % durability index. Arzola et al. (2012) observed difficulties in pelleting PKS without binder but it was better with molasses as binder. The blending ratio according to Nasrin et al. (2010) is an important parameter, which influences the quality of briquettes.

Erlich and Fransson (2011) reported the production of 0.006 and 0.008 m diameter EFB pellets in a 20 kg/hr laboratory mill with press lengths of 0.036 m and 0.05 m, respectively. Similarly, Nasrin et al. (2010) reported the production of briquettes from the mixture of EFB and PKS in a 60 tonne/hr mill. Husain et al. (2002) densified MF and PKS into briquettes of diameter 0.04, 0.05 and 0.06 m using hydraulic press with densities of the briquettes up to 1200 kg/m³. Nasrin et al. (2010) further stated that the specific energy requirement for the production of 1 tonne EFB/PKS briquettes is 200 kWh, which is technically viable. 1 tonne of EFB/PKS briquette can generate about 1.25 million kWh of electricity according to Nasrin et al. (2010). Economically, EFB/PKS briquette is similar to coal and attract the same price of USD 60-70/tonne (Nasrin et al., 2010). Table 3-2 is properties of the EFB/PKS briquette and the feedstock (Nasrin et al., 2010). Chin and Siddiqui (2000) demonstrated that the shear strength of MF briquette increased with die pressure and a negative correlation between combustion rate and die pressure. Nasrin et al. (2011) demonstrated that blending PKS with EFB would increase calorific value and specific density of the briquettes compared to 100 % EFB. The calorific values of the briquette at 60 % PKS was 18323 kJ/kg and that of 100 % EFB was 17660 kJ/kg while the specific densities up to 1200 kg/m³ for 60 % PKS compared to about 1100 kg/m³ for 100 % EFB. The authors also demonstrated that calorific value and specific density of briquettes increased with the addition of PKS at 20, 30 and 60 % to EFB. According to Nasrin et al. (2010), additional benefits of densification especially briquetting are the possible tax exemptions, and carbon credits and most importantly the possibility of co-firing with other solid fuel (Kaliyan and Morey, 2009).

3.5 Challenges and potentials of co-firing fresh fruit bunch solid wastes

Ninduangdee and Kuprianov (2014a) demonstrated that varying excess air from 20 - 80 % for each of 45 kg/hr and 30 kg/hr fuel feed rates led to combustion efficiency of about 99 % during the combustion of PKS in a fluidized-bed combustor using dolomite as bed material. The CO and NOx emissions were at acceptable levels of 0.025 % and 0.012 %, respectively. Conversely, under optimum conditions of 0.005 m particle size and excess air of 40–5 %, Ninduangdee and Kuprianov (2014b) demonstrated that 99.4–99.7 % combustion efficiency can be achieved during the combustion of PKS in a fluidized-bed combustor. Most researches on either combustion, gasification and pyrolysis of each of EFB, MF, and PKS are on how different factors including operating temperature, air/nitrogen flow rate, catalyst, feedstock characteristics and origin, design of thermal conversion system, bed design, fluidizing velocity, reaction time, and equivalence ratio affect the outputs (Esfahani et al., 2012; Ninduangdee and Kuprianov, 2014a; Nor-Azemi et al., 2015; Parshetti et al., 2014; Shariff et al., 2014). These parameters are important not only on yield of primary products in terms of quantity and quality but also on the minimisation of residues and pollutants.

Table 3-2 General specifications of raw materials used in the production of palm biomass briquettes (Source: Nasrin et al., 2010).

Raw material	calorific value (kJ/kg)	Moisture content (%)	Ash content (%)	Volatile matter (%)	Fixed carbon (%)
EFB fibre	17500	<20	6.43	80.21	13.03
PKS	18500	<10	4.36	77.36	17.01
Briquetted EFB/PKS	17895 – 18235	<8	6.12	79.53	13.5

EFB-empty fruit bunch, PKS-palm kernel shell

Lua and Guo (1998) demonstrated that the maximum Brunauer–Emmett–Teller (BET) surface area of MF was 521 m²/g with optimum pyrolysis conditions of 0.0005 - 0.001 m MF particle size, 850 °C temperature for 3.5 hour hold time, 10 °C/min heating rate, and 0.15 l/min nitrogen flow rate. The largest particle size of 0.001– 0.002 m and the smallest particle size of <0.0003 m led to the smallest BET surface area. Low reaction time was attributed to the low BET surface area due to the large particle size. Abnisa et al. (2013) stated that the chemical composition of bio-oil depends mainly on the biomass used and the operating conditions. Therefore, the combined effects of co-pyrolysis of the three biomass will influence the composition of bio-oil.

Another fact is the compositions of lignocellulose in EFB, MF, and PKS (Table 3-1). EFB has the highest cellulose than MF and PKS, MF has more hemicellulose than EFB and PKS, while PKS has more lignin than EFB and MF. The yields of bio-oil, biochar and non-condensable gases varied with EFB, MF and PKS according to Abnisa et al. (2013). The yields increased as follows: bio-oil (MF-EFB-PKS); biochar (EFB-MF-PKS) and non-condensable gases (PKS-EFB-MF), with viscosity of the bio-oil following the same trend as bio-oil yield (MF-EFB-PKS). According to Ninduangdee and Kuprianov, (2014b), during thermal degradation of biomass, hemicellulose and cellulose are generally responsible for the formation of volatile matter, while lignin is a major contributor to the biomass char. Therefore, co-pyrolysis of EFB, MF, and PKS will influence yields of bio-oil, biochar and non-condensable gases.

The production of syngas involves the reduction of biomass to biochar and then to CO and H₂ by the reaction of water vapour and CO₂ (Rajvanshi, 1986). Feedstock influences gasification and therefore co-gasification of EFB, MF and PKS will affect the properties of the fuel gas and the amount of tar and ash produced. Suheri and Kuprianov (2015b) demonstrated that the co-firing of EFB and PKS reduced NO_x emissions by 35 % compared to firing only the palm kernel shell.

Similarly, co-combustion will increase heat output, influence gaseous products and residues. There is also possibility of influencing fouling, which is an

important process in thermal conversion system as demonstrated by Nordgren et al. (2013).

Thermal conversion of FFB solid wastes will lead to the release of CO₂, hydrocarbons, polycyclic aromatic hydrocarbon, NO_x and SO_x (Agbor et al., 2014). NO_x and SO_x emissions may not be a problem during FFB solid wastes combustion due to the low contents of nitrogen and sulphur in FFB solid wastes (Table 3-1). According to Agbor et al. (2014), NO_x is formed in three different reactions during combustion namely thermal, prompt and fuel NO_x. Thermal and prompt NO_x are process dependent (Agbor et al., 2014; Treier et al., 2006; Werther et al., 2000) while fuel NO_x is due to nitrogen content of fuel, which is of low content in FFB solid wastes. CaO and MgO can absorb SO_x released during combustion to form CaSO₄ and MgSO₄ with high melting points, respectively (Agbor et al., 2014). These reactions may differ for example due to the difference in EFB and PKS CaO contents, which are 6.23 wt.% ash (Omar et al., 2011) and 23.21 wt.% ash (Ninduangdee and Kuprianov, 2014a), respectively.

The FFB solid wastes effects on global CO₂ emissions is carbon neutral due to the fact that CO₂ is used during the growth of the oil palm from photosynthesis. Therefore, the benefit of FFB solid wastes utilisation is in replacing fossil fuels, which are not carbon neutral. Ninduangdee and Kuprianov (2014b) demonstrated that CO, and CH₄ can be effectively controlled by decreasing the particle size of PKS or increasing air while NO_x emissions can be reduced using coarser PKS particle and excess air during combustion.

3.5.1 Co-firing fresh fruit bunch solid wastes, agglomeration, and ash utilisation

Residues of FFB solid wastes thermal conversion are the solid materials left after the process, which include ash, biochar, and slag. The formation of these residues depends mainly on the thermal conversion technique, the system characteristics and operating parameters and properties of the biomass. Typical compounds formed during combustion are alkali chlorides, hydroxides and

sulphates. According to Robinson et al. (1998), alkali sulphates have a higher melting temperature than the others and therefore the sulphates will reduce stickiness of deposit and fly ash particles in comparison with deposit made by the chlorides and hydroxides. The presence of sulphur in a fuel can also convert K_2O to K_2SO_4 of high melting point (Lahijani and Zainal, 2011). Since PKS has a lower content of sulphur than EFB and MF (Table 3-1), its thermal conversion contributes less to the production of K_2SO_4 , which could be altered when co-fired with either EFB or MF.

The ash forming elements in biomass influence gaseous and solid products, ash composition and ash melting behaviour, which leads to fouling and corrosion of heat exchangers (Obernberger et al., 1997). Since ash deposited on furnace surfaces reduces heat transfer as well as causes corrosion of these surfaces, bed materials including silica sand, alumina, and dolomite sand are used to control agglomeration (Ninduangdee and Kuprianov, 2014a, 2014b, 2013). Low quality biomass are known for high alkali metals, which leads to bed agglomeration, slagging, fouling and corrosion. This represents the biggest challenge of using biomass as fuels (Díaz-Ramírez et al. 2014; Gogebakan et al., 2009; Werther et al., 2000). Agglomeration leads to the production of slags, which limit efficiency of boilers and reduces residue (ash) quantity and quality. The uses of additives, alternative bed materials and co-firing have been found effective in reducing the effects of low quality biomass on agglomeration and fouling due to alkali metals; although the quantity of the alkali metals varies from biomass to biomass (Gogebakan et al., 2009; Werther et al., 2000). However, the addition of bed materials will affect the properties of the residues especially in their utilisation for agricultural purposes.

Lahijani and Zainal (2011) demonstrated that bed agglomeration can be eliminated by lowering the gasification temperature from 1050 °C to 770 ± 20 °C, and using the equivalence ratio of 0.21. However, the maximum gas heating value reduced from 5370 to 4530 kJN/m³. There is an opportunity to reduce agglomeration without reducing the operating temperature especially during combustion where the fuels are required to produce maximum heat. According

to Lahijani and Zainal (2011), biomass with high alkali content can be co-fired with another fuel with less alkali or rich in transition metals. The EFB has a higher potassium content (Table 3-3) than the MF and PKS combined and therefore when used at higher temperatures will lead to agglomeration. Similarly, oxides of alkali earth metals for example CaO (2572 °C) and MgO (2852 °C) have higher melting points than oxides of alkali metals K₂O (740 °C) and Na₂O (1132 °C). An addition of MgO has been found useful in altering the eutectic of the resultant ash by increasing the melting point, and thereby reducing agglomeration (Paisley, 2004). It therefore offers the opportunity to reduce agglomeration when fuel with high alkali earth metal is co-fired with fuel with high alkali metal. MF has a higher Mg and Ca than EFB and PKS combined (Table 3-3). Conversely, SiO₂ with a melting point of about 1450 °C reacts with alkali metals to form compounds of lower melting points (Werther et al., 2000) when used as bed material. An example is presented in equation (3-12) below; where K₂O·4SiO₂ has a melting point of 764 °C (Werther et al., 2000).



Therefore, feedstock of higher Si could alter the ash melting point when co-fired. Idris et al. (2010) demonstrated that EFB, MF, and PKS have varying silicon contents of 3.96, 16, and 2.51 wt.%, respectively. Additionally, the high potassium content in ash is important in the utilisation of ash for agricultural purposes; due to the differences in potassium contents of raw EFB, MF, and PKS (Table 3-3), the respective potassium ash contents may also vary (Lahijani et al., 2013).

Table 3-3 Elemental composition of empty fruit bunch, mesocarp fibre and palm kernel shell in mg/kg (Source: García-Núñez et al., 2008)

Parameter	Empty fruit bunch	Mesocarp fibre	Palm kernel shell
Ash (%)	7.87±0.3	8.44±0.22	1.82±0.34
Na	102.29±16.02	32.87±19.72	10.78±3.02
Mg	913.12±264.97	1509.53±180.22	262.69±10.29
Al	802.08±263.65	1216.33±133.75	31.65±9.02
P	572.7±226.44	594.91±68.08	115.04±4.35
K	22289.15±2022.18	5188.26±368.07	1477.70±58.84
Ca	889.34±290.96	1771.62±104.34	173.72±10.77
Cr	2.68±0.34	3.48±0.14	1.52±0.05
Mn	83.67±34.49	97.03±9.72	15.82±0.81
Fe	812.35±310.2	1239.39±128.21	56.25±3.9

3.5.2 Benefits of co-firing fresh fruit bunch solid wastes

The possible benefits of the co-firing of FFB solid wastes are the increase in the use of EFB, MF and PKS for energy purposes, the control of emissions, reduction in fouling and agglomeration. Most palm oil mills co-fire MF and PKS (Husain et al., 2002) and occasionally EFB is used. Increasing the use of EFB, MF, and PKS will increase heat and power generation, biochar, bio-oil and fuel gas (syngas) production. EFB, which is more likely to be disposed, will be utilised as fuel. PKS is a major contributor to unburnt carbon (Ninduangdee and Kuprianov, 2014b) especially when co-fired with MF and therefore there is opportunity to reduce the amount of unburnt carbon using a control quantity of PKS. The co-firing also offers several additional environmental benefits including the potential for reduction of NO_x and SO_x emissions, elimination of the negative environmental effects of incinerating and landfilling the biomass as a means of disposal (Sami et al., 2001). For example, when biomass including FFB solid wastes are co-fired with coal, it offers a low-cost, low-risk means of decreasing net CO₂ emissions (Idris et al., 2010; Robinson et al., 1998). This

also offers an opportunity for FFB solid wastes to be used in existing coal facilities to produce heat and power.

3.6 Conclusions

The co-firing EFB, MF and PKS is a long tradition in most palm oil mills. There is increasing research in the co-firing of FFB solid wastes with other solid fuels including coal and agricultural residues.

- Each of EFB, MF, and PKS are used in pyrolysis, gasification, and combustion, providing opportunities for co-firing these mixtures.
- The co-firing of EFB, MF, and PKS increases sources of energy and utilisation and therefore create more sustainable energy.
- The co-firing of EFB, MF and PKS opens more opportunities for densification and therefore improves transportation and makes blending of the fuels simpler. The ground biomass can be easily used in fluidized furnaces.
- The ash deposition rate during EFB, MF, and PKS co-combustion or co-gasification is a balance between the three fuels and therefore a fraction of each fuel affects the deposition rate. Similarly, synergic reactions are possible during co-firing, which affect the eutectic temperatures of the mixtures, the gaseous output of combustion, syngas from gasification, or bio-oil and biochar during pyrolysis.

The other benefits of co-firing of the EFB, MF, and PKS are reduced tar yield and improvement in the ash quality. Therefore, there is need for a sustained research on simultaneous use of the EFB, MF, and PKS in pyrolysis, gasification, and combustion with a focus on efficiency, quality and quantity of the products including the residues. More importantly, on how the challenges including tar formation, agglomeration, and emissions can be controlled in co-firing.

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3.8 References

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4 Evaluating Oil Palm Fresh Fruit Bunch Processing in Nigeria

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Abstract

Three routes of the oil palm fresh fruit bunch (FFB) processing in Nigeria namely, industrial, small-scale and traditional were compared by means of determining fruit losses associated with each route. The fruits that are not recovered after each process were hand-picked and quantified in terms of the crude palm oil (CPO), palm kernel (PK), mesocarp fibre (MF), and palm kernel shell (PKS). The energy value of EFB, MF, and PKS were used to determine the value of energy lost for each route. Additionally, the environmental implications of disposal of EFB was estimated, and socio-economics of the industrial and small-scale routes were related. The analysis showed that 29, 18, 75, and 27 kg of CPO, PK, MF, and PKS were lost for every 1000 kg of FFB processed with the industrial route, whereas less than 1 kg were lost with the small-scale and traditional routes, respectively. Approximately 89 kWh and 31 kWh more energy were lost from MF and PKS with the industrial route than the other two routes, respectively. An estimated 6,670 tonnes carbon dioxide equivalent of methane and nitrogen oxide was released due to the disposal of 29 000 tonnes of EFB from one palm oil mill. The monetary value of lost CPO per 1000 kg of FFB processed in industrial route is more than the labour cost of processing 1000 kg of FFB in the small-scale route. The advantages of industrial route are high throughput in terms of FFB processed per hour and

high quality of CPO however, high fruit loss is associated with it and therefore, the poorly threshed EFB is recommended to be fed into the small-scale route.

Keywords: Fresh fruit bunch, oil palm processing, empty fruit bunch, mesocarp fibre, palm kernel shell, crude palm oil

4.1 Introduction

The oil palm (*Elaeis guineensis*) is generally believed to originate from West Africa. The oil palm produces fruits in bunches known as fresh fruit bunch (FFB). An Oil palm tree produces more than 8 - 12 FFB/yr, each weighing up to 13 kg (Jagustyn et al., 2013; Evbuomwan et al., 2013). A bunch contains about 800 to 1000 fruits (Jagustyn et al., 2013). Nigerian farmers grow the Dura (thick shell), Tenera (thin shell) and Pisifera (shell-less or very thin shell) varieties (Izah et. al., 2016a). The oil palm produces more oil per hectare of land than any other known oil crop (Evbuomwan et al., 2013; Ohimain et. al., 2013).

Nigeria played a leading role in palm oil production and export contributing 43 % of global palm oil production (Thomas et al., 2011) but at present produces 1.5 % of the world's consumption (Izah et al., 2016a), though still produces more than half of Africa's total palm oil production (Gourichon, 2013). Indonesia and Malaysia are the largest producers of palm oil from the oil palm tree in the world (Zainal et al., 2016) and Nigeria is the fifth largest producer after Thailand and Colombia (FAOSTAT, 2017). Global palm oil production in 2014 has been estimated to be 57 million tonnes according to FAOSTAT, (2017).

The main products of the oil palm industry are crude palm oil (CPO) and palm kernel (PK), which yields another type of oil known as palm kernel oil (PKO) and residue known as palm kernel cake (PKC). The wastes generated from processing FFB are known as FFB wastes. The solid wastes include the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS), which represent important biomass in the oil palm industry (Kabir et al., 2017). Another important waste of the industry is palm oil mill effluent (POME), which comprises of all the liquid wastes generated in the palm oil mills. As the demand for palm oil increases, FFB wastes generation will also follow similar trend.

For every 1 kg of palm oil produced, 1.3 kg of FFB solid wastes were produced (Sulaiman et al., 2011); therefore, the total FFB solid wastes produced globally in 2014 was 75 million tonnes. This is equivalent to 8 million tonnes of CPO, 4.7 million tonnes of PK, 21 million tonnes of MF, 7.5 million tonnes of PKS and 23 million tonnes of EFB, respectively. Izah et al. (2016b) reported that Nigeria produced about 0.93 million tonnes of palm oil in 2013, which is equivalent to 1.3, 1.1 and 0.5 million tonnes of EFB, MF, and PKS, respectively.

Most palm oil producing nations in Africa are known for their traditional techniques in FFB processing compared to the world's leading producers – Indonesia and Malaysia. Izah et al. (2016b) reported three scales of FFB processing in Nigeria namely smallholder, semi-mechanised and mechanised mills. However, Ohimain and Izah (2014) and Zu et al. (2012) classified FFB processing into small-scale and large-scale (industrial) mills, and added that the large-scale mill is between 20 - 23 % while the small-scale mill is between 77 – 80 % of FFB production in Nigeria. Ohimain and Izah (2014) and Zu et al. (2012) reports suggested that the smallholder and semi-mechanised scales from Izah et al. (2016) report can be described as small-scale due to the low level of production while the mechanised mill according to Izah et al. (2016b) is the large-scale mill. However, in terms of how the fruits are separated (threshed) from the bunch, FFB processing routes (technology) in Nigeria are better classified into industrial (large-scale or mechanised mill), small-scale (semi-mechanised mill) and traditional (subsistence or smallholder) routes. The industrial route is characterised by the use of large-scale facilities, high throughput (FFB processed per hour of up to 30 tonnes/ha) and high quality palm oil in terms of low free fatty acids (FFA) content of less than 5 %. The FFB are sterilised using steam with fruits still attached to it while threshing of the fruits is carried out afterwards (Ohimain and Izah, 2014). The small-scale route utilises lower technology than the industrial route (Ohimain and Izah, 2014) but more than the traditional route (Izah et al., 2016b). The traditional route is tedious, time consuming and the FFB are usually first quartered to allow for quicker fermentation (Zu et al., 2012). Fermentation makes the removal of the fruit easier, which is one of the functions of sterilisation of the fruits in the

industrial scale. The traditional route is employed by families using manual labour and rudimentary equipment (Izah et al., 2016b) to process FFB for the palm oil consumed by the individual families, the excess palm oil is usually sold and therefore of very low throughput. A FFB comprises of a stalk known as bunch stalk (BS), and fresh fruit spikelet (FFS), which holds the fruits. The FFB in the traditional route is usually first separated into BS and FFS (Nafu et al., 2015) to allow for quick fermentation. Ohimain and Izah (2014) reported that the industrial route uses the wet milling method, while the small-scale and traditional routes uses the dry milling method resulting in dry EFB - quartered EFB or BS/empty fruit spikelet (EFS). The wet milling involves the use of hot water in oil extraction while in dry milling the oil is extracted under pressure (mechanical press). Figure 4-1 A and B, C and D, and E and F are from the industrial, small-scale, and traditional routes, respectively.

Industrial route is known to have increased productivity as well as improved the quality of palm oil giving the ability of processors to process fruits the same day they are harvested, hence the production capacity of Indonesia and Malaysia. However, there are challenges associated with the industrial route regarding utilisation of the EFB, which include low bulk density, and the high moisture content (60 – 70 %) according to Aziz et al. (2017) that will require enormous amount of energy to dry and reduce its size to fit into most existing boilers used in palm oil mill for steam production.

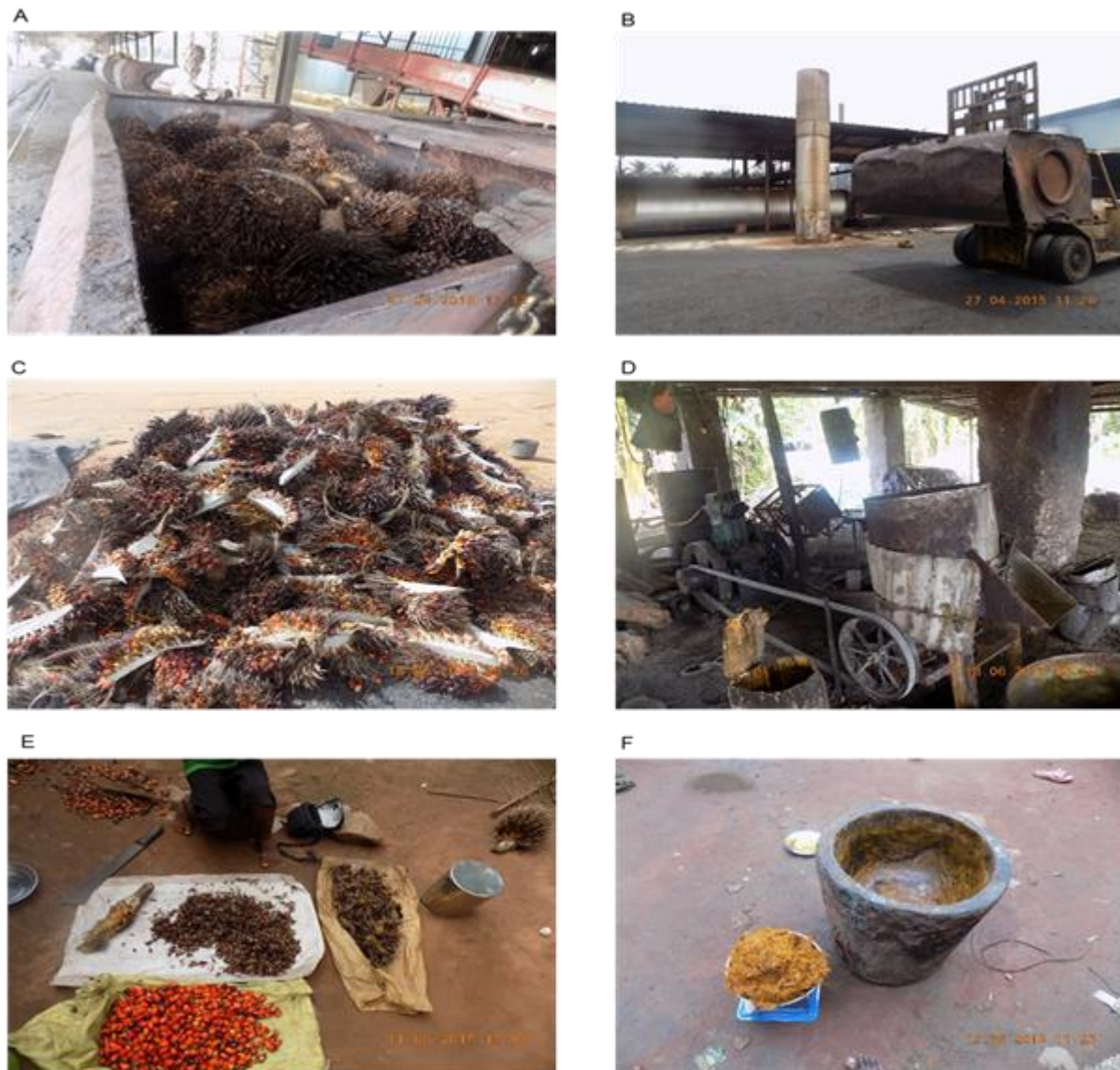


Figure 4-1 (A) sterilised FFB from the industrial route, (B) part of the facilities of the industrial route, (C) quartered FFB from small-scale route, (D) part of the facility of the small-scale route, (E) bunch stalk, empty fruit spikelet and fruits from the traditional route, (F) wooden mortar from the traditional route use in fruit digestion.

Nyakuma et al. (2014) reported that the calorific value of MF and PKS could be improved by reducing the moisture contents, which also applies to EFB. Aziz et al. (2017) demonstrated an increase in efficiency of power generation through EFB gasification from 11.2 to 24.6 % as the gasification temperature increased from 800 to 1000 °C. Kabir et al. (2017) reported 48 % bio-oil yield and 23000

kJ/kg higher heating value during MF pyrolysis. Lee et al. (2017) demonstrated an increase in higher heating values of EFB and PKS biochar to 26200 kJ/kg and 27500 kJ/kg from the corresponding values of the raw fuel of 19700 kJ/kg and 19700 kJ/kg, respectively. Shahbaz et al. (2017) investigated the gasification of PKS and found a maximum syngas production of 61.9 % at the temperature of 692 °C and particle size of approximately 8×10^{-4} m. However, there are limited reports on how the processing of FFB affects the quality of EFB as fuel, and the study of the three processing routes in terms of CPO, PK, MF and PKS yield.

Therefore, the objectives of this study are 1) to determine how the FFB processing routes affect fruit losses, 2) to determine environmental and socio-economic implications of the different processing routes on EFB utilisation as fuel, and 3) to make recommendations on reducing fruit and EFB losses from FFB processing.

4.2 Materials and Methods

4.2.1 Data collection

Two palm oil mills (industrial routes), each 60 tonnes/hr and 30 tonnes/hr mills throughput, respectively, and one small-scale mill (Ohaji, Imo State) of about 0.6 tonnes/hr (small-scale route), which are in South Eastern region of Nigeria (Figure 4-2) were visited in 2015 and 2016. The two mills located in Ikwere, Rivers State and Ohaji, Imo State (industrial routes) are the largest and only mills of 30 tonnes/hr and above within 100 square kilometres of any of the two locations. The traditional route is used more widely in other parts of Imo State. Currently, the 60 tonnes/hr mill gets supply of FFB from the surrounding areas in addition to harvest from their plantations and was used in the analysis for fruit losses. Therefore, the palm oil and wastes from the area are mixture of the three varieties of the oil palm (Dura, Pisifera and Tenera), which are available within the study area. An assumption was that any sample from the area of study is a representative sample. The basic processes for all the routes include

sterilisation, stripping, fruit digestion, oil extraction and oil clarification (Figure 4-3).

These three processing routes of FFB were investigated to determine fruit losses associated with each route. On each day of data collection for the industrial route, FFB were randomly weighed before and after sterilisation. The sterilised FFB threshed in the industrial thresher were randomly weighed and each of them manually threshed to recover the fruits left after the mechanical threshing. The lost fruits (not recovered by the processors) were weighed and recorded. In the small-scale route, the FFB were weighed after reception in the mill and later quartered. After four days when the fruits became detachable from the FFS, the fruits were threshed by manually hammering (using a wooden rod) the quartered FFB by the labourers. The fruits left (not recovered by the labourers) after the hammering operation was manually picked, weighed and recorded. In the traditional route, the FFB were weighed before its separation into BS and FFS. After four days, the fruits were manually removed from the FFS by the labourers. The fruits left (not recovered by the family labour) with the FFS were carefully picked and weighed. The measurements were carried out using Camry Emperors weighing balance (15 kg x 50g).

The unstripped fruits left by the processors with the fruit bunch/spikelet are considered lost because there was no system to recover them without losing CPO, MF, PKS, and PK derivable from the fruits, which are important products. Comparisons were made to determine the significance of the lost fruits for each processing route using analysis of variance carried out using Statistica 12 software (Dell - USA).

The air-dried samples of EFB, MF, and PKS sourced from the small-scale mill visited in South Eastern Nigeria were taken to Cranfield University, United Kingdom and were stored at room temperature in sealed containers for 6 months. The oil palm trees are 9 - 29 years old.

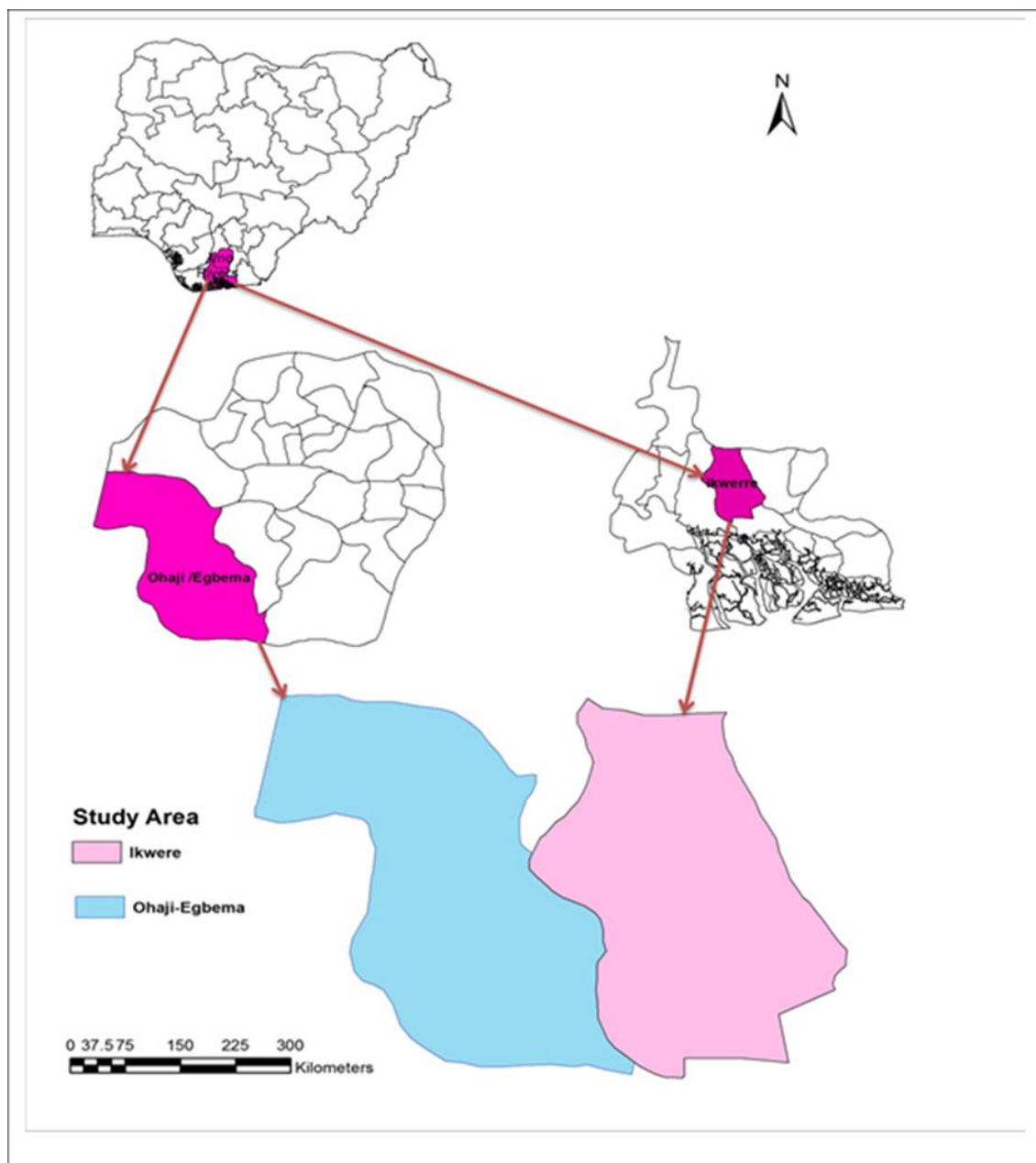


Figure 4-2 Map of Nigeria's regions showing the area of interest in two states of Imo (Ohaji/Egbema) and Rivers (Ikwerre).

The EFB, MF, and PKS were later taken to Marchwood Scientific Services (external laboratory) Southampton United Kingdom, for the determination of the heating values according to British Standards Institute (2011) using the Parr Adiabatic bomb calorimeter model 6100. Similar analyses were carried out a year after for the determination of higher heating values of EFB, MF, and PKS from the three routes at Cranfield University using the Bomb Calorimeter (Parr

6400). The bulk densities and moisture contents of EFB, MF and PKS, were measured as received from the 60 tonnes/hr mill using a 0.018 m³ cylindrical container (0.261 m diameter and 0.332 m height) for PKS and MF, and a 0.146 m³ cylindrical container (0.499 m diameter and 0.741 m height) for EFB (British Standard Institute, 2009 and British Standard Institute, 2011). The bulk densities of quartered EFB, MF and PKS, BS and EFS from small-scale and traditional routes were also determined.

4.2.2 Losses of different processing routes

The fruits left with EFB/spikelets after FFB processing for each of the processing routes were weighed and quantified in terms of CPO, PK, MF, and PKS. A fruit consists of CPO, PK, MF, and PKS. The value of fruit lost for each route was multiplied with the percentage value of each of CPO (10.9 %), MF (28.1 %), PK (6.3 %), and PKS (10 %) per processed FFB as reported by Ohimain et al. (2013), which is the only report in the area of study detailing material-mass balance of FFB. The average values of CPO, MF, PK, and PKS in kg lost (not recovered) calculated were normalised in terms of every 1000 kg of FFB processed. This was done by dividing the product of 1000 and the quantity of CPO, PK, MF, and PKS lost with the total weight of the FFB in each case (Table A-1 – A-3).

4.2.3 Energy losses associated with each processing route

The kWh generated per unit of fuel (EFB, MF, and PKS) was calculated by dividing the fuel heat content (1.055 kJ/physical unit) with the heat rate (kJ/kWh) (Energy Information Administration, 2012) where 1.055 is the conversion factor from Btu to kJ. The value of 15825 kJ/kWh was used as representative heat rate for biomass (Mayhead, 2010) and with the lower heating values of EFB, MF and PKS, the values of EFB, MF and PKS for 1 kg of fuel was estimated in kilowatt-hour (kWh). The energy values lost were estimated by multiplying the lost value of EFB, MF, and PKS with the kWh value, respectively (Table A-4 - Table A-6).

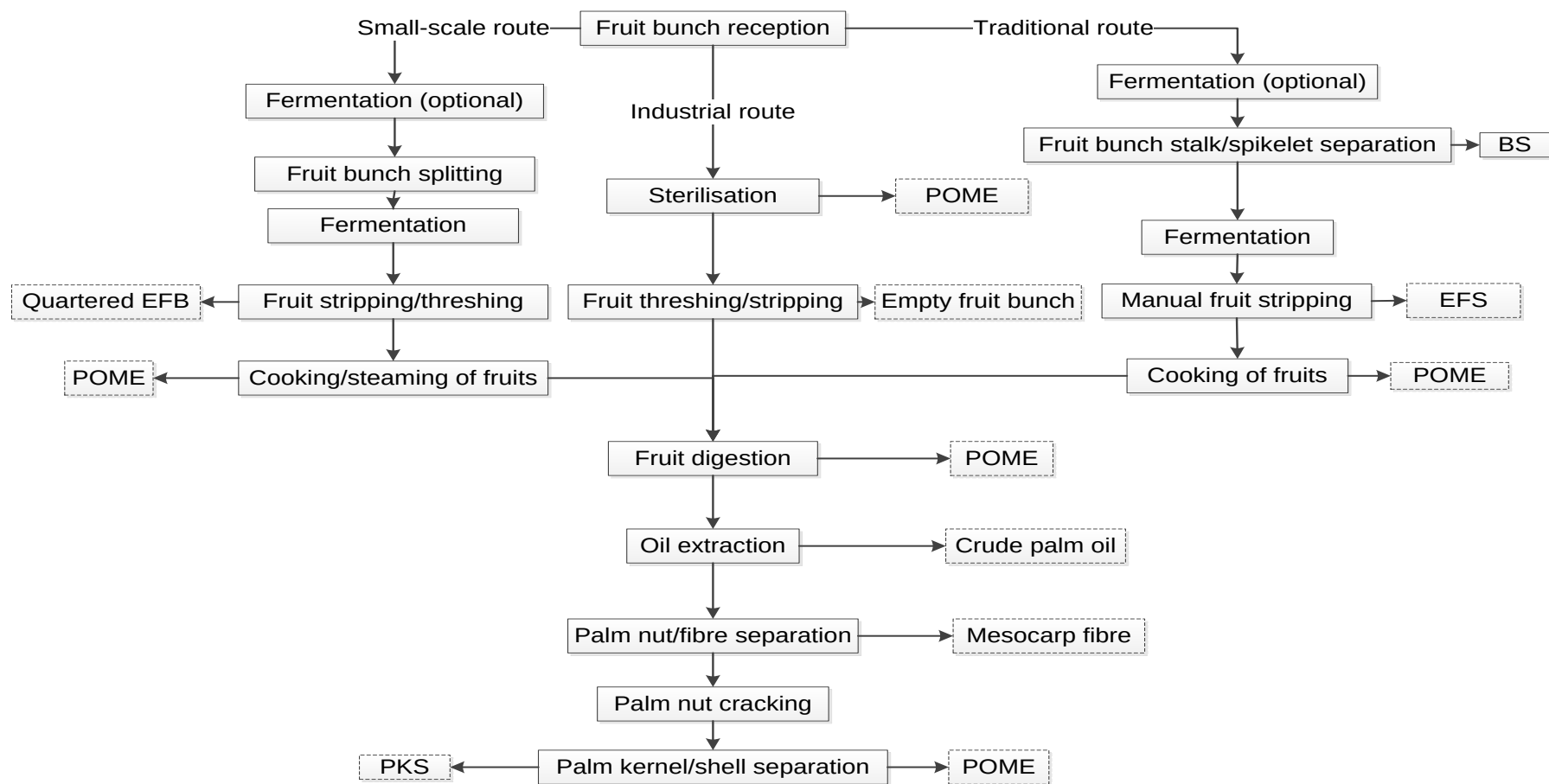


Figure 4-3 Flow chart of industrial, small-scale, and traditional routes of fresh fruit bunch processing showing points of generation of waste. Solid box = process, dashed box = waste/output, EFB – empty fruit bunch, POME – palm oil mill effluent, BS – bunch stalk, EFS – empty fruit spikelet, PKS – palm kernel shell.

4.2.4 Economic Analysis

The economic analysis was carried out for the small-scale route with emphasis on the labour cost and value of CPO as estimated above. The different tasks in the processing of the FFB in the small-scale route were divided into i) quartering of the FFB, ii) dusting and loading of fruits, which have fallen off during the quartering operation into the cooking drum iii) threshing of the quartered FFB, dusting and loading of the fruits into the cooking drum, iv) water supply and cooking operation, v) fruit digestion/oil extraction (pressing), and vi) MF/palm nut separation. Dusting is the process of removing the chaff, which is attached to the base of the fruit. The total costs as calculated were only the costs of labour for each of the tasks by people whose job is to carry out these activities for the mill owners in the area of study. The labour cost of processing the FFB in the small-scale route was measured considering the barrel was filled with fruits. The barrel is the name of the drum used in cooking the fruit. A barrel on average is filled by 125 FFB.

Table 4-1 Total weight of fresh fruit bunch (FFB) and total weight of fruits lost (TWF) from industrial (I), small-scale (S) and traditional (T) routes of FFB processing.

Day number	Number of FFB weighed			Total weight of FFB (kg)			TWF (kg)		
	I	S	T	I	S	T	I	S	T
1	11	27	6	129.1100	236.2500	52.7500	25.6000	0.0096	0.0001
2	12	35	11	189.1500	318.9200	93.5000	42.8000	0.0056	0.0018
3	11	21	6	137.4000	168.0800	50.4300	34.9000	0.0101	0.0011
4	11	18	15	113.5000	180.7200	121.6800	26.8000	0.0144	0.0072
5	14	40	6	190.0300	240.5800	54.0300	56.3000	0.0064	0.0009
6	17	20	10	199.3300	180.3400	90.0800	58.2000	0.0160	0.0014
7	14	28	8	164.4800	263.2300	60.7300	41.5000	0.0134	0.0026
8	13	42	10	137.2000	294.5600	85.8000	47.4000	0.0134	0.0032
9	12	33	15	117.0500	297.7800	119.3500	26.9000	0.0158	0.0048
10	15	20	4	170.5000	178.8500	40.7300	55.2000	0.0086	0.0023
Total	130	284	91	1547.7400	2359.3100	769.0600	415.6000	0.1133	0.0254

Table 4-2 Crude palm oil (CPO), palm kernel (PK), palm kernel shell (PKS) and mesocarp fibre (MF) lost for every 1000 kg of fresh fruit bunch processed for the industrial (I), small-scale (S), and traditional (T) routes.

Day number	CPO (kg)			PK (kg)			PKS (kg)			MF (kg)		
	I	S	T	I	S	T	I	S	T	I	S	T
1	21.61	<0.01	<0.01	12.49	<0.01	<0.01	19.83	<0.01	<0.01	55.72	<0.01	<0.01
2	24.66	<0.01	<0.01	14.26	<0.01	<0.01	22.63	<0.01	<0.01	63.58	<0.01	<0.01
3	27.69	<0.01	<0.01	16.00	<0.01	<0.01	25.40	<0.01	<0.01	71.37	<0.01	<0.01
4	25.74	<0.01	<0.01	14.88	<0.01	<0.01	23.61	<0.01	<0.01	66.35	<0.01	<0.01
5	32.29	<0.01	<0.01	18.67	<0.01	<0.01	29.63	<0.01	<0.01	83.25	<0.01	<0.01
6	31.83	<0.01	<0.01	18.40	<0.01	<0.01	29.20	<0.01	<0.01	82.05	<0.01	<0.01
7	27.5	<0.01	<0.01	15.90	<0.01	<0.01	25.23	<0.01	<0.01	70.90	<0.01	<0.01
8	37.66	<0.01	<0.01	21.77	<0.01	<0.01	34.55	<0.01	<0.01	97.08	<0.01	<0.01
9	25.05	<0.01	<0.01	14.48	<0.01	<0.01	22.98	<0.01	<0.01	64.58	<0.01	<0.01
10	35.29	<0.01	<0.01	20.40	<0.01	<0.01	32.38	<0.01	<0.01	90.97	<0.01	<0.01
Average	28.93	<0.01	<0.01	16.73	<0.01	<0.01	26.54	<0.01	<0.01	74.59	<0.01	<0.01

Table 4-3. Mean ($\pm$ standard error) of the crude palm oil (CPO), palm kernel, palm kernel shell, and mesocarp fibre lost for every 1000 kg of fresh fruit bunch processed in the industrial, small-scale and traditional routes for 10 days of measurement. In each column, values with same letters are not significantly different at 5 % Duncan Multiple Range Test.

Route	CPO (kg)	Palm kernel (kg)	Palm Kernel Shell (kg)	Mesocarp fibre (kg)
Industrial	28.9300 $\pm$ 1.6200a	16.7300 $\pm$ 0.9400a	26.5400 $\pm$ 1.4900a	74.5900 $\pm$ 4.1800a
Small-scale	0.0056 $\pm$ 0.0008b	0.0032 $\pm$ 0.0004b	0.0051 $\pm$ 0.0007b	0.0140 $\pm$ 0.0019b
Traditional	0.0034 $\pm$ 0.0007b	0.0020 $\pm$ 0.0004b	0.0031 $\pm$ 0.0006b	0.0087 $\pm$ 0.0017b

4.3 Results and Discussion

4.3.1 Fresh fruit bunch losses

The total weight of fruits (TWF) from industrial, small-scale and traditional routes of the FFB processing recovered during the experiments are presented in Table 4-1 while the average values of CPO, MF, PK, and PKS in kg estimated from the recovered fruits for every 1000 kg of the FFB processed are presented in Table 4-2. The detail calculations are presented in supplementary Table A-1 – Table A-3. The CPO, PK, MF, and PKS lost in the industrial route are significantly higher ($p < 0.05$) than in the small-scale and traditional routes (Table 4-3). The results showed on the average that 28.9 kg of CPO, 16.7 kg of PK, 74.6 kg of MF, and 26.5 kg of PKS were lost for every 1000 kg of FFB processed in the industrial route while less than 1 kg of CPO, PK, MF, and PKS were lost in the small-scale and traditional routes, respectively. These represent almost 100 % more CPO, PK, MF, and PKS lost in the industrial route than the small-scale and traditional routes for every 1000 kg the FFB processed, respectively. The losses with the small-scale and traditional routes for every 1000kg of the FFB processed were very small and insignificant making them quite efficient in ensuring the fruits are recovered from the FFB.

Under the industrial route, the FFB are sterilised same day they are harvested while for the small-scale and traditional routes, the FFB can stay for few days that subsequently enables the fruits to loosen from the spikelet. Nevertheless, the longer the fruits are allowed to stay before sterilisation, the more the activity of lipase in the mesocarp of the fruit, which leads to increase in the FFA content in the palm oil (Vincent et al., 2014). The FFA level is an important quality indicator of the palm oil (Saad et al., 2007). It is used to measure both the quality of palm oil for food consumption and non-food uses (Hayyan et al., 2013). Overall, low grade CPO has FFA content of more than 5 % (Hayyan et al., 2013). The fresh ripe fruit without any bruises has FFA content of less than 0.3 % (Vincent et al., 2014). The factors responsible for the increase in the FFA content in the oil palm fruits include bruises, time lapse after bruising, and

activity of lipase enzyme in the mesocarp, which increases with time (Vincent et al., 2014). Cooking of palm fruits as carried out by the small-scale and traditional routes, and sterilisation by industrial route, respectively provide the needed heat to inactivate the lipase enzymes, soften the fruits and break the oil-bearing cells to release oil. The heat also makes it easier for the fruits to be detached from the spikelet (industrial route), loosen the attachment between the palm nut and the mesocarp, and between the shell and the palm kernel. Therefore, immediate sterilisation after harvesting of the FFB in the industrial processing route offers the best quality oil in the processing of FFB. As a standard, CPO from large-scale mills (industrial route) have FFA content of less than 5 % (Vincent et al., 2014 and Zu et al., 2012). However, sterilisation of the entire FFB is responsible for high moisture content of EFB.

In addition, another interesting operation is splitting the FFB into quarters and into FFS and BS for small-scale and traditional routes, respectively. The size reduction makes it easier for BS and EFS from traditional route (Figure 4-4A) and the quartered bunches from small-scale route (Figure 4-4B) to dry faster under an ambient temperature condition. The sterilised EFB (Figure 4-4C) from the industrial route with considerable quantity of oil takes a longer time to dry unless an enormous amount of energy is invested. Additionally, the fruit attached to the EFB, which is more in the industrial route, limits its utilisation especially as fuel. The volume generated at any time in the industrial route and the availability of PKS and MF limits the use of EFB as fuel. However, the use of EFB for fuel generation remains an energy option for increased power generation and it is being encouraged in Malaysia (Nasrin et al., 2010).

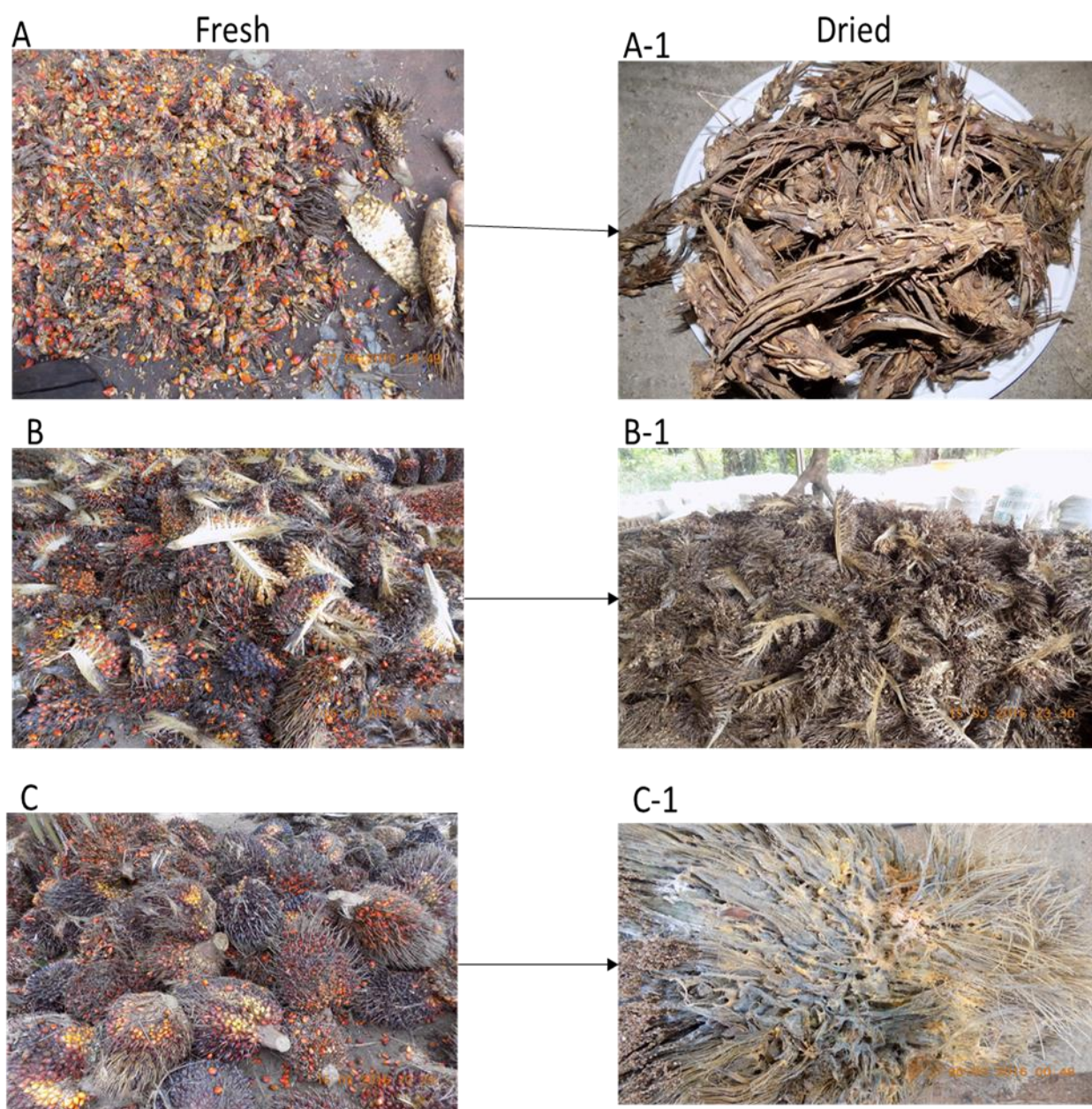


Figure 4-4 (A) Fresh fruit spikelet and bunch stalk of fresh fruit bunch separated in the traditional route, (A-1) natural drying empty fruit spikelet; (B) fresh quartered empty fruit bunch from a small-scale route in Nigeria, (B-1) natural drying empty quartered fresh fruit bunch; (C) fresh fruit bunch, (C-1) natural drying empty fruit bunch processed from an industrial route in Nigeria.

4.3.2 Energy losses

The lower heating values (LHV) and moisture contents “as received” (after more than six months in storage) of the EFB, MF, and PKS from a small scale mill

were determined as 14499, 17846, and 17336 kJ/kg and 14.4, 12.1 and 12 % at the external laboratory, respectively. The moisture contents of EFB, MF, and PKS from the industrial mill as received were determined as 56, 33 and 14 %, respectively. The high moisture content of EFB makes it unsuitable to be used directly as fuel compared to MF and PKS. The heating values of EFB, MF, and PKS determined at Cranfield University for the three routes are presented in Table 4-4. The higher heating values of the EFB was the lowest, followed by that of the PKS for the industrial route. The similar pattern repeated itself for the small-scale and traditional routes. The FFB varieties processed in the study area are similar, which may explain the similarity in the heating values. Expectedly, the bulk density of the EFB was lower than that of the MF, and PKS for the three routes (Table 4-4). However, the bulk densities of the BS, and EFS and the combination of the two were higher than the corresponding value for MF. This is attributed to the relatively good packing with the BS and EFS compared to MF, which supports the importance of size reduction. The values of the MF and PKS lost for each processing route was estimated in kWh using 1.19 kWh and 1.16 kWh as energy value for every 1 kg each of MF and PKS, respectively. Therefore, 89 kWh of energy value was lost from the MF and 31 kWh of energy value was lost from the PKS with the industrial route. An insignificant 0.02 and 0.01 kWh energy values from the MF, approximately 0.01 kWh and less than 0.01 kWh energy values from the PKS were lost for the small-scale and traditional routes, respectively. The detail calculations of the energy values for the MF and PKS are presented in supplementary Table A-4 and Table A-5, respectively and the procedure explained further in Table A-6.

Table 4-4 Bulk density and high heating value (as received) of empty fruit bunch, mesocarp fibre, and palm kernel shell from industrial, small-scale, and traditional routes.

Parameter	Bulk density (kg/m ³)	High heating value (kJ/kg)
		Industrial Route
Palm kernel shell	715	18316
Mesocarp fibre	225	19331
Empty fruit bunch	144	15742
Small-scale route		
Palm kernel shell	705	18645
Mesocarp fibre	219	19846
Quartered Empty fruit bunch	132	15302
Traditional route		
Palm kernel shell	701	18381
Mesocarp fibre	213	19606
Bunch stalk	268	
Empty fruit spikelet	282	
Bunch stalk/empty fruit spikelet	224	15911

As shown in Table 4-5, the energy loss from the industrial route is huge. Data from one of the palm oil mills (industrial route – 60 tonnes/hr mill) visited in 2015 showed that about 95 million kg of FFB was processed in 2014. From Table 4-5, the value of the EFB produced was estimated at 29 million kg. The total energy resources produced in 2014 in the mill was estimated at 70.9 million kWh of which 30.9 million kWh was lost through the poor processing of the FFB. The World Bank report on electrical power consumption in Nigeria in 2014 was 142 kWh per capita compared to the corresponding figures of the United States (12088 kWh), and United Kingdom (5407 kWh). From Table 4-5 the total lost biomass from a single industrial mill in Nigeria in 2014 per capital, considering

population of 167 million people (Ohimain, 2014) was 0.185 kWh in its energy value. The lost energy value is huge and would have been enough to power 3 million homes (10 million kWh per million homes). The electricity consumption and steam demand for the production of 1 kg of palm oil according to Sulaiman et al. (2011), which are approximately 0.1 kWh and 2.5 kg, respectively can be met by burning 0.3 – 0.4 kg of the oil palm wastes. Therefore, over 29 million kg of EFB deposited in the plantation could be used to produce approximately 73 million kg of palm oil.

4.3.3 Environmental impact

The industrial route leads to the generation of more POME, which constitutes environmental hazard, requires high-energy and cost to process and dispose. The POME from small-scale and traditional routes are minimal and manageable. The bulk of the POME is from the water used in the sterilisation of the FFB in the industrial route, the hot water used in oil extraction, and most importantly due to the amount of the FFB processed per hour. Chan et al. (2010) reported that 5 - 7.5 tonnes of water is required for a tonne of CPO production and over 50 % of the water will result in POME in the large-scale mill (industrial route). Conversely, Ohimain et al. (2013) demonstrated that the processing of FFB in the small-scale route led to the production of 3.4 – 12.1 % of water (POME), while Ohimain and Iza (2014) reported 60 - 70 % POME from processing a tonne of FFB in the industrial route. The sterilisation of FFB is responsible for the high moisture content of the EFB, increased the POME generation and consequently the poor utilisation of the EFB for energy purposes.

The disposal of POME pose a serious environmental threat with release of greenhouse gas (methane) and nutrients into surface and underground water (Verla et al., 2014 and Wu et al., 2010). The poor decomposition of the EFB leads to the release of methane and nitrogen oxide up to 0.23 tonne carbon-dioxide equivalent per tonne of FFB processed according to Elbersen et al. (2013).

This is equivalent to the release of 6,670 tonnes carbon dioxide equivalent of methane and nitrogen oxide from the 29 million kg of the EFB disposed of in one of the industrial mill as shown in Table 4-5.

This value equals 0.2 % of United States of America's greenhouse gas emission from wastes composting in 2014 and 2015 (United States Environmental Protection, Agency 2017).

Positive changes towards improving the quality of the EFB from industrial route require the use of less water and therefore small amount of the POME will be generated. Tan et al. (2009) investigated the drying of fruits in place of sterilisation and demonstrated that the lack of water from sterilisation inhibits the action of lipase enzyme responsible for the high FFA content. Sukaribin and Khalid (2009) reported on the effectiveness of sterilisation of the oil palm FFB using microwave technology aimed at reducing oil loss and stripping efficiency. Similarly, Cheng et al. (2011) observed that using microwave for FFB processing improved the quality of CPO. However, it is yet to be reported how commercially viable microwave technology would be in the processing of FFB.

In some countries, incineration of the EFB is forbidden because of smoke pollution (Nieves et al., 2011), which is largely due to the high moisture content of EFB from the industrial route. Though, the EFB dumped in the plantations over time decays and add nutrient to the soil, it is usually applied in excess at the same location (Claoston et al., 2014) especially in combination with the ash from the boilers, which follows the same disposal route. In Nigeria with low power production, using the EFB for energy purposes is a promising option. Igwe et al. (2010) reported that the treatment of the EFB would involve mechanically dewatering and de-oiling, and possible size reduction.

Table 4-5 Data on production for 2014 of one of the palm oil mills in South Eastern Nigeria (approximate values). This mill has a capacity to process 60 tonnes of fresh fruit bunch per hour. Empty fruit bunch (EFB), crude palm oil (CPO), palm kernel (PK), mesocarp (MF), palm kernel shell (PKS).

Parameter	Estimated quantity produced, million kg	Estimated quantity lost, million kg	Estimated Value produced in million kWh	Estimated Value lost in million kWh
EFB	29.0	29.0	28.2	28.2
*¥CPO	10.3	0.3	-	-
*PK	6.0	0.1	-	-
MF	26.7	2.0	31.7	0.3
PKS	9.5	0.3	11.0	2.4
Total	81.5	31.7	70.9	30.9

¥ Actual value produced by the mill in 2014 was about 19 % of FFB processed. *Used mainly as animal feed. 1 kg of EFB = 0.97 kWh.

4.3.4 Socio - Economic impact

The cost of processing the FFB in the small-scale route was compared with the value of lost CPO in the industrial route in order to estimate the possibility of reducing the losses associated with the industrial route. Table 4-6 summarizes the cost estimate of processing the FFB in the small-scale route. The labour cost for processing 125 FFB was ₦5950 Nigeria Naira, which is equivalent to \$21 (1 USA pounds (\$) = ₦282 (Central Bank of Nigeria, 2016). At an average weight of 8.9 kg of a FFB, the labour cost of processing 1000 kg was ₦5348 (\$19). In terms of benefit, the value of 20 kg of oil was ₦5320 (\$19). Therefore, 28.93 kg of oil lost per 1000 kg of the FFB processed from the industrial route was ₦7695 (\$27). The value (\$27) of lost CPO per 1000 kg of the FFB in industrial route can offset the cost (\$19) of processing 1000 kg of the FFB in the small-scale route. This represents a significant amount of money in terms of employment and economic value at the local communities where the FFB are processed. The small-scale and traditional routes of processing the FFB discourage high productivity and reduce the quality of CPO as already explained. Obviously, the industrial route offers more opportunities in employment and wealth generation because of amount of the FFB that can be processed per hour of operation. A balance between the benefits associated with the current industrial route and the losses is very important with the increasing demand for utilisation of the biomass in energy production.

The small-scale and traditional routes are less wasteful but the palm oil from the industrial route is of higher standard because the fruits are processed faster and in shorter time frame between harvest and sterilisation. It can take few hours to process the fruits in the industrial route but minimum of 4 days to process the fruits in the small-scale and traditional routes. The lower grade EFB from the industrial route makes available a waste that can only be disposed of in the oil palm plantation because of its poor quality as energy resource and therefore limits the value. In the small-scale level, the EFB produced is used as fuel, which represents an economic benefit at that level.

Although, the sterilisation and stripping of fruits are important steps in the FFB processing, these processes contribute more to the POME generation and the losses as the above study has shown; therefore new approaches on sterilisation and stripping of fruits are needed. This is important not only to process the fruits at a faster rate with a high quality CPO as the industrial route can do but also to increase the chances of threshing all the fruits from the FFB like the small-scale and traditional routes. Additionally, this will make it easier to use the EFB as a fuel in terms of the low moisture content and high bulk density material, which could increase the transportation and utilisation of the EFB cost efficiently beyond the point of generation.

Figure 4-5 is a process model for increase in the utilisation of the EFB and a catalyst for in economic activity and power generation in Southern Nigeria where the FFB is processed. As stated above, the value (\$27) of the lost CPO per 1000 kg of the FFB in the industrial route can offset the labour cost (\$19) of processing 1000 kg of the FFB in the small-scale route. This represents a significant amount of money in terms of employment and economic value at the local communities where FFB are processed. The local labourer who makes a living by processing 1000 kg of FFB for \$19 could make more money by re-threshing the poorly threshed EFB from the industrial route. The CPO that would be recovered is worth \$27. The involvement of the local labourer, which will be at no cost to the industrial millers will ensure the recovery of all the fruits and drying of EFB for use as fuel to industrial processors creating a closed loop system. The abundance of fuel due to the availability of the EFB will create an opportunity for independent power producers, which can also be spinoffs of the palm oil mills.

Table 4-6 Cost estimation of labour for the small-scale route. All units in ₦ except where stated otherwise. Crude palm oil (CPO), fresh fruit bunch (FFB).

Operation	Cost per barrel (₦)
Quartering of FFB	1250 (₦10 per FFB)
Dusting and loading of fruits threshed during quartering	900
Threshing of FFB, dusting and loading	2000
Providing water for cooking and the cooking operation	500
Fruit digestion and oil extraction (pressing)	1200
Mesocarp fibre and palm nut separation	1000
Total cost of processing a barrel	5950
Cost per FFB	47.60
Average weight of a FFB	8.90 kg
Average weight of 125 FFB	1112.50 kg
Cost of processing 1000 kg of FFB	5348
Average weight of lost CPO from processing 1000 kg of FFB in the industrial route	28.90 kg
Cost of 20 kg of CPO	5320
Cost of 28.93 kg of CPO (same as quantity lost by processing 1000 kg of FFB in the industrial route)	7695.40

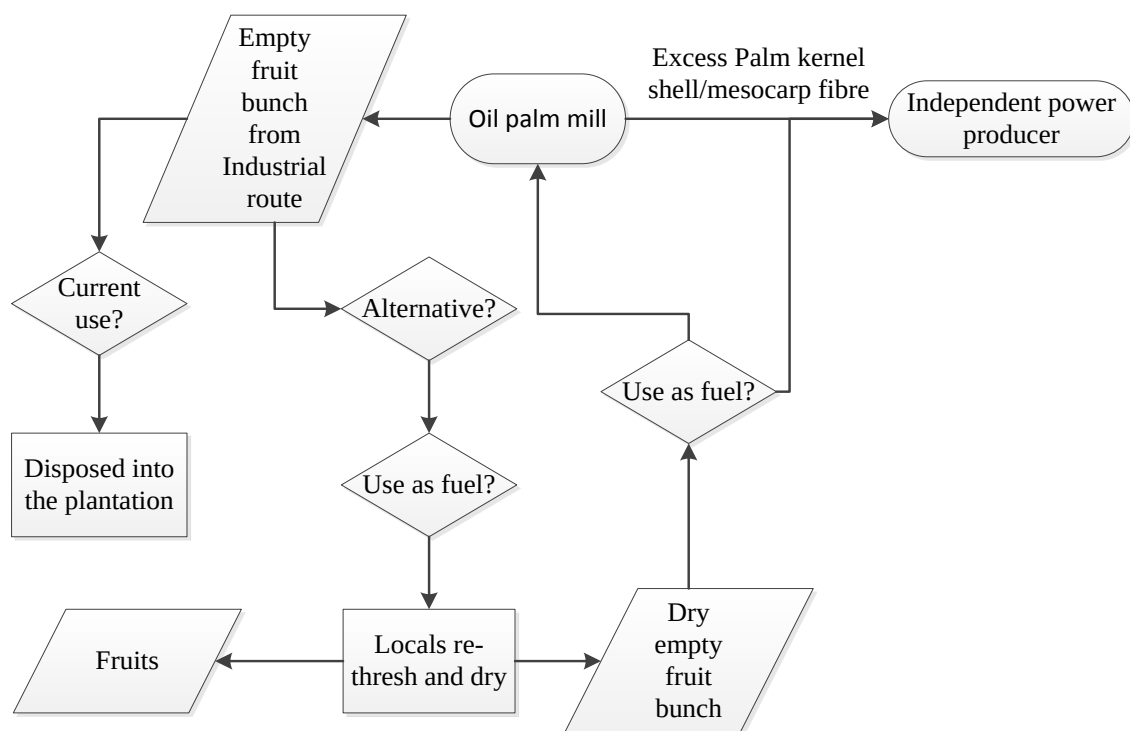


Figure 4-5 Process model for increased utilisation of EFB and a catalyst for economic activity and power generation in Southern Nigeria

4.4 Conclusions

The results of the analysis of losses due to FFB processing routes showed that more CPO, PK, MF, and PKS are lost for every 1000 kg of FFB processed using the industrial route than small-scale and traditional routes. The industrial route of the FFB processing leads to higher energy losses, more methane and nitrogen oxide emissions than the small-scale and traditional routes due to poorly processed EFB. In terms of the amount of FFB processed per hour, the industrial route is recommended; however, there is need to reduce the size of the FFB prior to sterilisation to ensure complete recovery of the fruits during the threshing operation. This will enable the striking hammers to reach all the fruits especially those that are attached closer to the stalk, which are usually difficult to be threshed. Additionally, the use of microwave instead of steam is highly recommended to reduce the moisture content of EFB; however, it could lead to additional cost in FFB processing and therefore require further study. In

summary, further study is needed in the sterilization operations to reduce the size and moisture content of the EFB during the FFB processing operation to ensure a ready to use fuel. Alternatively, it is also recommended that threshed EFB from the industrial route be supplied to the local labourers for re-threshing and drying. The dried EFB will be sent back to the palm oil mills, and independent power producers. Considering the lost energy value, the EFB is enough to power 3 million homes (10 million kWh per million homes); neighbouring communities can be powered in this model. Finally, the utilisation of EFB and POME together in compositing (co-composting) will reduce the effects of poor decomposition of the EFB. The enactment of laws against disposal of EFB particularly will encourage efforts towards better ways of processing of the oil palm FFB.

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5 Co-gasification of Nigerian biomass in a pilot scale 75 kW_{th} downdraft gasifier

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Abstract

The present study focused on co-gasification of the empty fruit bunch (EFB), mesocarp fibre (MF) and palm kernel shell (PKS) in a 75 kW_{th} pilot scale fixed bed downdraft gasifier for possible synergic reactions between these biomass. A series of experiments were carried out comparing the equal mixture of EFB, MF, and PKS with two different particle sizes of PKS and another with the equal mixture of MF and PKS but one particle size of PKS. The Online Fourier transform infrared spectroscopy gas analyser, advanced infrared, and thermal conductivity gas analysers were employed to measure the gases produced. The elemental compositions of the raw biomass, the ash and slag generated were determined using Scanning Field Emission Gun Scanning Electron Microscopy with accelerating voltage of 20.0 kV and working distance of 0.006 m. The co-gasification of the equal mixture of EFB, MF and PKS, compared to the equal mixture of MF and PKS led to higher gas yield (4.82 and 3.47 m³/kg_{biomass}), cold gas efficiency (16.2 and 13.4 %) and carbon conversion efficiency (56.3 and 34.2 %), respectively. Compared to particle size of 0.0140 m, PKS of particle size of 0.0067 m in the equal mixture of EFB, MF and PKS increased the lower heating value of the gas (650 and 780 kJ/m³), the higher heating values of the gas (690 and 830 kJ/m³), reduced the residue yield (4.8 and 3.9 %) and the potassium/calcium ratio (3.69 and 3.63). The overall result has provided evidence on the importance of co-firing biomass especially the EFB,

MF and PKS, which will result in increased utilisation of EFB and reduce emissions due to poor disposal of EFB.

Keywords: Empty fruit bunch, Palm kernel shell, Mesocarp fibre, Residue, Co-gasification

5.1 Introduction

The importance of biomass in reducing the environmental impacts of fossil fuel utilisation has taken centre stage. The utilisation of Biomass for energy production offers a more sustainable option especially in developing world. It is renewable and readily available in different forms and types, and in different parts of the world. Its utilisation for energy generation reduces the challenges of landfills and greenhouse gas emissions.

Nigeria's biomass resources is estimated to be about 144 million tonnes/yr (Diji, 2013a) of which the oil palm (*Elaeis guineensis*) fresh fruit bunch (FFB) solid wastes are important part of it. Izah et al. (2016) estimated that in 2013, 2.894 million tonnes of FFB solid wastes were produced in Nigeria. The other identified biomass resources include sawmill wastes and agricultural wastes (Diji, 2013b). The FFB solid wastes include the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS), which provide energy used for powering boilers in palm oil mills for the processing of FFB. The palm oil mills are known to be independent in power generation using the abundant FFB solid wastes for energy purposes. However, there is reliance on the PKS and MF especially during peak periods of the FFB harvesting with little or no effort in the use of the EFB for energy production. The main challenges of the co-firing of the EFB with MF and PKS are the higher relative particle size of the EFB and the higher moisture content due to sterilisation. These will require size and moisture reduction before the EFB could be co-fired with the MF and PKS. The EFB, which is up to 32 % by weight of the FFB (Ohimain et al., 2013), is therefore dumped in the plantation with attendant environmental challenges including greenhouse gas emissions as it decomposes. However, there is an increasing interest in the utilisation of EFB for energy purpose including in

Malaysia (Nasrin et al., 2010), which is the second largest palm oil producer in the world after Indonesia (Sembiring et al., 2015).

Biomass is composed of cellulose, hemicellulose, lignin, extractives (resin compounds, fatty acids and sterols.), elements, minerals, moisture, and ash, (Mckendry, 2002). These characteristics determine the use of the biomass in the conversion process. Similarly, the differences in chemical compositions of EFB, MF and PKS are the result of their structural and metabolic functions within the oil palm tree (García-Núñez et al., 2008). According to García-Núñez et al. (2008) potassium and sodium salts in the biomass can act as catalysts in the thermal degradation of cellulose while calcium promotes the degradation of hemicellulose. These catalyst elements reduce degradation temperature, and therefore increase the reaction rate and char yield (Zaror et al., 1985).

García-Núñez et al. (2008) investigated the thermal degradation of EFB, MF and PKS using thermogravimetric and differential scanning calorimetric analyses and compared the effects of sample sizes, extractives and ash on thermal behaviour of the biomass. The authors concluded that ash and extractives had a strong effect on EFB thermal behaviour. Idris et al. (2010) investigated thermogravimetric behaviour of coal, EFB, MF and PKS with their blends. The authors reported an increase in volatile matter released as the proportion of EFB, MF and PKS increased in the blends except with 60:40 and 50:50 coal:PKS blends, which could be attributed to more volatile matter of the biomass. Notably, Idris et al. (2010) concluded that there was no thermal reaction of the blends of EFB, MF and PKS with coal.

The ash/residue content is an important property of biomass, which influences decisions in biomass thermal conversion operations. The ash forming elements in biomass include alkali earth metals and alkali metals. Some of these elements available in ash are important in agriculture. The challenges associated with ash in thermal conversion system are bed agglomeration and slagging on the furnace, fouling of heat transfer systems (Cotton et al., 2014; Lahijani and Zainal, 2011). The ash especially in downdraft gasifier could block the flow of the produced gas. These will reduce system efficiency and result in

increased operational cost (Chin et al., 2015). The utilisation of biomass in thermal conversion operations will lead to increase in biomass ash generation due to the quantity of the biomass being used. The challenge of ash disposal/utilisation requires that measures be put in place before and during the thermal conversion process to reduce the amount of the ash that would go to landfills and as well increase agricultural utilisation of the residues. The increase in the utilisation of biomass for energy generation would require the use of a mixture of different biomass particularly biomass from the same source. Therefore, optimising the effects of the co-firing on thermal conversion process efficiency, thermal conversion infrastructure, and on ash yield and properties is imperative.

Research on gasification has advanced over the years leading to increased utilisation of both fossil fuels and biomass, more importantly the utilisation of the blends of coal and biomass. As efforts are being made to increase the utilisation of EFB, co-firing offers a better option. For example, Moghadam et al. (2014) co-fired PKS with polyethylene in a fluidized bed gasifier, which produced the gas yield of 422 g syngas/kg feedstock at a temperature of 800 °C, a polyethylene/PKS ratio of 1:0.3, and a steam/feedstock ratio of 1:1. Moghadam et al. (2014) concluded that the faster degradation of polyethylene led to increased conversion of the feedstock to gaseous products. However, there are limited reports on the effects of the co-firing of a blend of EFB, MF, and PKS on the outputs. The aim of this study is to determine the effects of blending of EFB, MF and PKS on the gasification performances. The specific targets are (i) to compare the co-gasification of equal blend of MF, and PKS and equal blend of EFB, MF, and PKS in a fixed bed downdraft gasifier, (ii) to determine the effects of two different particle sizes of 0.0140 and 0.0067 m for PKS on the co-gasification of equal blend of EFB, MF, and PKS, and (iii) to evaluate the differences between the residues (ash) from the co-gasification of equal blend of MF and PKS and equal blend of EFB, MF, and PKS.

5.2 Materials and methods

5.2.1 Raw material

The air-dried EFB, MF and PKS, used in the gasification experiments were imported from Nigeria. The PKS was sorted using 0.0140 and 0.0067 m sieves while the EFB was first crushed using a locally made hammer mill at Imo State Polytechnic Umuagwo, Nigeria and was later sorted to pass through a 0.0140 m sieve. Most of the materials in the PKS above 0.0140 m were poorly cracked and the uncracked palm kernel nuts. The “as-received” MF passed through the 0.0067 m sieve. The heating values, proximate and ultimate analyses were analysed for the fuel (British Standards Institute, 2011a, 2011b, 2011c), respectively at Marchwood Scientific Services (external laboratory) Southampton United Kingdom. Additionally, the higher heating value of the different blends of EFB, MF, and PKS were also determined using bomb calorimeter (Parr 6400 from the Parr Instrument Company United States of America) at Cranfield University.

5.2.2 Experimental set-up

Figures 5-1A, B and C are pictures of the 75 kW_{th} pilot scale downdraft gasifier, inside of the reactor during one of the co-gasification experiment, and the tar-sampling unit, respectively. The experimental set-up consists of a downdraft reactor, biomass feeding section, air supply unit, temperature monitoring section, gas cleaning and sampling section, ash collection system, and gas analysis section. Figure 5-2A is a schematic diagram of the 75 kW_{th} pilot scale downdraft gasifier used in the co-gasification experiment including the tar sampling unit, while Figure 5-2B represents the sampling locations. The gasification unit is cylindrical refractory vessel of 0.65 m high measured from the grate and internal diameter of 0.24 m. The height of the gasifier from the hopper to the cylindrical refractory vessel was 1.35 m. The air/nitrogen supply hose, an ignitor, and thermocouples for temperature measurement were mounted at different points on the gasifier chamber. Type K thermocouples were used. The ignitor, which is electrically operated is located below the grate

to ignite the biomass. The biomass settles on a grate during the gasification process. The ash collection system consists of two pots, one for bottom ash and the other for fly/cyclone ash. The gaseous products pass through the gas conditioning units and are either collected for further analysis or discharging to the atmosphere after flare. After each run of experiment, the gasifier was allowed to cool and the fly ash and bottom ash were removed. Three gas analysers: Protea “atmosFIR” online Fourier transform infrared spectroscopy (FTIR) gas analyser, advanced infrared multi-gas analyser MGA300 (Siemens Ultramat 2), and thermal conductivity gas analyser (Siemens Calomat 2) were employed to measure the produced gases.

The tar sampling unit was developed to operate under isokinetic conditions using standard protocol-BSI DD CEB/TS 15439:2006 (British Standard, 2006). The tar-sampling unit consists of 1) gas preconditioning unit for gas cooling and pressure reduction, 2) particle collection unit to separate and collect solids, 3) tar collection unit for moisture and tar condensation using 6 impinger bottles, 4) gas volume measurement unit for gas suction, measurement and off-gas handling (Figure 5-1C).

Five of the six bottles were filled with Isopropanol for tar absorption while the sixth bottle was left empty. Isopropanol is considered suitable for use with the gas chromatography program. The bottles were arranged into hot bath (temperature between 35 °C and 40 °C) for bottle 1, 2, and 4 and cold bath (temperature between -15 °C and -20 °C) for bottle 3, 5, and 6. The impinger bottles 2, 3, 5, and 6 were fitted with glass frits at the end of the connecting tubes.

The samples of tars and particulate matter were trapped in the heated and/or chilled impinge bottles and heated particulate filter, respectively. Thimble filters were used with a diameter of 0.03 m and a length of 0.10 m with a retention capacity of 99.9 % for particles of size 0.30 microns. The sampled gas volume was measured under dry conditions using a gas meter. The tar and particulate samples collected were stored in a sealed, dark bottle and kept at a temperature below 6 °C for further analysis.

5.2.3 Experimental procedures

A series of experiments with the equal mixture by weight of MF and PKS denoted as the MP, and equal mixtures by weight of EFB, MF, and PKS denoted as the EMP1 and EMP2 were carried out using the gasifier. The EMP1 has PKS of particle size 0.0140 m while the EMP2 has PKS of particle size 0.0067 m. Figures 5-3A, B, C, D and E are EFB, MF, PKS, the mixture of EFB, MF, and PKS of 0.0067 m particle size, and the mixture of EFB, MF, and PKS of 0.0140 m particle size used in the experiment. A total of 16.8, 21.4, and 13.5 kg of the MP, EMP1, and EMP2 were used in the gasification experiments, respectively. The gasifier can hold between 10 – 15 kg of biomass depending on the characteristics of the fuel. The air supply valve was left closed initially while the ignitor was switched on. After about five minutes of igniting the fuel, the ignitor was switched off while the air supply was opened. The biomass were fed in batches at a feeding rate of 2.8 kg/h and the process was continuously monitored to ensure there was smooth gasification. The next batch of each run was fed after flame was seen through the viewpoint, which is situated above the grate. The operating parameters are given in Table 5-1. The gasifier temperature was maintained at 800 °C by varying the air/nitrogen ratio. This is done by adjusting the airflow rate or by introducing nitrogen into the reactor. Few occasions during the operations, the grate was blocked by the PKS, which slowed down the process and was reopened by hitting on the body of the reactor closer to the grate.

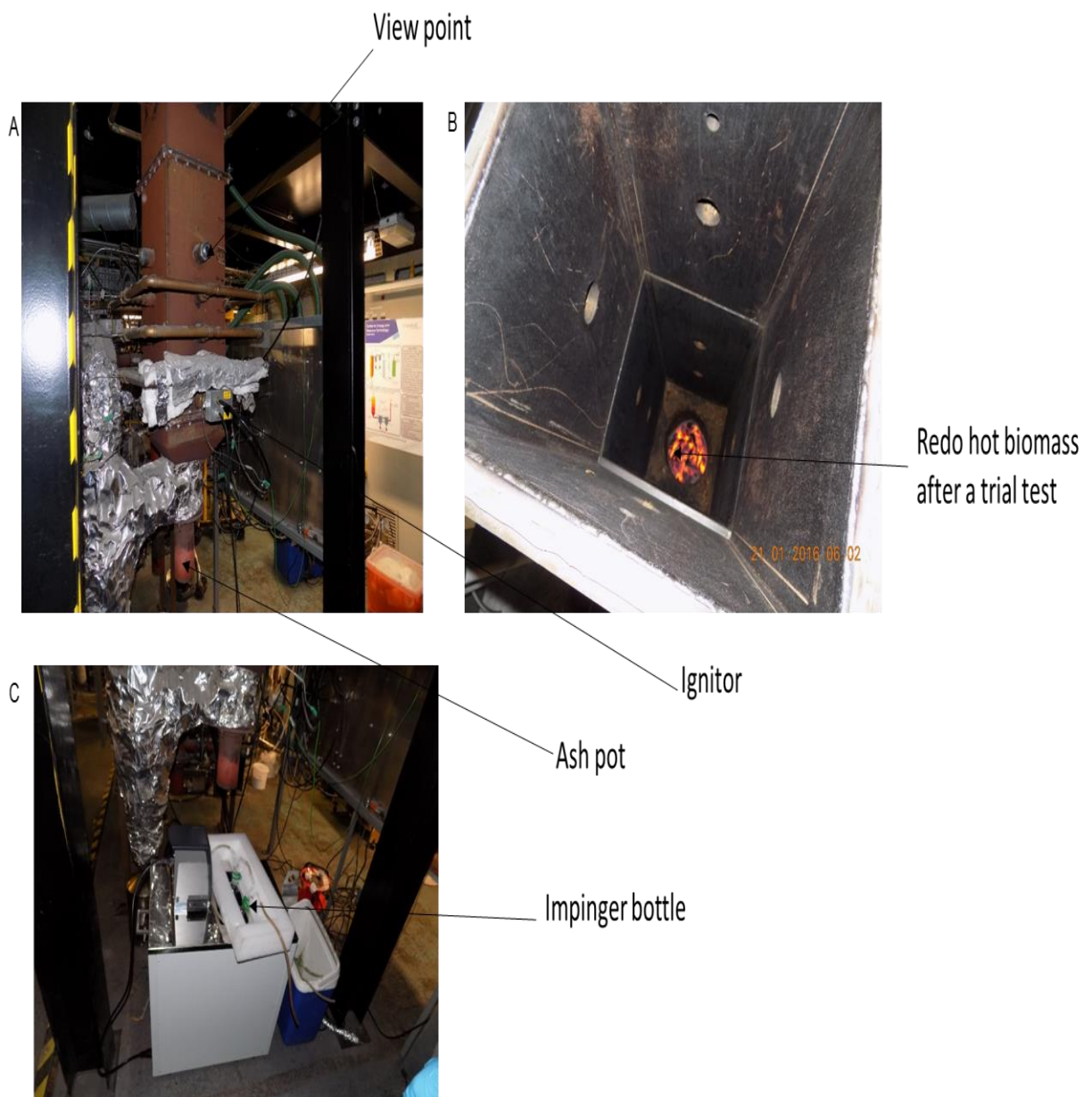


Figure 5-1 (A) The 75 kW_{th} pilot scale downdraft gasifier, (B) inside the reactor during one of the tests, and (C) the tar-sampling unit.

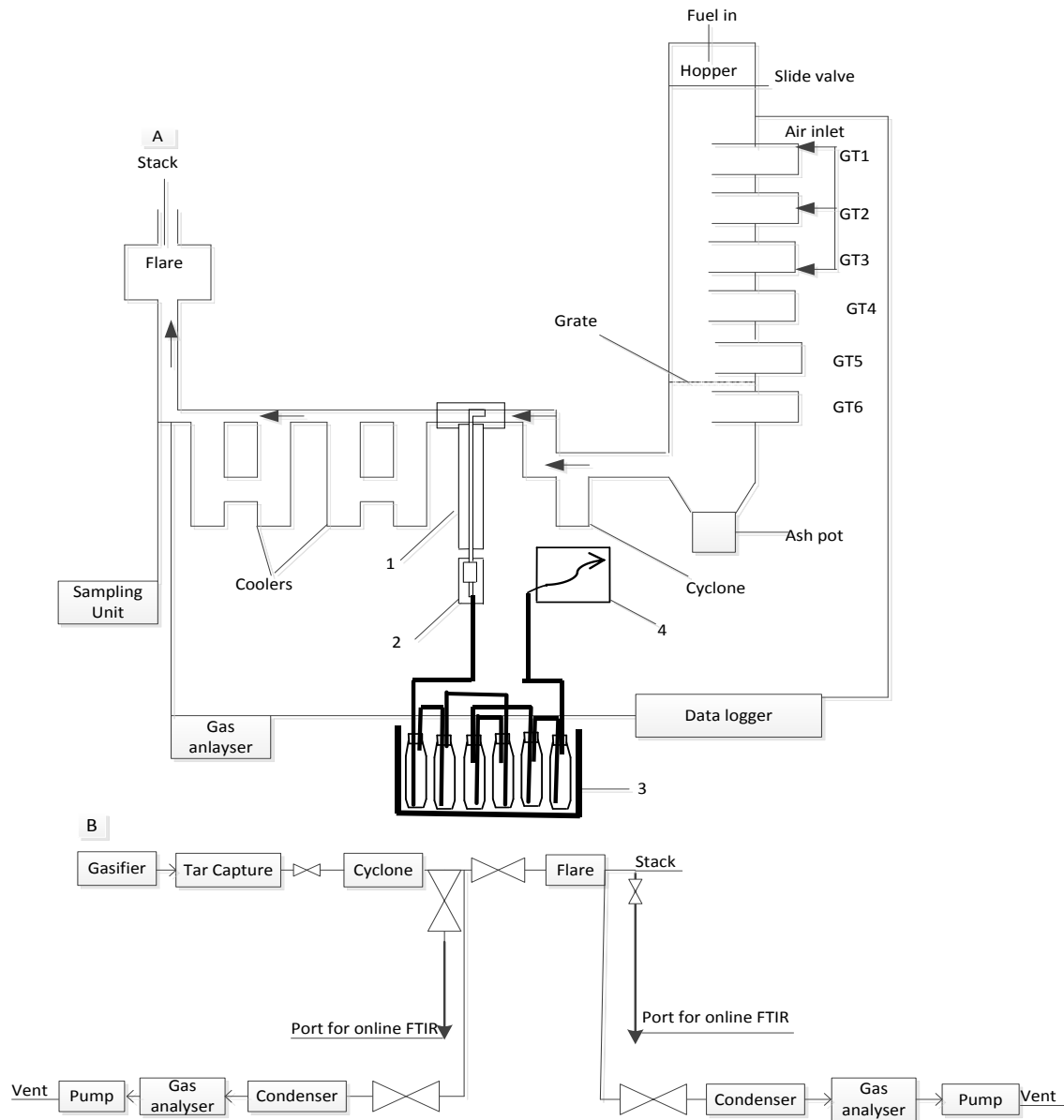


Figure 5-2 (A) Schematic diagram of the 75 kW_{th} pilot scale gasifier and tar sampling unit used in co-gasification of empty fruit bunch, mesocarp fibre and palm kernel shell. (B) Gasifier sampling locations during the test. 1 - Gas preconditioning unit for gas cooling and pressure reduction, 2 - particle collection unit to separate and collect solids, 3 - Tar collection unit for moisture and tar condensation using 6 impinger bottle, 4 - Gas volume measurement unit for gas suction, measurement and off-gas handling.

The gasification process occurs in the following sequence from top to bottom: heating up>flaming pyrolysis>reduction upper layer>reduction lower layer. The heating up is the layer at which introduction of biomass happened and where the mass gradually heat ups from bottom to the top. The biomass devolatilisation takes place at the flaming pyrolysis zone. Gasification occurs in the reduction layer, which includes upper layer (reduction reaction) and lower layer (ash bed). The syngas and ash are produced in this layer. The ash and syngas passed through the grate and the bottom ash settled in the ash pot beneath. The fly ash was collected by the cyclone and the syngas passed through to the cooling system for tar and water condensation. The gas sampling unit was used to clean the dirty gaseous products before it enters into the gas analyser. The gases measured were CO, CO₂, CH₄, and H₂ for the MP, EMP1 and EMP2 fuel mixtures. Finally, the gas passed through a flare and to an exhaust.

The Protea “atmosFIR” online FTIR gas analyser was used to determine the volumetric compositions of CO₂, CO, and CH₄ only. Additionally, this study used advanced infrared multi-gas analyser using non-dispersive infrared absorption with solid-state detector for measuring CO₂, CO and CH₄ for the MP, EMP1 and EMP2, and the thermal conductivity gas analyser was used for measuring H₂. The compositions of CO₂, CO, CH₄ and H₂ were measured at intervals of every 5 seconds. The Pico Technology data logger was used to monitor the temperature profile continuously throughout the gasifier chamber at every 5 seconds interval for the duration of the operations.

Table 5-1 Operating parameters for the fixed-bed downdraft gasifier.

Parameter	MP	EMP1	EMP2
Biomass particle size (m)	0.0140	0.0140	0.0067
Temperature (°C)	800	800	800
Biomass feeding rate (kg/hr)	2.8	2.8	2.8
Flowrate (l/min)			
Air	160	160	160
N₂	<20	<20	<20
Equivalence ratio	0.54	0.59	0.59

MP – feedstock of the equal mixture of mesocarp fibre and palm kernel shell, EMP1 - feedstock of the equal mixture of empty fruit bunch, mesocarp fibre and palm kernel shell of 0.0140 m, EMP2 - feedstock of the equal mixture of empty fruit bunch, mesocarp fibre and palm kernel shell of 0.0067 m. Equivalence ratio is equal to the ratio of the actual air-fuel ratio stoichiometric air-fuel.

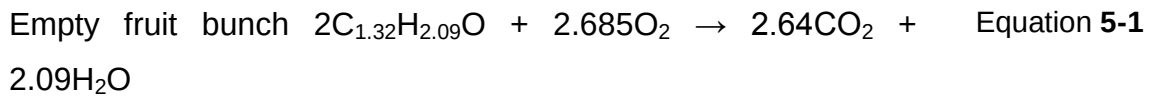
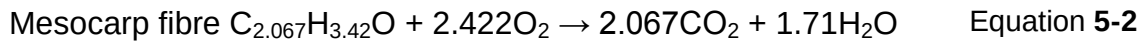
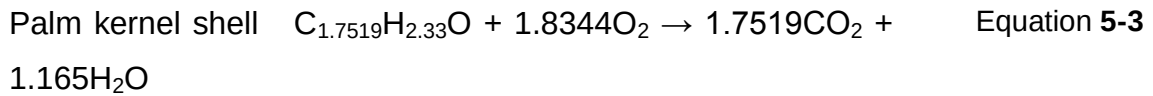


Figure 5-3 Fresh fruit bunch solid wastes (A) empty fruit bunch, (B) mesocarp fibre, (C) palm kernel shell, (D) mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell of 0.0067 m particle size, and (E) mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell of 0.0140 m particle size.

Several assumptions were considered in this study and they are:

- The biomass were evenly mixed
- A stoichiometric air fuel ratio was considered
- An average biomass calorific value was used

The chemical expressions of the biomass used in this study are (more information are presented in Appendix B-1):



The equivalence ratio was calculated according to equation 5-4

$$ER = AF_{actual}/AF_{stoichiometric} \quad \text{Equation 5-4}$$

AF_{actual} is the actual air-fuel ratio, which is equal to the amount of oxidant injected into the gasifier divided by the amount of biomass. $AF_{stoichiometric}$ is the stoichiometric air-fuel ratio, which is equal to the amount of air needed to burn the biomass divided by the amount of biomass.

The gas yield in $m^3/kg_{biomass}$ was calculated according to equation 5-5 (Kallis et al., 2013)

$$Y_{gas} = V_{gas}/Mass_{biomass} \quad \text{Equation 5-5}$$

V_{gas} is the volumetric flow-rate of the dry gas in m^3/hr calculated using the output gas flow-rate, while $\text{Mass}_{\text{biomass}}$ is the biomass mass feed rate in kg/hr

The lower heating value (LHV_{gas}) in kJ/m^3 of the gas produced was calculated according to equation 5-6 (Kallis et al., 2013), while the higher heating value (HHV_{gas}) in kJ/m^3 was estimated according to equation 5-7 (Kallis et al., 2013).

$$\text{LHV}_{\text{gas}} = (12.63 \cdot \text{CO} + 35.82 \cdot \text{CH}_4 + 10.8 \cdot \text{H}_2) / 100 \quad \text{Equation 5-6}$$

$$\text{HHV}_{\text{gas}} = (12.63 \cdot \text{CO} + 39.82 \cdot \text{CH}_4 + 12.75 \cdot \text{H}_2) / 100 \quad \text{Equation 5-7}$$

The values used for CO, CH_4 , and H_2 were the compositions of the species in the gas product.

The cold gas efficiency (CGE) and the carbon conversion efficiency (CCE) are important indicators of the gasification process. The CGE, which is the ratio of the energy in the produced gas to the energy in the biomass was calculated according to equation 5-8 (Inayat et al., 2016).

$$\text{CGE \%} = (Y_{\text{gas}} \cdot \text{HHV}_{\text{gas}} / \text{HHV}_{\text{biomass}}) \cdot 100 \quad \text{Equation 5-8}$$

LHV_{gas} is the lower heating value of the gas product, Y_{gas} is the gas yield in $\text{m}^3/\text{kg}_{\text{biomass}}$, and $\text{LHV}_{\text{biomass}}$ is the lower heating value of the biomass used, while HHV_{gas} and $\text{HHV}_{\text{biomass}}$ are the higher heating values of the gas and biomass, respectively.

The CCE, which is the ratio of carbon in the syngas to the carbon in the biomass, was determined according to equation 5-9 (Kallis et al., 2013):

$$\text{CCE \%} = [12 \cdot Y_{\text{gas}} \cdot (\text{CO \%} + \text{CO}_2 \% + \text{CH}_4 \%) / (22.4 \cdot \text{C \%})] \cdot 100 \quad \text{Equation 5-9}$$

The compositions of CO, CO₂ and CH₄ in the syngas gas were used in the calculation of the CCE, and C is the percentage composition of the carbon from the ultimate analysis.

The fly/cyclone ash and bottom ash were collected after each experimental run. The ash was used as soil amendment to test the effects of ash on the properties of a loamy sand soil and cassava yield in Nigeria (results are presented in chapter 6). The experimental residue yield for each of the experimental test was measured by weighing ash, char and the slag left. The calculated residue yield was according to equation 5-10 (Ogi et al., 2013)

Yield of solid residues wt.% = (weight of solid residue/weight of biomass feedstock)*100 Equation 5-10

The elemental compositions of the raw biomass, the ash and slag generated were determined using Scanning Field Emission Gun Scanning Electron Microscopy (SFEG SEM) with accelerating voltage of 20.0 kV and working distance of 0.006 m. The samples were first coated with Gold and the measurements processed using AztecEnergy V2.2 software.

The detail calculations are presented in supplementary appendix B including Table A-7.

5.2.4 Accuracy and error

Calomat 2

The calomat 2 is a thermal conductivity gas analyser used to measure a sample gas mixture and to calculate the concentration. The analyser can carry out internal cross correction after transmission of the external measuring results. The calomat 2 operates with a micro-mechanically manufactured silicon chip with a measuring diaphragm, which contains thin-film resistors. The magnitude of the resistors, which are regulated at a constant temperature, assumes a particular value depending on the thermal conductivity of the sample gas. The raw value is further processed to calculate the gas concentration. The

interfering gases in this analyser contribute to inaccuracies; therefore the resulting error can be up to 5% of the smallest measuring range.

Ultramat 2

The multicomponent gas analyser ultramat 2 is used to analyse CO, CO₂, H₂ and CH₄ based on the molecule specific absorption of bands of infrared radiation, which is peculiar to the individual gases. A micro-flow sensor converts a generated pulsating flow into an electric signal. The micro-flow sensor consists of two nickel-plated grids, which form a Wheatstone bridge with two supplementary resistors. The change in resistance as a result of the pulsating flow causes offset in the bridge depending on the concentration of the sample gas. The error is less than 1 % of the full-scale value.

Pico thermocouples

The principle of a thermocouple is that a voltage is generated between the junction of two metals when there is a temperature difference. The accuracy depends on the temperature range and the thermocouple type, which are B, E, J, K, N, R, S, and T. The error is very small.

Protea “atmosFIR” online Fourier transform infrared spectroscopy gas analyser

The Protea atmosFIR online FTIR gas analyser was used to determine the volumetric compositions of CO₂, CO, CH₄. The online FTIR collects a full infrared spectrum continuously allowing the different gases to be detected and measured at once. The single calibration spectrum is used as a reference to predict the concentration in the samples. It has error of less than 2%.

Downdraft feeding system

During the experiments, the gasifier was fed in batches by opening the hopper. The rate of fuel consumption influences the feeding rate and thus changes the gasification condition. The sources of error are due to air supply and limited repeat tests.

5.3 Results and discussion

5.3.1 Biomass characterization

Table 5-2 shows the proximate and ultimate analyses of Nigerian EFB, MF and PKS as well as the higher heating value (HHV) and lower heating value (LHV). There is consistency in the HHV and LHV for EFB, MF and PKS with values decreasing in the following order: MF>PKS>EFB. This is important considering the fact that MF and PKS are used more than EFB as fuels. The moisture contents “as received” for the biomass were below 15 % making it suitable for use directly as fuel. The ‘dry basis’ ash content of EFB and MF are higher than that of PKS by 3.4 and 3.8 times respectively, which agrees with García-Núñez et al. (2008). The fixed carbon and volatile matter contents of the biomass are similar, which agrees with a report by Idris et al. (2010).

Table 5-2 Chemical properties of the empty fruit bunch, mesocarp fibre, and palm kernel shell as measured by the external laboratory (dry basis).

Parameter	EFB	MF	PKS
Proximate analyses (%)			
Moisture (as received basis)	14.40	12.10	12.00
Fixed carbon	8.80	8.10	7.60
Ash	5.10	5.50	1.70
Volatile matter	86.10	86.40	90.40
Ultimate analyses (%)			
C	43.80	52.10	52.30
H	5.80	7.20	5.80
N	0.50	1.00	0.40
Cl	0.33	0.38	0.03
S	0.10	0.20	0.02
O (by difference)	44.40	33.60	39.80
HHV (kJ/kg)	18580	22170	21260
LHV (kJ/kg)	17470	20840	19980

all in % w/w except where it is stated otherwise. EFB - empty fruit bunch, MF - mesocarp fibre, PKS - palm kernel shell, HHV – higher heating value of the biomass, LHV - lower heating value of the biomass. The higher heating values for the equal mixture of mesocarp fibre and palm kernel shell blend, the equal mixture of and empty fruit bunch, mesocarp fibre and palm kernel shell blend were 21720 kJ/kg and 19940 kJ/kg, respectively using the bomb calorimeter (Parr 6400).

5.3.2 Gaseous product yield

The temperature profiles of the experimental runs are presented in Figures 5-4A, B and C. The longest time (70 minutes) it took for heat to propagate upwards was during the gasification of the MP, which was a mixture of MF and PKS. The PKS due to its higher lignin content (44 % compared to 21.3 and 27.3 % for EFB and MF, respectively) (Abnisa et al., 2013), hard structure and bigger particle size led to poor heat transfer and slow start to gasification (Figure 5-4A). The high lignin content is associated with a higher degradation temperature (Sembiring et al., 2015). The initial phase temperatures of the EMP1 and EMP2 were within the range of 30 to 40 minutes, which was an indication of the feedstock mixture (EFB, MF, and PKS). Conversely, the gasification phase of the EMP1, and EMP2 showed similarity and lasted longer than the MP. The PKS in the MP mixture started burning at the later stage of the process but the built up heat was able to complete the process in a shorter time, while the combination of the EFB and MF in the EMP1 and EMP2 initiated the process due to their relatively higher quantity than PKS. They continue to burn faster than the PKS, while the PKS continue to build up heat gradually leading to a longer gasification phase. These were evident in the flaming pyrolysis, reduction upper layer, reduction lower layer and heat up temperature profiles for the EMP1, and EMP2, which were different from those of MP. The quantity of the PKS in the MP relative to its quantity in the EMP1 and EMP2 also led to overall very low average temperatures for heat up and flaming pyrolysis stages for the MP (Figure 5-4).

The slow start to rise in the temperature for the MP led to slow start to the yield of the gaseous species after 75 minutes (Figure 5-5A) while the EMP1, and EMP2 took less than 15, and 30 minutes, respectively (Figures 5-5B and C). The variations in the feedstock of the MP, and EMP1 and EMP2 also led to a more sinusoid-like profile of the gaseous species for the EMP1, and EMP2, than the MP, which corresponded to the heat build-up inside the reactor. The results are similar to that as measured by the Protea “atmosFIR” online FTIR gas analyser for the MP and EMP1 (Figures 5-6A and B, respectively). The lower heating value of the MP gas was higher than those of the EMP1, and EMP2, (Table 5-3), which could be due to the relatively high higher heating values of the feedstock of the MP.

Table 5-3 The gasification results for the different biomass mixtures.

Parameter	MP	EMP1	EMP2
Gas composition (mol. %)			
CO ₂	6.01	7.72	8.64
CO	2.90	2.69	3.18
CH ₄	0.69	0.36	0.53
H ₂	1.54	2.89	1.73
Gas yield (m³/kg_biomass)	3.47	4.82	4.60
Lower heating value_gas (kJ/m³)	780	650	780
Higher heating value_gas (kJ/m³)	840	690	830
Cold gas efficiency (%)	13.37	16.20	18.54
Carbon conversion efficiency (%)	34.18	56.30	61.65
Yield of ash (wt.%)	1.55	3.16	2.59
Yield of slag (wt.%)	0.39	1.67	1.35
Yield of char (wt.%)	2.14	nm	nm
Yield of solid residues (wt.%)	4.08	4.84	3.94

nm –not measureable, MP – feedstock of the equal mixture of mesocarp fibre and palm kernel shell, EMP1 - feedstock of the equal mixture of empty fruit bunch, mesocarp fibre and palm kernel shell of 0.014 m, EMP2 - feedstock of the equal mixture of empty fruit bunch, mesocarp fibre and palm kernel shell of 0.0067 m.

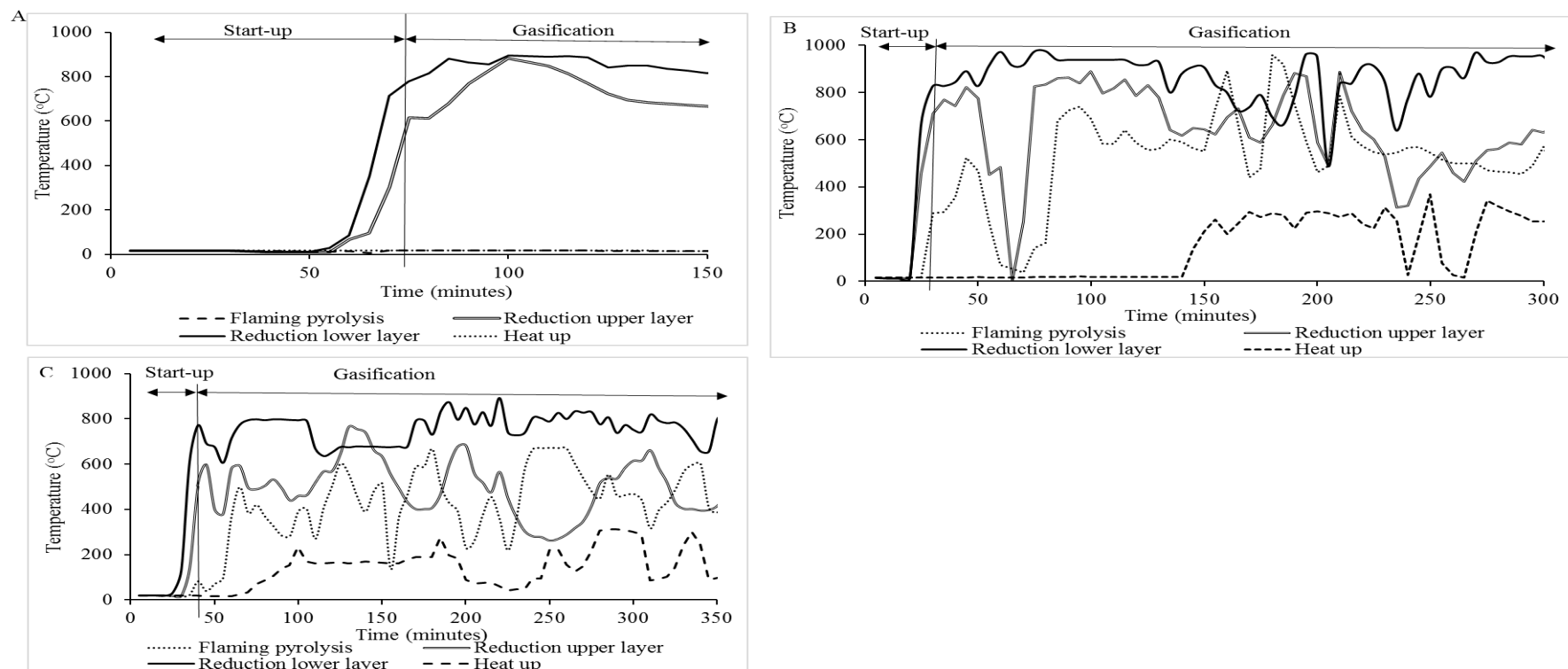


Figure 5-4 The temperature profiles (A) MP co-gasification, (B) EMP1 co-gasification, and (C) EMP2 co-gasification. MP –mesocarp fibre and palm kernel shell feedstock, EMP1 – empty fruit bunch, mesocarp fibre, and palm kernel shell (particle size of 0.0140 m) feedstock, EMP2 – empty fruit bunch, mesocarp fibre, and palm kernel shell (particle size of 0.0067 m) feedstock

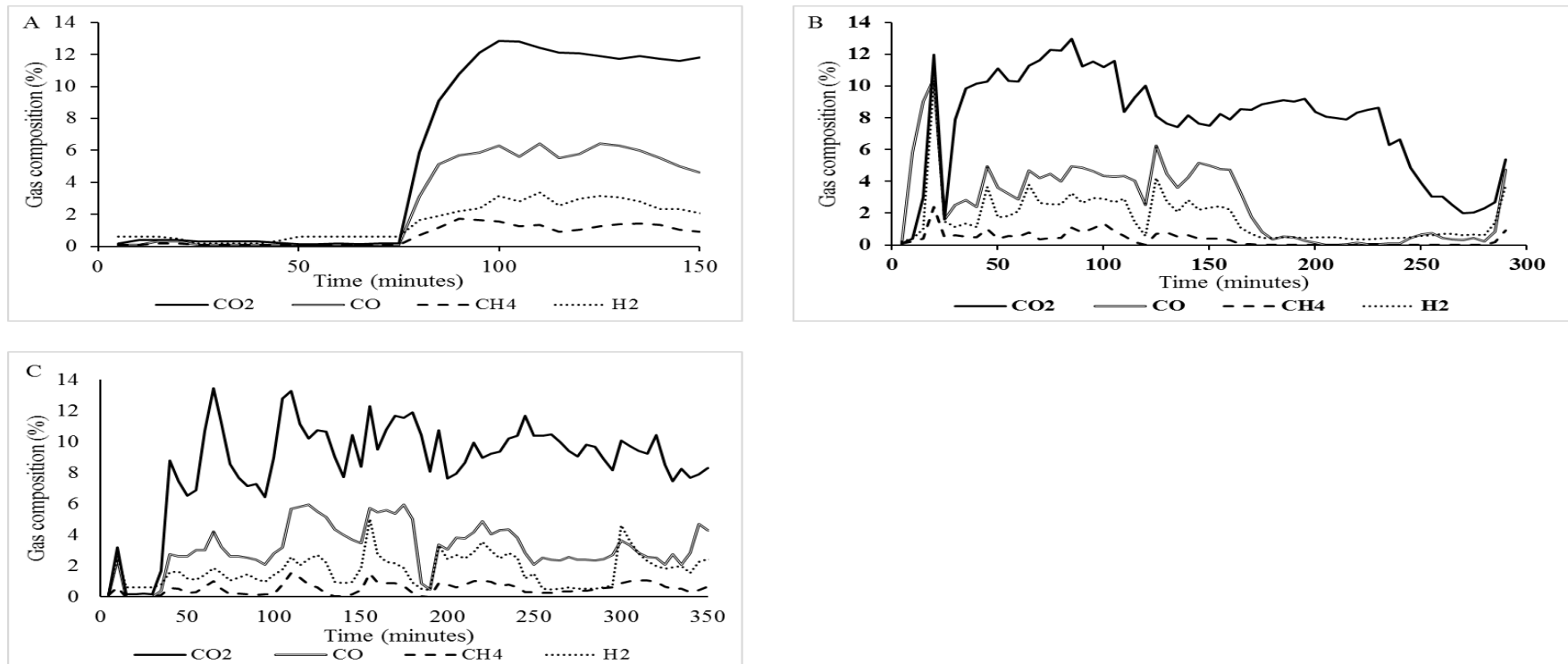


Figure 5-5 The gas composition of the process (A) MP co-gasification, (B) EMP1 co-gasification, and (C) EMP2 co-gasification. MP –mesocarp fibre and palm kernel shell feedstock, EMP1 – empty fruit bunch, mesocarp fibre, and palm kernel shell (particle size of 0.0140 m) feedstock, EMP2 – empty fruit bunch, mesocarp fibre, and palm kernel shell (particle size of 0.0067 m) feedstock

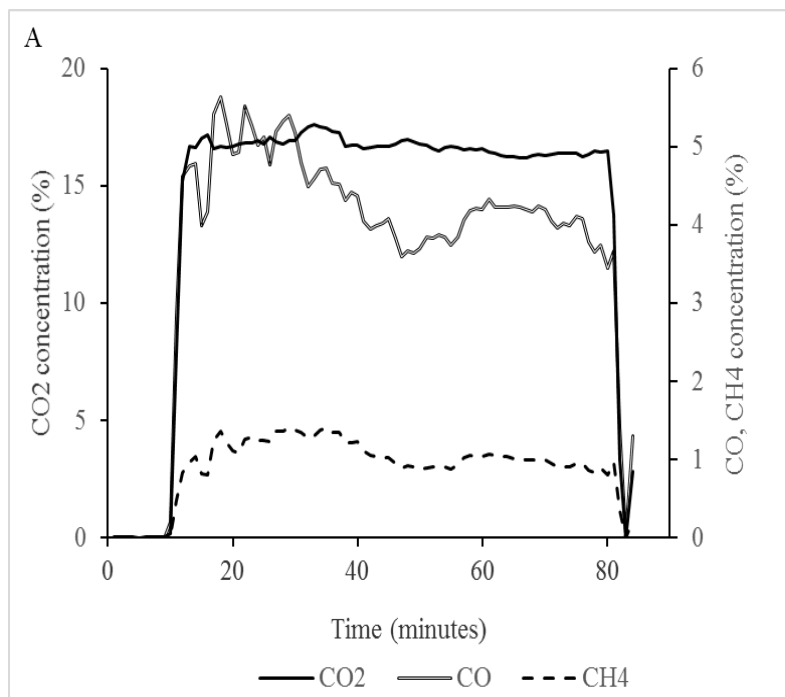
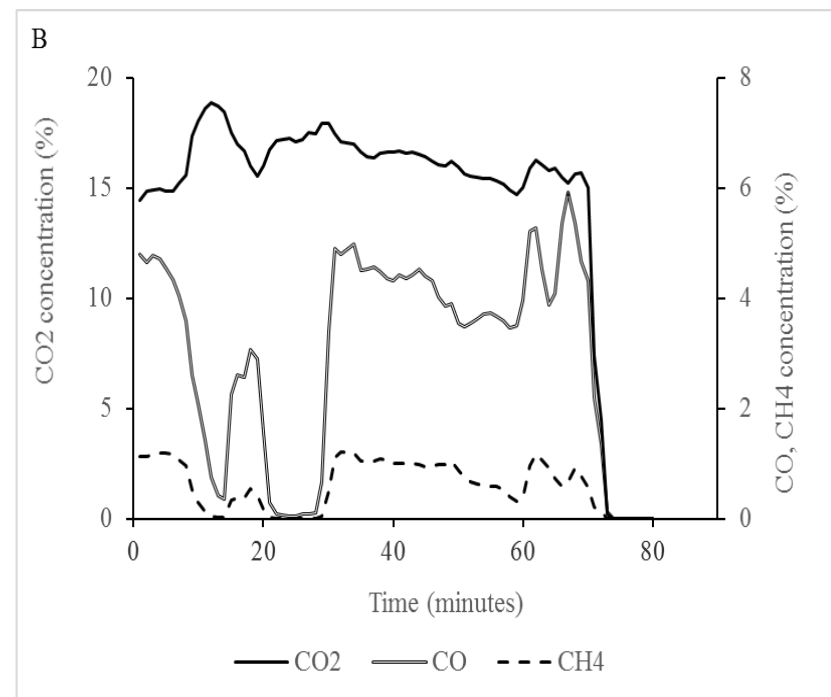


Figure 5-6 The gas composition measured by the online FTIR gas analyser (A) MP co-gasification, and (B) EMP1 co-gasification. MP–mesocarp fibre and palm kernel shell feedstock, EMP1 – empty fruit bunch, mesocarp fibre, and palm kernel shell (particle size of 0.0140 m) feedstock.

From Table 5-3, it can be observed that the LHV_{gas} and HHV_{gas} increased as the particle size decreased. The EMP2 with the low particle size of PKS (0.0067 m) in the blend than in the EMP1 had higher syngas yield, higher LHV_{gas} and HHV_{gas} . This was because of increased reactivity of the smaller particles leading to better heat transfer (Inayat et al., 2016). However, the LHV_{gas} and HHV of EMP2 and MP biomass are approximately the same. This was because the average calorific value of the MP feedstock (MF, and PKS) was more than that of the EMP2 feedstock (EFB, MF and PKS). From Table 5-2, the calorific values of the blends are the average values of the feedstock.

The opposite effect of particle size on the LHV_{gas} and HHV_{gas} was recorded with the gas yield. The gas yield decreased with decrease in particle size. The gas yield of the EMP2 (0.0067 m) was lower than that of the EMP1 (0.0140 m particle size) by 0.2 m³/kg. According to Inayat et al. (2016), this was due to longer devolatilisation time. This was evident in the gas yield of the MP, which was lower than that of the EMP2 due to relatively more PKS in the MP feedstock than in the EMP feedstock.

This study recorded lower values of the gas composition compared to literature, and this was due to higher particle sizes of the feedstock used in this study (Esfahani et al., 2012; Mohammed et al., 2011). The authors carried out their experiments in fluidised bed gasifiers. This led to slow devolatilisation and char gasification that are favoured by higher surface area, and therefore poor conversion of the biomass to syngas. The factors responsible to the differences in the gas yield compared to Mohammed et al. (2011) are due to 1) this study was a combination of EFB, MF, and PKS, while Mohammed et al. (2011) referred to EFB only, 2) difference in gasifier geometry, Mohammed et al. (2011) used fluidized-bed reactor while this study used fixed bed concept, and 3) variation in physical and chemical properties of the biomass used in both experiments. For example, the nitrogen content of the EFB used in this study was 0.5 % while the cited literature was 1.2 %. Lastly, this study used a higher particle size (0.0067 m and 0.014 m against $<3 \times 10^{-4} - 1 \times 10^{-3}$ m for Mohammed et al. (2011)), which according to Mohammed et al. (2011)

influences gas yield negatively while with increased ER, gas yield increased. This was evident in the gas yield of the MP and EMP1 and EMP2 (Table 5-3). The batch process leading to additional air supply and the choking of biomass and the relatively high particle sizes of the biomass may explain the low yield in gaseous output, calorific values, and cold gas efficiency, compared to other literature reports.

5.3.3 Residue characteristics

The results of residue yields are shown in Table 5-3. The MP led to the generation of more char than the ash while the EMP1 and EMP2 led to PKS char that was too small to be measured. Any biomass mixture of the EFB, MF, and PKS will comprise of relatively less PKS char and more ash available for soil use compared to any mixture of MF and PKS, which will lead to more char. According to García-Núñez et al. (2008), PKS has high lignin content than the sum of the lignin content of the EFB and MF, and lignin content is a major contributor to char formation (Ninduangdee and Kuprianov, 2014). This is evident considering the amount of char formed in the gasification of the MP. The residues recorded include ash, slag, and char (only PKS char). After each experiment, the glowing residue was allowed to completely extinguish with the reactor remaining open, this led to increase in ash formation at the end of the process. The residue yield for the MP was 2.10 % char of the 4.08 % total residue, and more than the sum of ash and slag yields of 1.55 % and 0.39 %, respectively. This was a result of low carbon conversion as evidenced by the low CCE of 34.18 % for the MP. Conversely, the EMP1 and EMP2 have higher CCE values of 56.30 and 61.65 %, and with no char yield, though with higher total residue yield of 4.84 and 3.94 %, respectively. The slag yield of the EMP1 and EMP2 were higher than that of MP by 1.28 and 0.96 %, respectively. The EMP2 has lower yield of solid residues (ash and slag), which can be attributed to lower particle size of the PKS used in the feedstock mixture (Table 5-1). This also led to the higher CCE of 61.65 %, higher CGE and the LHV_{gas} and HHV_{gas} for the EMP2 (Table 5-3) compared to the EMP1.

The values of alkali metals in the EFB are more than the sum of values for MF and PKS (García-Núñez et al., 2008). Ogi et al. (2013) noted that the EFB ash had a higher potassium content (56 wt. %) more than the sum of silicon (12 wt. %), calcium (12 wt. %), magnesium (4.6 wt. %), phosphorus (<1 wt. %), iron (<1 wt. %), sulphur (<1 wt. %), aluminium (<1 wt. %), and chromium (<1 wt. %), which is similar to Table 5-4. Ogi et al. (2013) concluded that the high contents of alkali and alkali earth metals accelerate gasification rate and the progress of the shift reaction. However, according to Steenari et al. (2009), the low ash melting point of biomass is due to the presence of alkali metal, and also chloride species in the biomass. The high potassium content makes EFB ash a valuable resource for soil amendment (Adjei-Nsiah, 2012; Gbaraneh and Chu, 2016; Ojeniyi et al., 2010), but will lead to high agglomeration in gasifiers for example when only the EFB is used. It is important to generate more usable residue from any thermal conversion process especially for agricultural uses. From Table 5-4, the values of alkali and alkali earth metals for the ash and slag are comparably the same and therefore can be used as soil amendment, although slag is undesirable. The sintering behaviour has been explained by the potassium/calcium (K/Ca) ratio. According to Steenari et al (2009), high silicon, and high K/Ca ratio led to high agglomeration rate in biomass by reducing the ash melting temperature. Table 5-4 shows the silicon, potassium, calcium, etc. contents of the raw EFB, MF and PKS, the ash and slag of their mixtures in the MP, EMP1 and EMP2. The MP recorded the lowest K/Ca ratio, which was evident of lower contents of potassium and calcium in the raw MF and PKS feedstock relative to EFB. The EMP2 had less K/Ca than the EMP1 in line with its low residue yield, and as stated above recorded higher carbon conversion efficiency. This is attributed to the lower particle size of the PKS in the fuel mixture. The lower the particle size, the less total residue yield, and the lower K/Ca ratio, favours lower agglomeration. The use of each of EFB, MF or PKS is therefore problematic in terms of agglomeration but the combined use increases the chances of synergic reactions taking into account the differences in elemental compositions of each biomass.

Table 5-4 Mean ($\pm$ standard error) of elemental compositions of raw empty fruit bunch, mesocarp fibre, palm kernel shell, MP, EMP1 and EMP2 ash and slag.

Parameter (%)	EFB	MF	PKS	MP	EMP1	EMP2	MP slag	EMP1 slag	EMP2 slag
Na	0.30 $\pm$ 0.21	1.72 $\pm$ 0.58	1.62 $\pm$ 0.66	0.28 $\pm$ 0.07	0.47 $\pm$ 0.18	0.34 $\pm$ 0.20	0.58 $\pm$ 0.26	0.36 $\pm$ 0.10	0.50 $\pm$ 0.11
Mg	10.575 $\pm$ 1.55	5.01 $\pm$ 1.19	9.36 $\pm$ 2.74	6.93 $\pm$ 0.44	6.09 $\pm$ 0.28	6.57 $\pm$ 0.34	4.378 $\pm$ 0.46	4.94 $\pm$ 1.38	6.77 $\pm$ 1.26
Al	0.47 $\pm$ 0.19	4.61 $\pm$ 0.66	3.08 $\pm$ 0.94	2.40 $\pm$ 0.26	1.52 $\pm$ 0.14	1.74 $\pm$ 0.18	4.42 $\pm$ 0.92	13.34 $\pm$ 5.63	1.72 $\pm$ 0.06
Si	25.19 $\pm$ 1.69	29.41 $\pm$ 4.22	41.36 $\pm$ 13.4	42.66 $\pm$ 2.69	26.71 $\pm$ 1.36	24.27 $\pm$ 1.19	51.5 $\pm$ 4.84	39.01 $\pm$ 2.81	41.64 $\pm$ 4.66
S	1.39 $\pm$ 0.57	5.68 $\pm$ 1.19	9.87 $\pm$ 1.73	1.78 $\pm$ 0.25	1.88 $\pm$ 0.10	1.67 $\pm$ 0.16	0.00 $\pm$ 0.00	0.1 $\pm$ 0.10	0.00 $\pm$ 0.00
Cl	5.65 $\pm$ 0.22	12.70 $\pm$ 1.04	3.17 $\pm$ 0.84	0.92 $\pm$ 0.02	6.44 $\pm$ 0.45	7.20 $\pm$ 0.14	12.7 $\pm$ 1.04	1.56 $\pm$ 1.39	0.19 $\pm$ 0.11
K	42.17 $\pm$ 1.00	26.45 $\pm$ 1.96	18.60 $\pm$ 4.69	24.57 $\pm$ 1.33	42.66 $\pm$ 0.78	43.60 $\pm$ 0.42	26.45 $\pm$ 1.96	26.02 $\pm$ 2.09	32.04 $\pm$ 1.47
Ca	13.81 $\pm$ 1.28	13.29 $\pm$ 2.24	9.29 $\pm$ 2.32	16.51 $\pm$ 0.73	11.57 $\pm$ 0.39	12.02 $\pm$ 0.34	13.29 $\pm$ 2.24	11.62 $\pm$ 3.10	14.62 $\pm$ 2.72
Fe	0.45 $\pm$ 0.36	1.13 $\pm$ 0.74	3.66 $\pm$ 0.59	3.97 $\pm$ 0.10	2.66 $\pm$ 0.32	2.61 $\pm$ 0.39	1.13 $\pm$ 0.74	3.06 $\pm$ 0.38	2.54 $\pm$ 0.36
K/Ca	3.05 $\pm$ 0.78	1.99 $\pm$ 0.88	2 $\pm$ 2.02	1.49 $\pm$ 1.82	3.69 $\pm$ 0.30	3.63 $\pm$ 1.24	1.99 $\pm$ 0.88	2.24 $\pm$ 0.67	2.19 $\pm$ 0.54

MP – feedstock of the equal mixture of mesocarp fibre and palm kernel shell, EMP1 - feedstock of the equal mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell of 0.014 m particle size, EMP1 – feedstock of the equal mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell of 0.0067 m particle size. K/Ca – potassium/calcium ratio, EFB-empty fruit bunch, MF-mesocarp fibre, PKS-palm kernel shell

5.4 Conclusions

The results of the co-gasification of the equal mixture of EFB, MF and PKS in a fixed bed gasifier showed that the addition of EFB to MF and PKS led to higher gas yield, cold gas efficiency and carbon conversion efficiency, compared to the equal mixture of MF and PKS. The smaller particle size of PKS when compared to the larger particle size increased the lower heating values of the gas (650 and 780 kJ/m³), the higher heating values of the gas (690 and 830 kJ/m³), and reduced the residue yield (4.8 and 3.9 %) for the equal mixture of EFB, MF and PKS feedstock composition. The lower particle size of PKS in the feedstock mixture led to relatively lower K/Ca ratio (3.69 and 3.63) and consequently to lower agglomeration. The gasification of only the EFB potentially will result in high agglomeration due to high potassium content, however from this study the addition of MF and PKS reduced the rate of agglomeration and led to a valuable residue for use as soil amendment. The co-gasification of the EFB, MF and PKS blends has shown merits and the thermal conversion process helps in reduction of greenhouse gas emissions by the replacement of fossil fuel feedstock with renewable fuels.

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6 Variations in ash properties affecting soil and cassava yield in south East Nigeria

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Abstract

The increase in the use of the oil palm fresh fruit bunch (FFB) solid wastes as sources of energy has necessitated the need for proper utilisation of the resultant ash on returning nutrients to the soil and generally improving soil properties and crop performance. The ash from the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS) from different sources were used as amendments on soil and to determine the effects on cassava fresh tuber yield. A mixture of bottom ash and fly ash from a boiler in southern Nigeria using MF and PKS as feedstock was applied on an experimental site in 2015 in four levels of 0 tonnes/ha (control), 40 tonnes/ha, 80 tonnes/ha, and 160 tonnes/ha replicated 4 times. In another experiment at the same location, five treatments (ash) from Nigeria and Cranfield University, United Kingdom were replicated 3 times at 6 tonnes/ha. The Nigerian ash were i) fly ash, ii) bottom ash, and iii) a mixture of fly and bottom ash all of MF and PKS feedstock. The Cranfield University ash were iv) mixture of fly and bottom ash of MF and PKS feedstock and v) mixture of EFB, MF and PKS feedstock. The highest cassava fresh tuber yield was recorded by the 40 tonnes/ha treatment in both 2016 (13 tonnes/ha) and 2017 (12 tonnes/ha). The cassava tuber yield due to 40 tonnes/ha ash treatment was more than the control, 80, 160 tonnes/ha treatments by 106.1 %, 8.5 % and 15.6 %, respectively. The ash in experiment II with the EFB, MF and PKS feedstock led to significant higher ($p < 0.05$) available potassium (124.78 mg/kg) and cassava fresh tuber yield (6 tonnes/ha) from all treatments. Therefore, ash from the equal mixture of EFB, MF, and PKS feedstock is more valuable as soil amendment and cassava yield and a maximum level of 40 tonnes/ha is recommended for a two-year period.

Keywords: ash, soil, cassava, oil palm, empty fruit bunch, mesocarp fibre, palm kernel shell

6.1 Introduction

The oil palm (*Elaeis guineensis*) is an important oil tree in the tropical regions of the world. It produces fruits in bunches known as fresh fruit bunch (FFB). The 2014 global palm oil production has been estimated to be 57 million tonnes (FAOSTAT, 2017). Therefore, an estimated 75 million tonnes of the oil palm FFB solid wastes were produced in 2014 at 1.3 kg FFB per 1 kg of the palm oil (Sulaiman et al., 2011). The FFB solid wastes are important biomass in Nigeria and other places in the world including Indonesia and Malaysia, where the oil palm fruits are processed. The FFB solid wastes are the empty fruit bunch (EFB), mesocarp fibre (MF), and palm kernel shell (PKS). The EFB, MF, and PKS have been found useful as energy sources (Ninduangdee and Kuprianov, 2014a, 2014b; Yaakob, 2012). Due to climate change, there are efforts towards the utilisation of renewable sources of energy and less of fossil fuels. The increasing use of FFB biomass in thermal conversion will increase the availability of ash from the biomass. Therefore, finding a way to use the ash requires investigation such as its effects on soil and crops.

From the figure of FFB solid wastes produced in 2014 above, an equivalent of 23, 21 and 7.5 million tonnes of EFB, MF, and PKS were produced considering 30.6, 28.1, and 10 % of EFB, MF, and PKS per FFB according to Ohimain et al. (2013), respectively. Therefore, an estimated global production potential of EFB, MF, and PKS ash in 2014 were about 1.2 million tonnes of EFB and MF each, and 0.1 million tonnes of PKS based on 5.1, 5.5, and 1.7 % ash contents of EFB, MF, and PKS, respectively.

Cassava performs well under high concentration of potassium (Tauriq et al., 2015), which is the nutrient most needed to achieve a target yield of 8 tonnes/ha (Ezui et al., 2016). Since ash generally is known to contain considerable quantity of potassium (Maduakor, 1997), it can act as a suitable soil amendment for cassava. Therefore, ash potentially provides a cheap source of soil nutrient for the poor farmers. This becomes very important because of land availability issues in most

part of southern Nigeria where most poor farmers cultivate cassava (Adekunle et al., 2016) with limited input and are unable to allow the farms to fallow.

The reports on the effects of ash from FFB solid wastes on soil, or on crop performance focused more on EFB ash (Adjei-Nsiah, 2012; Gbaranah and Chu, 2016; Ojeniyi et al., 2010). There were positive responses to ash addition for different crop yields and soil nutrients investigated. Awodun et al. (2007) investigated the effects of EFB ash and NPK 15-15-15 fertiliser on maize grain yield of 0.187 kg/plant compared to the control of 0.141 kg/plant for 6 tonnes/ha EFB treatment. Obeng and Adjei-Nsiah (2013) demonstrated that EFB ash increased soil pH, soil phosphorus, and exchangeable cations, which resulted in 55-91 % in eggplants (*Solanum melongena*) fresh fruit yield and up to 65 % increase in fresh fruit yield of okra. Ojeniyi et al. (2009) investigated the effects of EFB ash on cassava and demonstrated that EFB ash increased significantly ($p < 0.05$) cassava number of roots, root diameter, dry root weight and leaf nitrogen, phosphorus, and potassium concentrations. The 2.5 tonnes/ha EFB treatment was 5.2, 0.0038 m, 1.82 tonnes/ha and 0.12, 0.18, and 0.29 % more than the control for bitter cassava number of roots, root diameter, dry root weight, and leaf nitrogen, phosphorus, and potassium, respectively. However, the reports above did not consider the differences in fly and bottom ash and their effects on soil and crop yield. There are limited information on the use of MF and PKS ash, which are the mostly used biomass in palm oil mills in Nigeria. There are limited information on the influence of the combination of fly and bottom ash from MF and PKS on soil and cassava yield. As efforts are being made towards increasing utilisation of FFB solid wastes for energy purposes, there is need to study the influences of various ash from FFB solid wastes on soil and crops, more especially on cassava an important tropical crop and in high demand for potassium. The objectives of this study are (i) to determine the efficacy of the ash on soil properties and cassava fresh tuber yield, and (ii) to characterise the ash from different mixtures of EFB, MF and PKS.

6.2 Materials and Methods

6.2.1 Site description and preparation

The research site is located at Imo State Polytechnic Umuagwo, Imo State Nigeria (5° 19' 51" N. latitude; 6° 57' 21" E. longitude) with the height above sea level of 51.98 m. The topography is flat with overgrown grass and shrubs. The site has been fallow for five years and was manually cleared and the plots tilled using local hoe to a depth of about 0.3 m. Two different experiments were established on the same site. Experiment I was 12.5 x 24.5 m in size and was subdivided into four blocks of four rectangular plots each. Each plot was 5.0 m in length and 2.0 m wide with 1.5 m empty space between each plot and each block (Figure 6-1). Experiment II was 7 x 8.5 m in size and was subdivided into 15 plots of 1.0 x 1.0 m each.

6.2.2 Ash application and cassava planting

Experiment I was established in May 2015, with ash from Risonpalm (SIAT Nigeria Limited) located in Ikwerre Local Government Area River State, Nigeria. The ash came from a grate combustor supplying steam used in processing 60 tonnes/ha of the oil palm FFB to generate about 1 million Watts of electricity. The FFB are supplied from the company's oil palm plantations and about 22 % (personal communication) was sourced from local suppliers, expectedly from different plantations. The ash came from the combustion of MF and PKS, and the bottom and fly (cyclone) ashes used were thoroughly mixed. The ash was collected directly from boiler ash container less than 48 hours after combustion, and applied on the soil less than 24 hours later. The three ash treatment and the control were randomized and each was replicated four times for the entire site using randomized complete block design (RCBD). The mixture of bottom ash and fly ash was applied to the 12 plots while four plots were used as control. The levels of the treatments in the twelve plots were similar to those of Lee et al. (2006), which were 40 tonnes/ha, 80 tonnes/ha, and 160 tonnes/ha of the ash (equivalent of 40, 80, and 160 kg/plot) with each replicated four times. No other amendment was used on the soil. The higher treatments in experiment I were used to understand how long the ash will influence soil properties and cassava yield the second year after amendment without need for additional treatments.

Experiment II was established in March 2016, 10 months after Experiment I was set up. The ash used were from Risonpalm (SIAT Nigeria Limited) generated from MF and PKS using a grate combustor, and Cranfield University, United Kingdom generated using a downdraft gasifier. The EFB, MF, and PKS sourced from Nigeria were used for the ash generation in a 75-kWh reactor (downdraft gasifier) at Cranfield University and the ash was transported to Nigeria for the experiment. The Cranfield University ash comprises of:

1. The mixture of the fly and bottom ash of equal mixture of MF, and PKS feedstock denoted as MPC, and
2. The mixture of the fly and bottom ash of equal mixture of EFB, MF, and PKS denoted as EMPC.

The Nigerian ash from grate combustor comprises of:

1. The fly ash of MF and PKS feedstock denoted as MPFN
2. The bottom ash of MF and PKS feedstock denoted as MPBN, and
3. The mixture of fly and bottom ash of the MF and PKS feedstock denoted as MPMN. The treatments were replicated three times using Completely Randomized Design (CRD) and applied on the 15 plots at the level of 6 tonnes/ha each in line with Ojeniyi et al. (2009).

In Experiment I, cassava stems (NR 8083 – breed from National Root Crop Research Institute Nigeria) harvested from a nearby farm were planted in each plot of the experimental site. The cassava stems with 5 buds each (0.15 m length) were planted 2 stems together. The 10 stems of cassava were planted per plot and at the middle of the plot with spacing of 0.44 m similar to how cassava is planted by local farmers in Ohaji, Nigeria (personal communication). The cassava tubers were harvested and the weights were recorded per plot in March 2016 after 10 months. Cassava stems harvested from Experiment I were planted on the same plots in March 2016 with no further ash application. Cassava stems harvested from Experiment I were planted on Experiment II, with two stems per plot of the same length the same time as Experiment I in 2016. The cassava tubers were harvested in January 2017 for Experiment I (second harvest) and II (first harvest) after 10 months of planting.

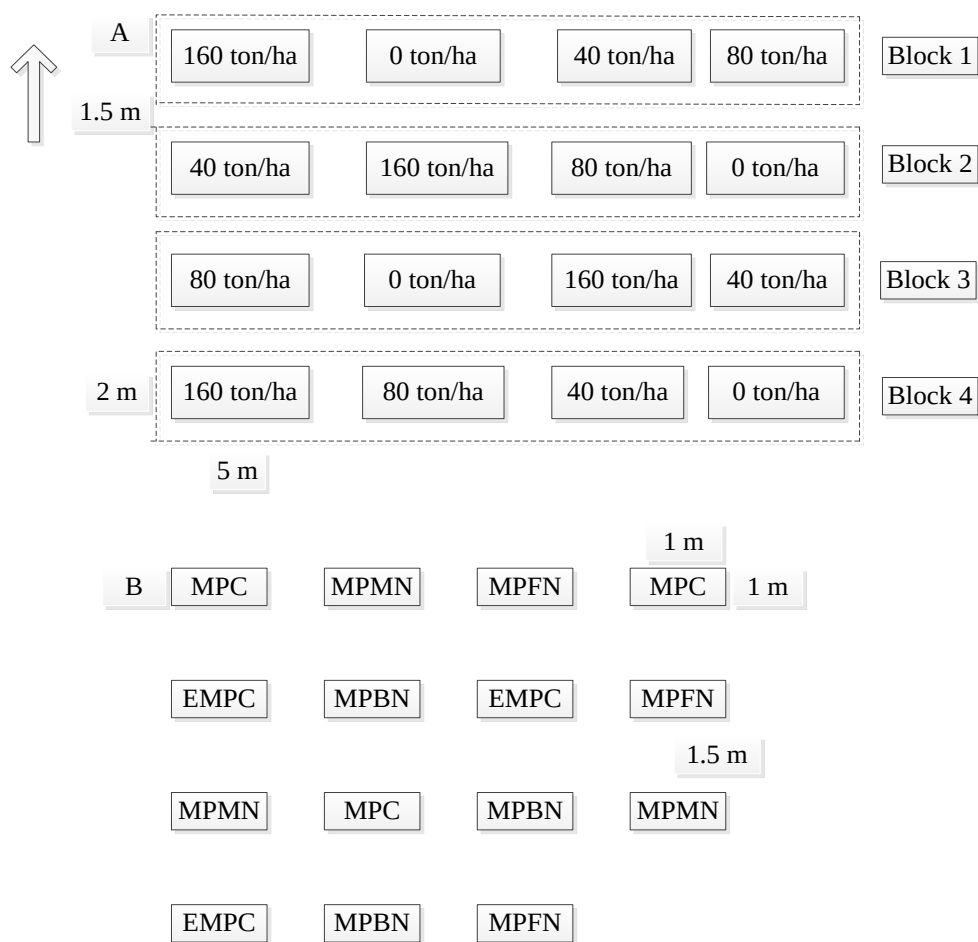


Figure 6-1 Schematic diagram of the experimental site showing the treatment combinations (A) Experiment I, and (B) Experiment II, 6 tonnes/ha treatment. MPC- mixture of fly and bottom ash of the equal mixture of mesocarp fibre and palm kernel shell feedstock from Cranfield University, EMPC - mixture of fly and bottom ash of the equal mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell feedstock from Cranfield University, MPFN - fly ash of mesocarp fibre and palm kernel shell feedstock denoted from Nigeria, MPBN - bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria, MPMN - mixture of fly and bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria.

6.2.3 Soil sampling and laboratory analyses

Four soil subsamples were collected randomly using an auger in each plot at two depths of 0 - 0.3 m and 0.3 – 0.6 m before ash application in 2015 and 2016, 10 months after the application of ash, and in 2017 after another ten months, and were bulked to obtain a homogenous sample for each plot. Samples for Experiment II

were collected only in 2016 and 2017. The samples were air dried and ground to pass through a 2 mm sieve and stored at the room temperature (British Standards Institute ISO 2006; MAFF, 1986). The available potassium was determined according to British Standards Institute (2015). The available potassium was extracted from the soil with a solution of ammonium nitrate. Total magnesium, calcium, potassium, nickel, copper and zinc in aqua regia extracts of the ash used in Experiments I and II were determined according to United States Environmental Protection Agency (1994) and British Standards Institute (1998). The other metals measured including lead and chromium were not detected. The available potassium, and total magnesium, calcium, potassium, nickel, copper and zinc were measured by atomic emission and flame atomic absorption, respectively using Atomic Absorption Spectrometer (PerkinElmer Precisely AAnalyst 800) using the standards for each of the metals within 0.005 accuracy. The available phosphorus was determined according to British Standards Institute (1995a). The soil sample was treated with a 0.5 mol/l sodium hydrogen carbonate solution at pH 8.5 and the extract analysed by spectrometric method using Spectrophotometer (Thermo Electron Corporation Nicolet evolution 100). The total nitrogen and carbon, and organic carbon in the soil and ash were determined according to British Standards Institute (2001), and British Standards Institute (1995b), respectively using Elementar Analyser Vario EL. The pH (H₂O) was determined in a 1:5 suspension of soil water (pH in H₂O) according to British Standards Institute (2005) using Mettler Toledo MA 235 pH/Ion Analyser. The bulk density was determined according to British Standards Institute (1999) and Soil Survey Technical Monograph (1974) using undisturbed soil core. The dry matter and water content were determined according to British Standards Institute (1994), while the loss on ignition was determined according to British Standards Institute (2000) using Thermo Scientific Heratherm Oven. The electrical conductivity was determined according to United States Department of Agriculture (1996) using Conductivity Meter 4310 (Jenway). The cation exchangeable capacity was determined using Burkard Segmented Flow Auto Analyser series 2000, and exchangeable calcium, and potassium according to MAFF (2006) using ICP Mass Spectrometer (PerkinElmer NexION 350D).

6.2.4 Cassava yield determination

The cassava tuber harvest was carried out by manually cutting all the cassava stems and uprooting the stumps with the tubers in 2016 and 2017 for experiment I and in 2017 only for experiment II. The cassava tubers were later cut off from the stumps. The weights of the cassava tubers from each plot were recorded using Camry Emperors weighing balance (15 kg x 50g).

6.2.5 Statistical analysis

Analysis of variance (ANOVA) was carried out using Statistica 12 at 5 % Duncan Multiple Range Test (DMRT). The soil depths (0 - 0.3 m and 0.3 – 0.6 m) and FFB solid wastes ash (control, 40 tonnes/ha, 80 tonnes/ha, and 160 tonnes/ha for Experiment I, and 6 tonnes/ha for Experiment II) were the sources of variation for soil properties. The cassava yields converted from kg to tonne/ha per plot was also statistically analysed with the treatments and source of ash as sources of variation in experiment I and experiment II, respectively.

6.3 Results and discussion

In the statistical analysis, where the interactions of soil depths and the ash from the FFB solid wastes (treatments) were significant, the effects were considered dependent on treatments as well as soil depths (Table 6-1). When the interactions were not significant, soil depths and the treatments were considered independently. The only exception is cassava fresh tuber with only treatments under consideration.

The soil is predominantly loamy sand in both layers (0 – 0.3 m and 0.3 – 0.6 m) and in both sites with more clay than silt (Table 6-2) and acidic with pH of less than 4.3 on both sites and both soil depths. The soil was low in exchangeable potassium and available phosphorus (Table 6-2) compared to results reported by Salami and Sangoyomi (2013) for cassava, which are 0.2 cmol+/k, for potassium, 8 mg/kg for phosphorus and 4.6-7.8 for pH. The organic matter content was approximately the same as the critical level (3%) for cassava production in Nigeria (Salami and Sangoyomi, 2013).

6.3.1 Characteristics of ash used in the experiments

The ash used in the experiments contains essential soil nutrient especially potassium, calcium, phosphorus, and low nitrogen (Table 6-3). The fly ash and bottom ash used in the experiment were analysed separately for nutrient contents. The mixture of the fly ash and bottom ash was also analysed for the nutrient contents, which expectedly were about average values for the fly ash and bottom ash. The fly ash in experiment I and II had more organic matter content, total calcium, potassium and phosphorus than the bottom ash, while more total nitrogen and magnesium were measured in the bottom ash. The similar trend in the levels of the nutrients was an indication of the similarity in feedstock (MF and PKS) and thermal conversion system. The other treatments (MPC and EMPC) used in experiment II differ in feedstock but the same thermal conversion system. The EMPC (EFB, MF and PKS feedstock from Cranfield) treatment had more total calcium, potassium, phosphorus, magnesium and nitrogen, than the MPC (MF and PKS feedstock from Cranfield) treatment, while the MPC recorded more pH and organic matter content. The difference in properties of the MPC and EMPC treatments was due to the presence of EFB in the EMPC treatment. The differences in the properties of the ash used in the experiments had provided evidence on the differences between the fly and bottom ash, feedstock and thermal conversion system.

6.3.2 Changes in soil properties

Experiment I

In 2016, the exchangeable magnesium concentration was highest in the 0.3 – 0.6 m soil layer due to 160 tonnes/ha treatment (3.34 cmol+/kg), followed by the 40 tonnes/ha treatment (3.18 cmol+/kg) in the 0 – 0.3 m soil layer, and therefore were significantly higher than other sources of variation except 80 tonnes/ha at 0 – 0.3 m soil layer (Figure 6-2A). Expectedly, the control at 0 – 0.3 m (0.84 cmol+/kg) and 0.3 – 0.6 m (0.04 cmol+/kg) soil layers recorded the lowest exchangeable magnesium concentrations.

The exchangeable calcium was significantly different ($p < 0.05$) in 2016 due to the combined effects of the treatment and soil depth (Figure 6-2B). The exchangeable calcium concentrations for the control, 40, 80, and 160 tonnes/ha treatments were

0.49, 0.98, 1.32, and 2.21, respectively in the 0 – 0.3 m soil layer. The other treatments were significant higher than the control, while only the 160 tonnes/ha was significantly higher than other treatments. The exchangeable calcium for the 160 tonnes/ha treatment was 1.23 cmol+/kg more than that of the 40 tonnes/ha treatment. The exchangeable calcium concentrations decreased from 0 – 0.3 m to 0.3 – 0.6 m soil layers by 0.30, 0.60, 0.99 and 1.68 cmol+/kg for the control, 40, 80 and 160 tonnes/ha, respectively. In 2017, exchangeable calcium was significantly different ($p<0.05$) due to the treatment effects only (Figure 6-2B). The 40 tonnes/ha treatment was higher than the control by more than 50 % though not significantly different. The 160 tonnes/ha was significantly higher than the other treatments and 0.66, 0.41, and 0.32 cmol+/kg more than the control, 40, and 80 tonnes/ha treatments, respectively.

The available potassium was significantly different at 5 % DMRT due to the interactions between treatments (40 tonnes/ha, 80 tonnes/ha, and 160 tonnes/ha) and soil depths (0 - 0.3 and 0.3 - 0.6 m) in 2016 (Figure 6-2C). The available potassium increased with the treatments, particularly in the 0.3 – 0.6 m soil layer. The 80 tonnes/ha treatment has more effect on potassium than the 160 tonnes/ha treatment by 6.1 mg/kg at 0 - 0.3 m soil depth. The 160 tonnes/ha treatment was highest at soil depth 0.3 – 0.6 m (99.5 mg/kg) and significantly higher ($p<0.05$) than all the treatments at both soil depths. The available potassium concentrations decreased by 3.15, 3.05, and 0.78 mg/kg for the control, 40, and 80 tonnes/ha treatments, and increased by 61.50 mg/kg for the 160 tonnes/ha treatment from 0 – 0.3 to 0.3 – 0.6 m soil layers, respectively. The available potassium in 2017 increased with the treatments only (Figure 6-3A). The 160 tonnes/ha treatment recorded the highest available potassium (28.32 mg/kg) and significantly higher ($p<0.05$) than the control and 40 tonnes/ha treatment. The soil exchangeable potassium was significantly different ($p<0.05$) in 2016 due to the treatments only (Figure 6-3A). The 160 tonnes/ha treatment was significantly more than the other treatments and 0.23, 0.18 and 1.13 cmol+/kg more than the control, 40 and 80 tonnes/ha treatments while the 80 tonnes/ha treatment was significant higher than the control and the 40 tonnes/ha treatment by 0.10 and 0.05 cmol+/kg, respectively.

Table 6-1 Statistical analysis of the soil depths and treatments effects on soil properties.

Soil Property/Source of Variation	Experiment I						Experiment II		
	2016			2017			2017		
	SD	T	SD x T	SD	T	SD x T	SD	T	SD x T
Total nitrogen	*	ns	ns	*	ns	ns	*	ns	ns
Total carbon	*	*	ns	*	ns	ns	*	*	ns
Available potassium	*	*	*	ns	*	ns	*	*	ns
Available phosphorus	*	*	ns	ns	ns	ns	*	ns	ns
Electrical conductivity	*	ns	*	ns	ns	ns	Ns	ns	ns
pH	ns	*	ns	ns	*	ns	Ns	ns	ns
Water content	ns	ns	ns	ns	ns	ns	*	ns	ns
Dry matter	ns	ns	ns	ns	ns	ns	*	ns	ns
CEC	ns	ns	ns	ns	ns	ns	Ns	ns	ns
Exchangeable potassium	ns	*	ns	ns	ns	ns	Ns	ns	ns
Exchangeable calcium	*	*	*	*	*	ns	*	*	ns
Exchangeable sodium	ns	ns	ns	ns	ns	ns	Ns	ns	ns
Exchangeable magnesium	*	*	*	*	*	ns	Ns	ns	ns
Organic matter	ns	ns	ns	ns	ns	ns	Ns	ns	ns
Bulk density	na	ns	na	na	ns	na	Na	ns	na
Yield	na	*	na	na	*	na	Na	ns	na

SD and T denote soil depth and the treatment, respectively while SD X T denote interaction between soil depth and treatments. CEC – cation exchangeable capacity, ns - not significantly different at 5 %, *significantly different at 5 %, na – not applicable

Table 6-2 Initial mean ($\pm$ standard error) physical and chemical properties of the soil in the field experiments before the application of ash.

Parameter	Experiment I		Experiment II	
	0 - 0.3 (m)	0.3 - 0.6 (m)	0 - 0.3 (m)	0.3 - 0.6 (m)
Sand (%)	85.80	84.80	86.10	83.60
Silt (%)	1.20	1.20	1.20	1.20
Clay (%)	13.00	14.00	12.70	15.20
Textural class	Loamy sand	Loamy sand	Loamy sand	Sandy loam
Available potassium (mg/kg)	48.13 $\pm$ 3.82	19.45 $\pm$ 1.45	32.43 $\pm$ 2.18	23.10 $\pm$ 2.29
Available phosphorus (mg/kg)	0.61 $\pm$ 0.04	0.63 $\pm$ 0.04	0.92 $\pm$ 0.09	0.63 $\pm$ 0.05
Electrical conductivity (μS/m)	5876 $\pm$ 62	4275 $\pm$ 187	5347 $\pm$ 181	361 $\pm$ 259
Total nitrogen (%)	0.08 $\pm$ 0.01	0.06 $\pm$ 0.00	0.06 $\pm$ 0.00	0.05 $\pm$ 0.00
Total carbon (%)	1.24 $\pm$ 0.07	0.92 $\pm$ 0.05	1.03 $\pm$ 0.04	0.78 $\pm$ 0.03
Carbon/Nitrogen ratio	15.50 $\pm$ 7	15.30 $\pm$ 5.00	17.2 $\pm$ 4.00	15.60 $\pm$ 3.00
Total organic carbon (%)	1.21 $\pm$ 0.07	0.86 $\pm$ 0.03	0.98 $\pm$ 0.04	0.76 $\pm$ 0.03
pH	4.08 $\pm$ 0.01	4.16 $\pm$ 0.02	4 $\pm$ 00.010	4.25 $\pm$ 0.14
Organic matter (%)	2.98 $\pm$ 0.15	2.99 $\pm$ 0.10	3.03 $\pm$ 0.09	3.01 $\pm$ 0.05
Bulk Density (g/cm³)	1.45 $\pm$ 0.04	na	1.51 $\pm$ 0.06	Na
Cation exchangeable capacity (cmol+/kg)	11.13 $\pm$ 0.6	12.42 $\pm$ 0.46	8.12 $\pm$ 0.79	6.93 $\pm$ 0.73
Calcium (cmol+/kg)	0.38 $\pm$ 0.05	0.36 $\pm$ 0.06	0.45 $\pm$ 0.06	0.29 $\pm$ 0.02
Potassium (cmol+/kg)	0.08 $\pm$ 0.01	0.06 $\pm$ 0.02	0.11 $\pm$ 0.01	0.09 $\pm$ 0.01
Sodium (cmol+/kg)	0.89 $\pm$ 0.01	0.87 $\pm$ 0.07	1.35 $\pm$ 0.05	1.43 $\pm$ 0.04
Magnesium (cmol+/kg)	0.79 $\pm$ 0.07	0.64 $\pm$ 0.08	0.91 $\pm$ 0.09	0.61 $\pm$ 0.05

na- not applicable

Table 6-3 Some physical and chemical properties of the ash used in the field experiment I and II.

Parameter	Experiment I				Experiment II			
	Fly ash	Bottom ash	Mixture of fly and bottom ash	MPC	EMPC	MPFN	MPBN	MPMN
Total calcium (mg/kg)	29535.4	2639.5	5883.1	15916.8	20982	23635.3	5370.7	16616.7
Total potassium (mg/kg)	35400.1	6009.4	11844.7	98457.5	134245.7	37409.7	18955.1	31950.8
Total phosphorus (mg/kg)	197.4	168.7	147.3	97	113.6	188.9	51.6	155.9
Total magnesium (mg/kg)	18808.6	33359	4272.1	23852.4	28033.3	2231.4	8814.8	21213
Total nitrogen (%)	0.1	0.5	0.3	0.2	0.3	0.2	0.3	0.2
pH (Soil:H₂O 1:5)	10.5	10.6	10.4	10.9	10.2	9.5	12	9.9
Organic matter (%)	9.2	7.3	8.5	19	10.1	10.1	2.5	9.3

MPC - mixture of fly and bottom ash of the equal mixture of mesocarp fibre and palm kernel shell feedstock from Cranfield University; EMPC - mixture of fly and bottom ash of the equal mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell feedstock from Cranfield University; MPFN - fly ash of mesocarp fibre and palm kernel shell feedstock denoted from Nigeria; MPBN - bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria; MPMN - mixture of fly and bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria.

The exchangeable potassium increased linearly as the treatments with the 160 tonnes/ha significantly higher than the control, 40, and 80 tonnes/ha treatments by 0.23, 0.18, and 0.13 cmol+/kg, respectively while the 80 tonnes/ha treatment was higher than the control, and 40 tonnes/ha treatment by 0.10 and 0.05 cmol+/kg, respectively. The 40 tonnes/ha was more than the control by 0.05 cmol+/kg. These reflected the amount of potassium in each treatment.

In 2016, electrical conductivity was significantly different ($p < 0.05$) due to the interactions between treatments (40, 80, and 160 tonnes/ha) and soil depths (0 - 0.3 and 0.3 - 0.6 m) (Figure 6-2D). The highest value of 6760 $\mu\text{S/m}$ was recorded for the 40 tonnes/ha treatment followed by the control (5770 $\mu\text{S/m}$) for the 0 – 0.3 m soil layer. The soil electrical conductivity increased as the treatments increased at the 0.3 – 0.6 m soil depth indicating translocation of the ions from the top soil to the sublayer. The electrical conductivity concentrations decreased from 0 – 0.3 m to 0.3 – 0.6 m soil layers by 2360, 3320, 1710, and 290 $\mu\text{S/m}$ for the control, 40, 80, and 160 tonnes/ha, respectively.

The available phosphorus was significantly different ($p < 0.05$) due to treatment effects and the differences (Figure 6-3B) in soil depths (Table 6-4) in 2016. The available phosphorus concentrations increased linearly as the treatments increased. The 40, 80, and 160 tonnes/ha treatments were higher than the control by 2.53, 3.51, and 7.1 mg/kg, respectively. The 80 tonnes/ha treatment was 0.98 mg/kg higher than the 40 tonnes/ha treatment. In the 0 – 0.3 m soil layer, the available phosphorus was 2.84 mg/kg more than in the 0.3 – 0.6 m soil layer in 2017. From the result for the available phosphorus, it can be concluded that adding ash to the soil will results in more availability of this important fertility parameter providing a valuable resource for cassava famers in phosphorus fertilisation.

In 2016, total carbon was significantly different due to the treatments (Figure 6-3B) and soil depths (Table 6-4), and only significant due to soil depths in 2017 (Table 6-4). The total carbon increased with the treatments but only the 160 tonnes/ha treatment was significantly higher than the control by 0.73 in 2016 (Figure 6-3B). In the 0 – 0.3 m soil layer, total carbon was 0.93 % more than the

0.3 – 0.6 m soil layer in 2016 and 0.43 % more than the 0.3 – 0.6 m soil layer in 2017. Expectedly, the total organic carbon was only significant due to soil depth in 2016 with the 0 – 0.3 m soil layer higher than the 0.3- 0.6 m soil layer by 0.58 % (Table 6-4). The increase in the total carbon with ash addition is important in carbon sequestration in the soil. However, the extent to which the treatment should be increased cannot be determined according to the treatments applied in this study in combination with the relatively short duration of the current experiment. Similarly, total nitrogen was only significantly different due to soil depth in 2016 and 2017 (Table 6-4). The same value of total nitrogen (0.05 %) was recorded for the 0.3 – 0.6 m in 2016 and 2017, and reduced by 0.02 % in 2017 for the 0 – 0.3 m soil layer. This demonstrated that the soil relied mostly on its natural source of nitrogen and that no effect of the applied ash on the soil nitrogen.

Figure 6-3C refers to variations in the pH of the soil due to ash in 2016 and 2017, respectively, where significant difference can be attributed to treatments effects; the pH increased with the treatments. In 2016, the pH of the control (4.1 ± 0.16) and the 160 tonnes/ha treatment (4.80 ± 0.24) treatments were significantly different ($p < 0.05$). In 2017, the 160 tonnes/ha treatment was significantly higher than the the control, 40, and 80 tonnes/ha treatment by 1.01, 0.69, and 0.63, respectively while the 80 tonnes/ha treatment was significantly higher than the control by 0.38. Most importantly, all treatments except the control increased the soil pH within the critical level (4.6-7.8) in 2017 as stated in section 6.3 above. The soil pH on all treatments increased in 2017 from 2016 values, indicating the pH continued to increase in the soil.

Experiment II

The results of the available potassium, available phosphorus, total carbon and nitrogen, dry matter and water content are presented in Table 6-4.

The available potassium was significantly different at 5 % DMRT due to the treatments and soil depths (0 - 0.3 and 0.3 - 0.6 m). The EMPC treatment recorded the highest available potassium of 124.78 mg/kg and was significantly higher ($p < 0.05$) than the MPC, MPFN, MPBN, and MPMN treatments by 42.86,

93.25, 94.71, and 98.78 mg/kg, respectively (Figure 6-4A). The MPC treatment was significantly higher ($p < 0.05$) than the MPFN, MPBN, and MPMN treatments by 50.39, 51.85, and 55.90 mg/kg, respectively. The ash treatments (MPFN, MPBN, and MPMN) from Nigeria were not significantly different, which is in line with results of Experiment I (even with comparatively higher levels) in 2016.

The exchangeable calcium was significantly different ($p < 0.05$) due to the treatments (Figure 6-4A) and soil depths (Table 6-4). The MPFN treatment was significantly higher than other treatments except the EMPC, which was due to the high content of total calcium of the MPFN treatment (Table 6-3). The EMPC treatment was higher than the MPC treatment by 0.15 cmol+/kg, although not significant. The exchangeable calcium for the 0 – 0.3 m soil depth was 0.15 cmol+/kg higher than that for 0.3 - 0.6 m soil depth.

The available phosphorus was significantly different due to the soil depths (0 - 0.3 and 0.3 - 0.6 m) only (Table 6-4). The available phosphorus for the 0 – 0.3 m soil depth was 6.51 mg/kg higher than that for the 0.3 - 0.6 m soil depth.

The electrical conductivity was significantly different ($p < 0.05$) due to the treatments only (Figure 6-4B). The highest soil electrical conductivity of 1800 $\mu\text{S/m}$ was recorded from the MPC treatment, while the lowest soil electrical conductivity of 1222 $\mu\text{S/m}$ was recorded by the MPMN treatment.

The total carbon was significantly different at 5 % DMRT due to the treatments (Figure 6-4B) and soil depths (Table 6-4), respectively while total nitrogen was significantly different due to soil depths only (Table 6-4). The MPFN treatment recorded the highest total carbon of 1.05 % and significantly higher than the MPC and MPBN treatments while the MPBN treatment was the lowest (0.85 %) and significantly lower than MPMN treatment. The total carbon for the 0 – 0.3 m soil depth was 0.15 % higher than that for the 0.3 - 0.6 m soil depth while the total nitrogen for the 0 – 0.3 m soil depth was 0.01 % higher than that for the 0.3 - 0.6 m soil depth. This is evidence of the low content of nitrogen in the ash used, which demonstrated that ash has no effect on soil total nitrogen.

The dry matter and water content were expectedly significantly different ($p<0.05$) for 0 – 0.3 and 0.3 – 0.6 m soil depths (Table 6-4). The water content for the 0 – 0.3 m soil depth was 0.56 % lower than that for the 0.3 - 0.6 m soil depth while the dry matter for the 0 – 0.3 m depth was 0.53 % higher than that for the 0.3 – 0.6 m soil depth. The difference in water content cannot be attributed to ash application as the lower soil layer is expected to be more moist than the upper layer.

Table 6-4 Mean ($\pm$ standard error) of some soil properties due to soil depths (0 - 0.3 and 0.3 – 0.6 m) effects for Experiments I and II.

Parameter	Experiment I		Experiment II	
	0 - 0.3 (m)	0.3 – 0.6 (m)	0 - 0.3 (m)	0.3 – 0.6 (m)
Total carbon (%)	1.96 $\pm$ 0.22a	1.03 $\pm$ 0.05b	1.02 $\pm$ 0.03a	0.87 $\pm$ 0.04b
Total nitrogen (%)	0.09 $\pm$ 0.00a	0.05 $\pm$ 0.00b	0.07 $\pm$ 0.00a	0.06 $\pm$ 0.00b
Available phosphorus (mg/kg)	5.00 $\pm$ 0.95a	2.16 $\pm$ 0.62b	12.88 $\pm$ 2.49a	6.37 $\pm$ 1.51b
Total organic carbon (%)	1.54 $\pm$ 0.11a	0.96 $\pm$ 0.05b	ns	Ns
Available potassium (mg/kg)	ns	ns	74.78 $\pm$ 16.19a	42.95 $\pm$ 7.73b
Dry matter (%)	ns	ns	99.42 $\pm$ 0.03a	98.89 $\pm$ 0.08b
Water content (%)	ns	ns	0.59 $\pm$ 0.03a	1.15 $\pm$ 0.08b
*Exchangeable calcium (cmol+/kg)	0.73 $\pm$ 0.11a	0.34 $\pm$ 0.07b	0.21 $\pm$ 0.05a	0.07 $\pm$ 0.03b
*Total carbon (%)	1.24 $\pm$ 0.04a	0.81 $\pm$ 0.04b	na	Na
*Total nitrogen (%)	0.07 $\pm$ 0.00a	0.05 $\pm$ 0.00b	na	Na

*Values for experiment I in 2017, values in each row for experiments I and II each with the same letter (a,b) are not significantly different at $p<0.05$ while values with different letters are significantly different, ns – not significantly different at $p<0.05$, na – not applicable.

6.3.3 Changes in weights of harvested cassava fresh tubers

Experiment I

Figure 6-5A shows the effects of ash applications on cassava fresh tuber yield in 2016 and 2017. The addition of ash significantly ($p < 0.05$) increased cassava fresh tuber yields in both 2016 and 2017, whereas the three treatments (40 tonnes/ha, 80 tonnes/ha, and 160 tonnes/ha) were not significantly different ($p < 0.05$). However, the highest cassava fresh tuber yield (12.78 tonnes/ha) recorded by the 40 tonnes/ha treatment in 2016, was more than the control, 80, 160 tonnes/ha treatments by 106.1 %, 8.5 % and 15.6 %, respectively.

The 40, 80 and 160 tonnes/ha treatments were significantly higher than the control by 6.58, 5.58, and 4.85 tonnes/ha, respectively in 2016 whereas only the 40 and 80 tonnes/ha treatments were significantly higher than the control by 9.76 and 7.80 tonnes/ha, respectively in 2017. This suggests from crop yield point of view that addition of ash at the levels of 40 and 80 tonnes/ha will result in higher yield. This is true for loamy sand, and further research is needed to confirm whether this is the case for other soil textures.

In 2017, the yield of 160 tonnes/ha treatment was 242 % more than the control. The 40 tonnes/ha, and 80 tonnes/ha treatments were 426.7 %, and 340.9 % more than the control, respectively. According to Nweke (2005), cassava fresh tuber yield in 1996 was 12.9 tonnes/ha in the present research State (Imo State, Nigeria), which is the same as the average mean yield for the 40 tonnes/ha treatment in 2016 obtained in the current study. The average farm yield of cassava in Nigeria is 10.8 tonnes/ha as reported by Salami and Sangoyomi (2013). According to Howeler et al. (2013), the world average cassava yield is 12.8 tonnes/ha as of 2011, which represented 25.6 % increase from 2000 yield. However, it further stated that under optimal conditions including mono-cropping and higher varieties, cassava yields can reach 80 tonnes/ha. The highest yields for the 40 tonnes/ha treatment replicates in 2016 and 2017 were 15.40 and 21.45 tonnes/ha, respectively.

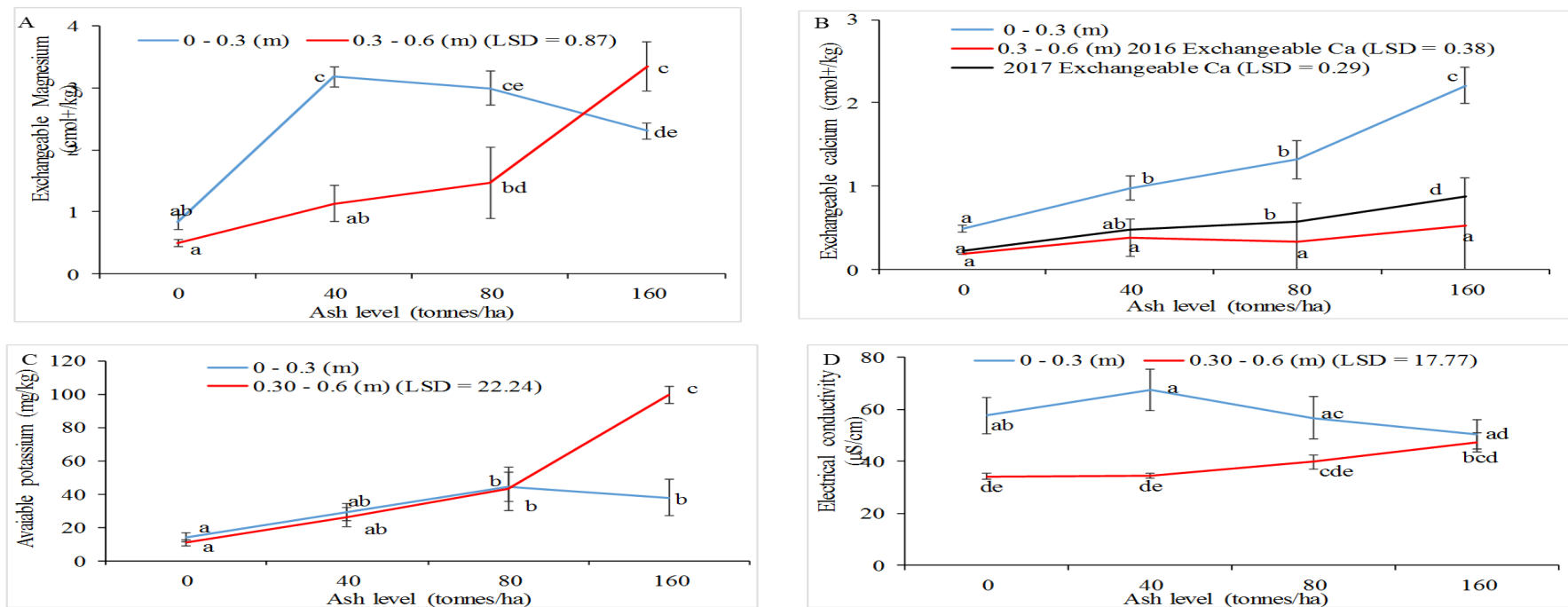


Figure 6-2 Effects of the different treatments for experiment I (A) soil exchangeable magnesium in 2016 due to interaction between treatments and soil depths, (B) soil exchangeable calcium in 2016 due to interaction between treatments and soil depths and soil exchangeable calcium due to treatment only in 2017, (C) soil available potassium in 2016 due to interaction between treatments and soil depths, (D) soil electrical conductivity in 2016 due to interaction between treatments and soil depths. Means of ash effects in each soil parameter with same letter are not significantly different at ($p < 0.05$), while means with different letters are significantly different. Ca – calcium, EC – electrical conductivity, K – potassium, LSD – least significant difference.

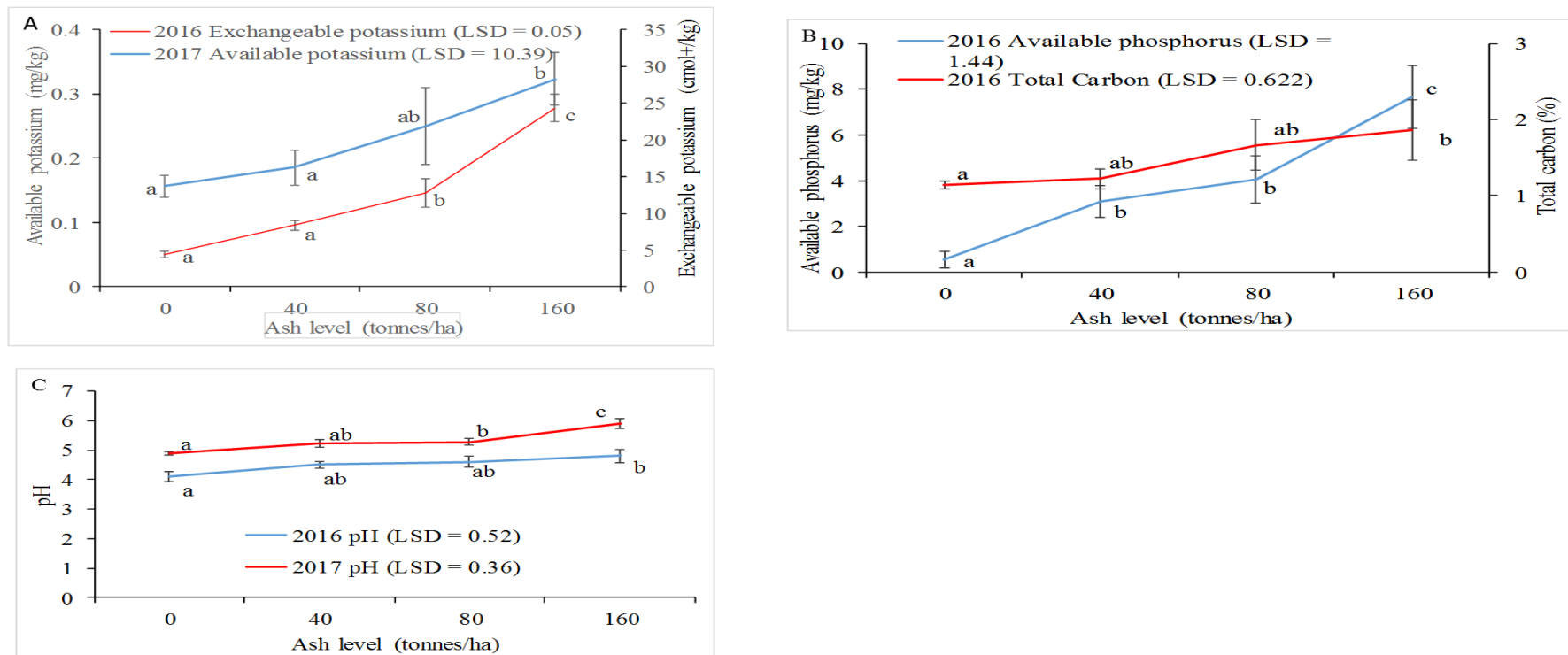


Figure 6-3 Effects of the different treatments for experiment I (A) soil exchangeable potassium in 2016 due to treatments and soil available potassium in 2017 due treatments only (B) soil available phosphorus and total carbon in 2016 due to treatments only, (C) soil pH in 2016 and 2017 due to treatments only. Means of ash effects in each soil parameter with same letter are not significantly different at ($p < 0.05$), while means with different letters are significantly different. LSD – least significant difference.

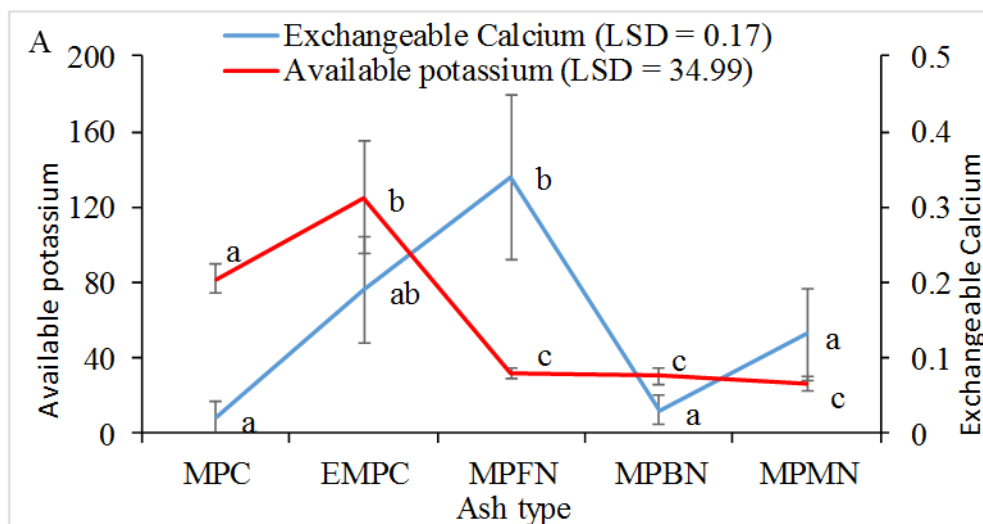
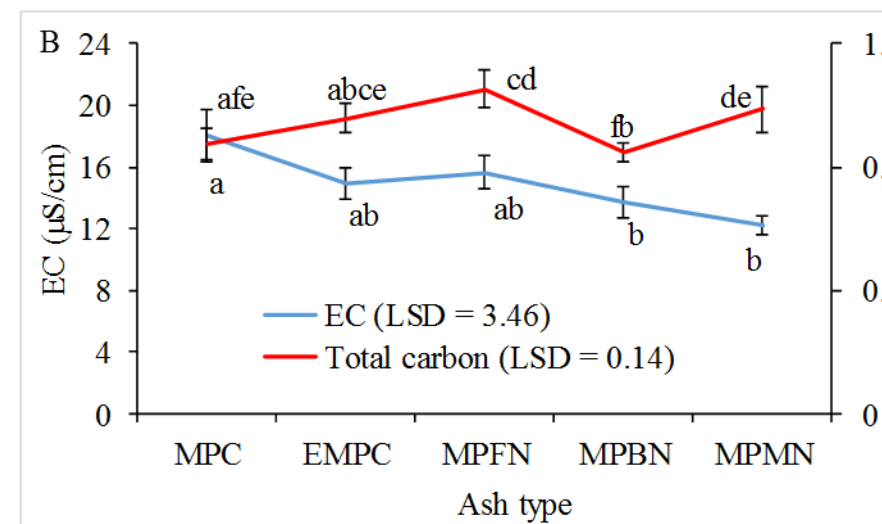


Figure 6-4 Effects of the different treatments (0.6 tonnes/ha) for experiment II (A) soil available potassium and exchangeable calcium, (B) soil electrical conductivity and total carbon. MPC – ash of mesocarp fibre and palm kernel shell from Cranfield University, EMPC - ash of empty fruit bunch, mesocarp fibre, and palm kernel shell feedstock from Cranfield University, MPFN - fly ash of mesocarp fibre, and palm kernel shell feedstock from Nigeria, bottom ash of mesocarp fibre, and palm kernel shell feedstock from Nigeria, MPMN - mixture of fly ash and bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria. Means of ash effects in each soil parameter and cassava yield with same letter are not significantly different at ($p < 0.05$), while means with different letters are significantly different. EC – electrical conductivity, C – carbon, LSD – least significant difference.

Onubuogu et al. (2014) reported that the mean cassava yield from local farmers in the same area of study was 1.40 tonnes/ha. Therefore, for the local farmer in Imo State and some parts of Sub-Sahara Africa with limited resources, the use of the FFB solid wastes ash without any other amendment can significantly increase cassava yield beyond local and regional average. Although, similar studies in other parts of Imo State and Sub-Sahara Africa are needed.

Experiment II

Figure 6-5B shows the effect of ash applications on cassava fresh tuber yield. The highest cassava tuber yield was 5.77 tonnes/ha (EMPC) while the lowest was 2.07 tonnes/ha (MPBN). Notably, the lowest yield was higher than the mean yield of 1.4 tonnes/ha by the local farmers in the same area as reported by Onubuogu et al. (2014), confirming the importance of ash as amendment. The EMPC treatment led to significantly higher ($p < 0.05$) yield than the MPC, MPFN, MPBN, and MPMN treatments. The MPC, MPFN, MPBN, and MPMN treatments were not significantly different ($p < 0.05$). However, the MPC treatment was higher than the MPFN, MPBN, and MPMN treatments by 53, 64, and 16 % respectively.

The MPFN, MPBN, and MPMN treatments were fly ash, bottom ash, and the equal mixture of fly and bottom ash from MF and PKS, respectively. The separate application of fly ash or bottom did not have any significant impact on cassava yield, which was similar to Experiment I ash. However, the MPMN treatment recorded the highest yield suggesting there could be a positive synergistic effect of using the mixture of fly and bottom ash as soil amendment against using fly and bottom ash separately. The MPC and EMPC treatments were mixtures of fly and bottom ash as generated by the downdraft gasifier, the difference being that the MPC treatment were only MF and PKS, while EMPC treatment were EFB, MF, and PKS. This was evident in the potassium and available potassium contents of the ash used in the experiment for the MPC and EMPC treatment (Table 6-4). The EMPC treatment recorded higher cassava fresh tuber yield than MPC by 2.4 tonnes/ha, with the only difference between the two amendments being the presence of EFB as part of the EMPC

treatment. This can be explained by the fact that the potassium content in the EFB is higher than in MF and PKS, which was evident in the initial properties of the ash used in the experiment (Table 6-4), and that measured in the soil after one year (124.88 mg/kg for the EMPC and 81.82 for the MPC treatments, respectively).

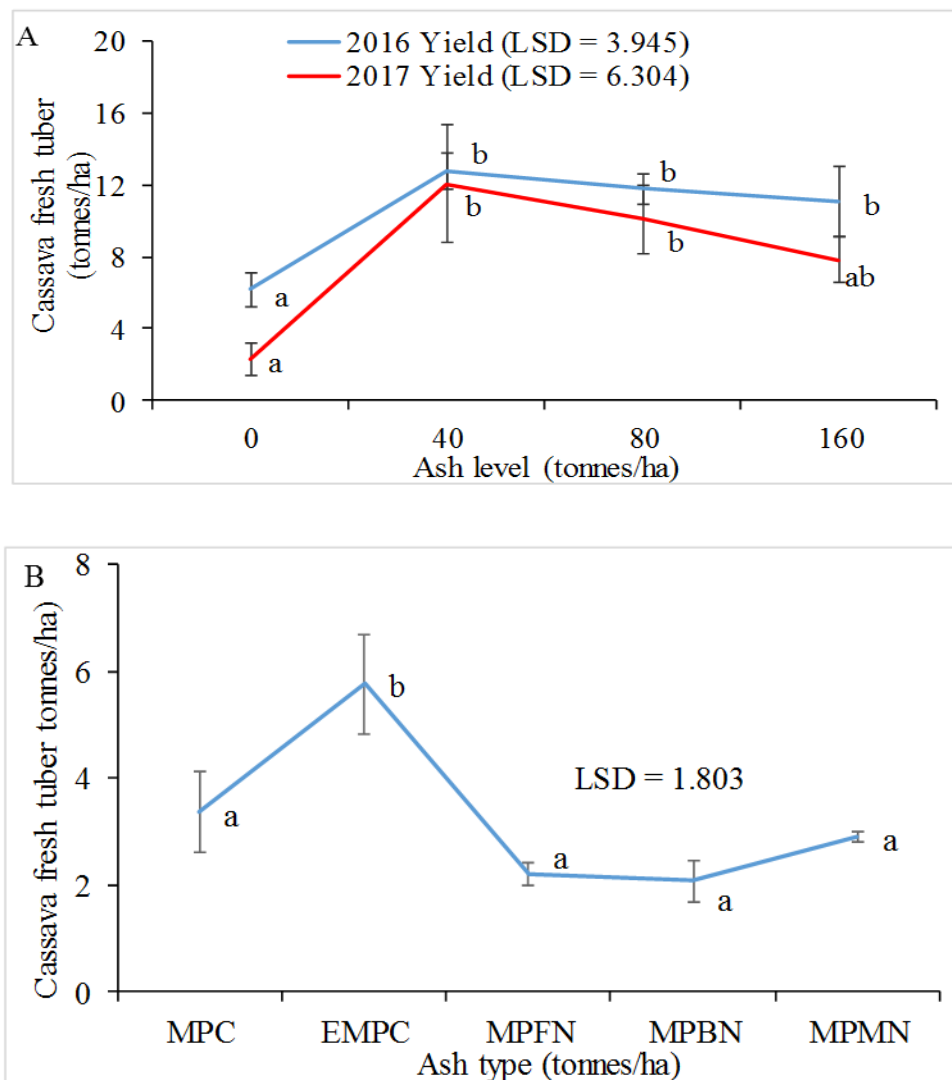


Figure 6-5 Effects of the different treatments on cassava fresh tuber weight (A) Experiment I for 2016 and 2017, (B) Experiment II for 2017 only (0.6 tonnes/ha treatment). MPC – ash of mesocarp fibre and palm kernel shell from Cranfield University, EMPC - ash of empty fruit bunch, mesocarp fibre, and palm kernel shell feedstock from Cranfield University,

MPFN - fly ash of mesocarp fibre and palm kernel shell feedstock from Nigeria, MPBN - bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria, MPMN - mixture of fly ash and bottom ash of mesocarp fibre and palm kernel shell feedstock from Nigeria. Means of ash effects in each soil parameter and cassava yield with same letter are not significantly different at ($p < 0.05$), while means with different letters are significantly different. EC – electrical conductivity, C – carbon, LSD – least significant difference.

According to Howeler (2002), the optimum levels of pH for cassava is 4.5 – 7.0; in our study, the initial soil pH for experiment I and II were more acidic, which are 4.08 and 4 for 0 – 0.3 m soil depth and 4.16 and 4.25 for 0.3 – 0.6 m soil depth, respectively, which are within the low range requirement for cassava production (Howeler, 2002). The 40, 80 and 160 tonnes/ha treatments increased the pH of the soil within the optimal levels for 2016 and 2017 while that of the control (4.1) was within the low range in 2016 and increased to 4.9 in 2017. The application of 40, 80, 160 tonnes/ha treatment led to increases from 4.5, 4.6, and 4.8 in 2016 to 5.2, 5.3, 5.9 in 2017, respectively. The increases from 2016 to 2017 represented 16, 14, 13 and 19 % for the control, 40, 80, and 160 tonnes/ha treatments, which corresponded to the highest cassava yields of 12.8 and 11.8 tonnes/ha for 40 and 80 tonnes/ha treatments, respectively. The pH range (4.9 – 5.5) due to the treatments in experiment II were in the range of the critical values for cassava. Therefore, pH of ≤ 5.3 is ideal for cassava production in the location of the experiment.

Kang (1984) demonstrated that the critical value of exchangeable magnesium for cassava production should be ≤ 0.2 cmol+/kg while Howeler (2002) reported a value of 0.25 cmol+/kg for exchangeable calcium. The exchangeable magnesium and calcium contents of all the treatments for experiment II were higher than the critical levels stated above. Kang (1984) has demonstrated that the magnesium decline in soil is much less compared to potassium. The soil contents of exchangeable magnesium and calcium for experiment I increased due to 40, 80 and 160 tonnes/ha treatments more than the values before the

experiment while that of the control decreased. This is an indication of cassava response to magnesium and calcium of which the applied ash replenished the levels due to 40, 80 and 160 tonnes/ha treatments while the nutrients were depleted due to the control.

Nweke (2005) reported that phosphorus leads to yield increase in cassava more than any crop, while cassava takes up potassium followed by calcium (Nweke, 2005) from the soil more than any other element. Cassava has high efficient utilisation of phosphorus as a result of cassava root association with soil mycorrhiza according to Maduakor (1997) and therefore can grow well in a soil low in phosphorus (Howeler, 2002). The critical values of phosphorus for cassava production are within 3 - 8 mg/kg (Howeler, 2002) in experiment II (11.2 mg/kg average values for all treatments). The available phosphorus from our study due to the ash applications were within the range for experiment I in 2016 due to 40, 80 and 160 tonnes/ha treatments and lower due to the control.

The 40 tonnes/ha treatment led to soil exchangeable potassium value of 0.1 cmol+/kg in 2016, while that of 80 tonnes/ha led to 0.15 cmol+/kg of exchangeable potassium. The exchangeable potassium values for 40 (0.08 cmol+/kg), 80 (0.12 cmol+/kg), and 160 tonnes/ha (0.18 cmol+/kg) treatments in 2017 decreased from the 2016 values (0.10, 0.15, and 0.28 cmol+/kg, respectively) while that of the control increased from 0.05 cmol+/kg in 2016 to 0.11 cmol+/kg in 2017. The increase in the value for the control did not reflect on the cassava yield as the control recorded the lowest yield. The exchangeable potassium (0.11 cmol+/kg) for the EMPC treatment in experiment II was higher than the other treatments, which reflected in the highest cassava yield. Although the levels of ash used in experiment I was more than that of experiment II in all the treatments, the ash of EFB, MF and PKS feedstock led to increase in the available potassium of the soil and significant increase in cassava yield for experiment II as explained in the sections above. Therefore, when the feedstock of the ash is the equal mixture EFB, MF and PKS, treatment lower than 40 tonnes/ha will be ideal.

According to Nweke (2005) deficiency of potassium affects the dry matter and starch contents and results in high cyanide content, and a good cassava variety extracts 0.1 tonne/ha of potassium or more; while Howeler and Cadavid (1983) reported a cap of 100-150 kg potassium per ha. The fresh cassava tuber contains cyanide, which is usually reduced to safe level during processing of the tuber through fermentation.

The cassava fresh tuber yield of 12.05 tonnes/ha in 2017 was the highest in the 40 tonnes/ha treatment, which is in line with the result in 2016 for experiment I. This is a clear indication of the level of ash required for maximum cassava fresh tuber yield, which in this case is 40 tonnes/ha, beyond which addition of more ash will not lead to any significant increase. Expectedly, the mean yield (8.06 tonnes/ha) in 2017, for all the treatments was lower than the average mean yield (10.45 tonnes/ha) in 2016, for all the treatments, which can be explained by the reduction in exchangeable potassium in 2017 from 2016 values. The overall leading indicator being that there was no ash application after the first harvest of cassava fresh tuber and therefore the cassava relied on the remaining ash nutrient.

Maduakor (1997) explained that high rainfall and the nature of the soil of the area (Southern Nigeria) led to leaching of potassium, depriving cassava the nutrient, a result that is in line with that achieved in this work. Onubuogu et al. (2014) reported annual rainfall of between 1.9 m and 2.2 m of the area. Tauriq et al. (2015) reported that cassava response to potassium availability in the soil is up to 160 days after planting, which explains the lower yield due higher ash levels. Considerable leaching of the potassium may have occurred during this period. There was 6 % reduction in the yield from 2016 to 2017 for the 40 tonnes/ha treatment, whereas there were 14 %, 29 % and 63 % reductions in the yield for the 80 tonnes/ha treatment, 160 tonnes/ha treatment and control, respectively for experiment I. Howeler (1991) reported that soil potassium exhaustion contributed more to cassava yield decline during continuous production. According to Howeler (1991) reduction in yield at high levels of soil potassium could be a negative interaction of potassium with magnesium and

calcium. In our study, the exchangeable magnesium and calcium were more than the critical levels. Although, exchangeable calcium in 2017 did not increase more than the 2016 levels, it was significantly different. In both 2016 and 2017, exchangeable magnesium, calcium and potassium increased linearly. However, our result was in line with Tauriq et al. (2015), which demonstrated that the highest cassava tuber yield was obtained at 60 kg K₂O/ha and no significant increase in cassava tuber yield with higher K dose.

The MPFN, MPBN, and MPMN treatments of the ash used in Experiment II were similar to the feedstock of the ash used in Experiment I and as well showed similar trend in the nutrient compositions of the soil (Table 6-4). Similar trends were observed in the effects of these treatments from the same feedstock in response to cassava yield for Experiments I and II, while the EMPC treatment with different feedstock mixture showed outstanding effects on the cassava fresh tuber yield and soil available potassium content in Experiment II. Since the applied ash was the only source of potassium, magnesium, and calcium, it was difficult to estimate the effects of interactions of these nutrients on cassava tuber yield. However, this offered opportunity to estimate how much of other nutrients of lower levels in ash for example nitrogen would be needed to supplement ash use for crop production especially crops that respond to nitrogen deficiency.

There were significant interaction between the soil depth and the ash application levels in experiment I for exchangeable magnesium, calcium and potassium in 2016. The concentrations increased with the soil depth and the ash levels. This may explain why the 160 tonnes/ha ash treatment led to a lower yield than the 80 and 40 tonnes/ha treatment implying the downward movement of the nutrients beyond the reach of the cassava roots.

6.3.4 Environmental challenges of ash application

Heavy metals including nickel, lead, cadmium, chromium, copper, zinc cobalt and manganese at higher levels cause phyto-toxicity, reduce plant growth and nutrient use efficiency (Baligar et al., 2007). The other factors affecting plant nutrient use efficiency are the soil capacity to supply adequate nutrients, the

plants ability to absorb and transport the nutrients, rainfall, and temperature. Igbozuruike et al. (2009) reported critical ranges of 20-70 mg/kg, 50-250 mg/kg, and 10-100 mg/kg for nickel, copper and zinc for soil. The results of nickel, copper and zinc concentrations before and after 10 months in experiments I were below these critical levels and the other heavy metals were not detected. The values for nickel, copper and zinc before the experiment were 13.93 ± 1.27 , 3.66 ± 0.21 , and 4.56 ± 0.28 mg/kg (mean $\pm$ standard error) in the 0-0.3 m soil layer and 15.8 ± 0.82 , 3.61 ± 0.24 , and 6.08 ± 0.5 mg/kg (mean $\pm$ standard error) in the 0.3 – 0.6 m soil layer. Zinc was not detected after 10 months whereas the values for nickel and copper were 19.06 ± 0.87 , and 2.48 ± 0.26 mg/kg (mean $\pm$ standard error) in the 0 – 0.3 m soil layer and 15.76 ± 1.06 , and 5.46 ± 0.53 mg/kg (mean $\pm$ standard error) in the 0.3 – 0.6 m soil layer.

6.4 Conclusions

The application of the 40 tonnes/ha, 80 tonnes/ha, 160 tonnes/ha treatments from a mixture of MF and PKS feedstock significantly increased the cassava fresh tuber yield (12.78, 11.78, and 11.05 tonnes/ha, respectively), soil available phosphorus (3.08, 4.06, and 7.65 mg/kg, respectively), and exchangeable magnesium (3.18, 2.99, and 2.31 cmol+/kg in the 0 - 0.3 m soil layer, respectively) and calcium (0.98, 1.32, 2.21 cmol+/kg in the 0 - 0.3 m soil layer, respectively), when compared to the control (without ash application) in 2016. The corresponding cassava fresh tuber yield, soil available phosphorus, exchangeable magnesium and calcium for the control were 6.2 tonnes/ha, 0.55 mg/kg, and 0.84 and 0.49 cmol+/kg. Therefore, beyond the 40 tonnes/ha treatment cassava fresh tuber yield will start to decrease even with increase in soil properties especially potassium. However, the feedstock of the ash used in the experiment should be taken into consideration, which in this case were MF and PKS. The lower treatments of 6 tonnes/ha led to significant increase in cassava fresh tuber yield for experiment II. The ash from the combination of EFB, MF and PKS used in Experiment II had the highest potassium content and therefore led to the highest increase in the available potassium in the soil. Therefore, (i) the ash application had more influence on soil calcium and

potassium contents than other soil nutrients measured, and (ii) the use of EFB due to its high potassium content is important in cassava production and the potassium and calcium effects on soil and therefore ash of EFB, MF and PKS feedstock is more valuable as soil amendment than the commonly used ash of MF and PKS feedstock.

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7 Integrated discussion: fresh fruit bunch processing, thermal conversion and utilisation nexus

The overall aim of the work is to understand the relationship between the processing of fresh fruit bunch (FFB), thermal conversion of FFB solid wastes, and the utilisation of the solid waste streams as fertiliser in agriculture. The work has been structured into three parts to summarize the impact of its implementation by answering the research questions related to the overall aim.

7.1 Is there relationship between oil palm fresh fruit bunch processing and the quality of the wastes as energy sources?

The challenge of utilisation of empty fruit bunch (EFB) for energy and its co-firing stems from the processing of FFB. From the reviews of Chapters 2 and 3 and Chapter 4, the EFB, mesocarp fibre (MF), and palm kernel shell (PKS) are used as boiler fuels and the ash generated used as soil amendments. Secondly, the co-firing of EFB, MF, and PKS increases sources of energy and utilisation and therefore create more sustainable energy. However, some of the challenges of FFB solid wastes utilisation as fuel especially the EFB for the generation of ash include low bulk density (144 kg/m^3), high moisture content (56 %), and high alkali content. The bulk density limits the transportation of the raw biomass especially EFB. It forces the palm oil millers to deposit the wastes including ash within the palm oil mills, adding pressure to the limited land spaces and leading to greenhouse gas emissions.

The key observation from this work is that the wastage of the EFB is due to its poor state as source of energy and therefore limits its co-firing with the MF and PKS. This limitation affects the quality of ash produced from most palm oil mills and the effects of the ash utilisation for agriculture purposes. The different routes of processing FFB have challenges (Chapter 4), however the industrial route demands more attention since more FFB are processed per hour and contribute enormously to the total amount of wastes generated per unit area.

The sterilisation of the full FFB and subsequent threshing contributes to the losses. The oil palm fruits that are not detached from the threshed bunch are discarded as wastes and therefore contribute to low crude palm oil (CPO) yield of the palm oil mills (Ali, 2014; Babatunde et al., 1988). This challenge of low CPO yield is more common with the industrial route of processing the FFB. The losses associated with FFB processing are of two parts. Firstly, the loss of value derivable from CPO, palm kernel (PK), MF, and PKS (for example 28.9 kg of CPO, 16.7 kg of PK, 74.6 kg of MF, and 26.5 kg of PKS lost for every 1000 kg of FFB processed in the industrial route). The PK is the source of oil known as palm kernel oil, and palm kernel cake, which is the residue after oil extraction. The palm kernel cake is used as animal feed, and also used as boiler fuel (Woods et al., 2006). The value of the lost CPO is estimated as \$27. The energy values of MF and PKS have been estimated as 89 kWh and 31 kWh, respectively. Secondly, the presence of fruits in EFB leads to additional cost to any attempt to use EFB as fuel. In order to use the EFB together or separately as boiler fuel especially in the existing boilers the fruits must be completely removed, and the size and moisture must be reduced (Igwe et al., 2010). Most palm oil mills have a separate plant to carry out these processes before using the EFB in the boilers, which is limited by the extra energy, time and labour required. Compared to the MF and PKS, the value of processing the EFB to fit into the facility does not bring in additional profit. Therefore, the default action is disposal of the EFB to nearby oil palm plantation (Chapters 2 and 4). The low bulk density of 110 kg/m^3 (Sung et al., 2010), and high moisture content of EFB (60 – 70 %) (Aziz, 2017) that will require enormous amount of energy to dry and reduce its particle size to fit into most existing boilers also impose a limit on how far from the mill the waste is dumped. The transportation is an additional cost of which benefits are hard to quantify considering that the vehicles used are part of the operational facilities in the palm oil mills.

The disposal of poorly threshed EFB leads to the equivalent of 6,670 tonnes carbon dioxide equivalent of methane and nitrogen oxide emissions from 29 000 tonnes of the EFB a year. This highlighted another limitation associated with FFB processing at the industrial route and represents a major greenhouse

gas contributor from a single mill. The threshed EFB from the industrial route when supplied to the local labourers for re-threshing and drying will earn them about the same amount (\$19) they currently earn (Chapter 4), while the dried EFB will be sent back to the palm oil mills, and independent power producers for energy use.

7.2 Is there any synergy in the thermal conversion of the mixture of empty fruit bunch, mesocarp fibre, and palm kernel shell?

From Chapters 2 and 3, the co-firing of the EFB, MF, and PKS is a suitable option for effective management of the FFB solid wastes, which will require the blending of the biomass and possible densification. From Chapter 4, the main set-backs in the utilisation of EFB for energy purpose are low bulk density (144 kg/m^3) and high moisture content (56 %). However, the key finding from this work is that the co-gasification of the equal mixture of EFB, MF, and PKS compared to the equal mixture of MF and PKS increased the gas yield, cold gas efficiency, carbon conversion efficiency and the ash quality for agricultural use. The quality of biomass (high bulk density, low moisture content, small particle size) influences the direct utilisation as fuel especially in co-firing, which requires that the different fuel be closely similar in physical properties (Chapter 3) for example, moisture content and particle size. In most palm oil mills, there is reliance on the PKS and MF especially with little or no effort in the use of the EFB for energy production. One of the challenges of the co-firing of the EFB with MF and PKS is the relative larger particle size of the EFB, which is because of sterilising and threshing the full FFB leading to the generation of high moisture and low bulk density biomass (Chapter 3, 4 and 5). However, there is increasing interest in the utilisation of the EFB for energy purposes including in Malaysia (Nasrin et al., 2010) and more so in biomass co-firing (Chapter 3). The co-firing of the EFB, MF and PKS potentially will increase the utilisation of biomass for energy purpose, reduction in greenhouse gas emission, and the generation of higher quality ash for agricultural purposes (Chapter 3). The co-gasification of the equal mixture of EFB, MF and PKS,

compared to the equal mixture of the MF and PKS (Chapter 5) led to gas yield of 4.82 and 3.47 m³/kg_biomass, cold gas efficiency of 16.2 and 13.4 %, carbon conversion efficiency of 56.3 and 34.2 %, and the ash quality (36 % in potassium content), respectively. This demonstrated that the addition of EFB to the fuel mixture led to increases in gas yield, carbon conversion efficiency and cold gas efficiency and therefore evident of the need to co-fire the biomass. More importantly is the need to generate ready to use EFB during FFB processing (Chapter 4). The PKS of smaller particle size (0.0067 m) led to improvements in the equal mixture of EFB, MF and PKS compared to that of 0.0140 m. The PKS of particle size of 0.0067 m led to increased heating values (780 and 830 kJ/m³), reduced residue yield (4.8 and 3.9 %) and potassium:calcium ratio (3.7 and 3.6). The overall result has provided evidence on the importance of co-firing biomass especially the EFB, MF and PKS, which will result in increased utilisation of the EFB and reduce emissions because of poor disposal of the EFB. It also supports the increase in the use of biomass in the co-firing operations (Chapters 3 and 5). One of the challenges of co-firing is the variations in properties of the feedstock, in this case properties of the EFB, MF, and PKS. However, it is important to take any variation into consideration since the co-firing of biomass is aimed at the synergistic effects due to differences in fuel properties.

7.3 What are the effects of the application of ash from FFB solid wastes on soil physico-chemical properties and cassava yield?

The ash from FFB solid wastes has been found effective in improving soil physical and chemical properties, and crop yield (Chapter 2). From Chapter 3, one of the benefits of the co-firing of the EFB, MF, and PKS is improvement in the ash quality.

One of the key contributions from this work is that for the feedstock of MF and PKS, the maximum treatment for a loamy sand texture for cassava production in a two-year period is 40 tonnes/ha, however less will be required when the

feedstock is of the equal mixture of EFB, MF and PKS. The co-firing of different biomass will lead to ash of mineral compositions reflecting the differences in the compositions of the feedstock, for example, the total potassium contents of the ash from MF/PKS and EFB/MF/PKS feedstock are 984578 and 134246 mg/kg, respectively (Table 6-3). The variations due to the co-firing on the ash properties will affect how and where the ash is used. The use of ash for agricultural purpose is a means of returning to the soil part of nutrient lost during harvest of crops. An important aspect to the ash utilisation in agriculture is ensuring high market value for the ash through standardisation. The agricultural utilisation of the ash is very important on crops for example cassava, which is limited by potassium (the most important nutrient in biomass ash) availability (Ezui et al., 2016; Tauriq et al., 2015). The properties of the fly ash and bottom ash differs (Chapter 6, Table 6-3) and more so from different feedstock (Table 6-3). Similarly, the properties of the mixture of fly ash and bottom ash will reflect the differences between the fly and bottom ash and on the soil and crop responses when applied to the soil. The potassium contents of fly ash, bottom ash and their mixture of MF/PKS feedstock are 37410, 18955, and 31951 mg/kg, respectively (Table 6-3). The application of the 40 tonnes/ha, 80 tonnes/ha, 160 tonnes/ha treatments from a mixture of MF and PKS feedstock (Chapter 6) significantly increased the cassava fresh tuber yield (12.78, 11.78, and 11.05 tonnes/ha, respectively), soil available phosphorus (3.08, 4.06, and 7.65 mg/kg, respectively), and exchangeable magnesium (3.18, 2.99, and 2.31 cmol+/kg in the 0 - 0.3 m soil layer, respectively) and calcium (0.98, 1.32, 2.21 cmol+/kg in the 0 - 0.3 m soil layer, respectively), when compared to the control (without ash application). The corresponding cassava fresh tuber yield, soil available phosphorus, exchangeable magnesium and calcium for the control were 6.2 tonnes/ha, 0.55 mg/kg, and 0.84 and 0.49 cmol+/kg. When the ash from the EFB, MF and PKS feedstock was compared with ash from MF and PKS feedstock, the ash of EFB, MF and PKS feedstock led to significant increase in the available potassium (125 and 82 mg/kg) and cassava fresh tuber yield (6 and 3 tonnes/ha), which was due to high potassium content in EFB. The results demonstrated the influence of EFB as feedstock and therefore

feedstock of the equal mixture of EFB, MF and PKS is more valuable for the generation of ash as soil amendment and cassava that requires high potassium content. This therefore supports the co-firing of EFB, MF and PKS, which will not only increase the use of EFB as fuel source but also increase the ash quality for agricultural purposes.

The complete utilisation of the FFB solid wastes in the palm oil mills will ensure the availability of energy and less impact on the environment due to disposal of the wastes. For example 0.23 tonne carbon-dioxide equivalent of methane and nitrogen oxide per tonne of FFB processed is released due to poor decomposition of EFB (Elbersen et al., 2013). From the results of the research above, two scenarios are possible for example using 2014 production figure of one of the palm oil mills studied (Table 7-1).

Table 7-1 Production figure of fresh fruit bunch wastes from an industrial mill for 2014. Total FFB processed was 94932.44 tonnes of which EFB, MF, and PKS represents 30.6, 28.1, and 10 %, respectively.

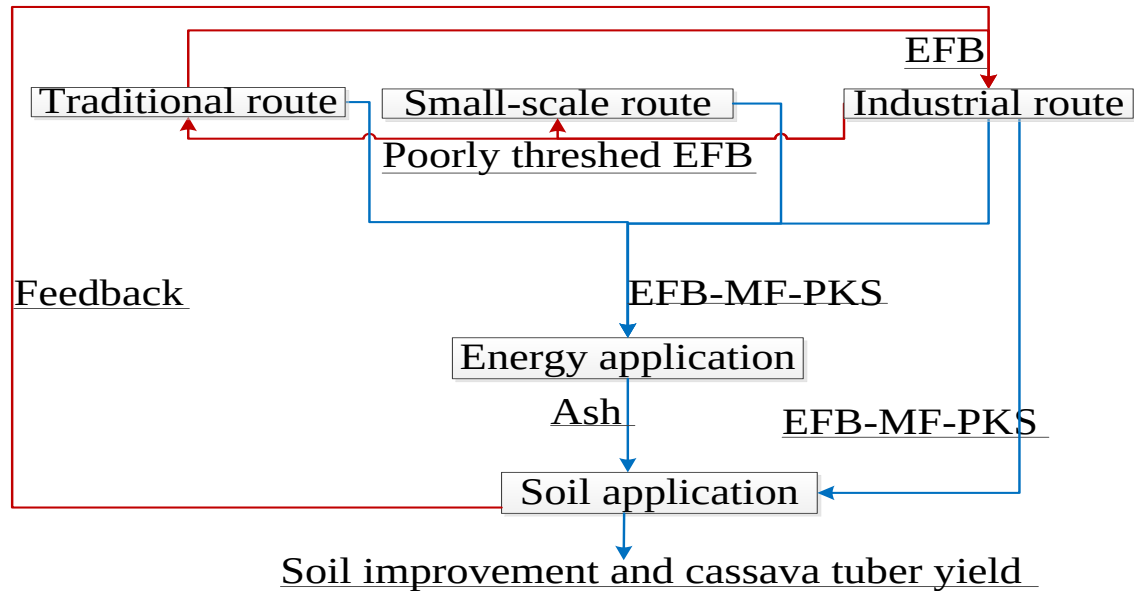
FFB waste	Quantity of waste produced (tonne)	Current option			Proposed option		
		Quantity currently used in combustion (tonne)	Quantity discarded (tonne)	Methane and nitrogen oxide emissions (carbon dioxide equivalent)	Quantity used in combustion (tonne)	Quantity left (tonne)	Methane and nitrogen oxide emissions (carbon dioxide equivalent)
PKS	9493	9493	0	0	9493	0	0
MF	26676	4747	21929	5044	9493	17183	3952
EFB	29049	0	29049	6681	9493	19556	4498

FFB – fresh fruit bunch, PKS – palm kernel shell, MF – mesocarp fibre, EFB – empty fruit bunch

In the current option, all the EFB and 82 % of MF produced are disposed leading to a total of approximately 11700 tonnes carbon-dioxide equivalent of methane and nitrogen oxide released in the mill from about 95000 tonnes of the FFB harvested in that year (assuming MF release same amount of greenhouse gas as EFB). The proposed option comprises of the use of the equal mixture the EFB, MF, and PKS in co-combustion, which will prevent the release of approximately 3300 tonnes carbon-dioxide equivalent of methane and nitrogen oxide. The remaining 36739 tonnes of EFB and MF will be used in co-composting.

The FFB processing determines the availability and utilisation of the solid wastes (EFB, MF, and PKS) for energy purposes and the ash generated on soil (Figure 7-1). Although, it has been recommended that poorly threshed EFB from the industrial route should be fed into the small-scale and traditional routes however, when properly threshed and at reduced particle size and moisture content, EFB is easily co-fired with MF and PKS and the ash produced is valuable as soil amendment and for cassava yield improvement. This work has demonstrated that the use of ash for soil improvement and crop yield is related to feedstock. Different feedstock have ash of different properties. The co-firing of the EFB, MF, and PKS has demonstrated that feedstock influence the properties of the ash. The co-firing of the feedstock depends on their availability, chemical and physical properties. Physical properties are related to the thermal conversion systems and the ability of the feedstock to form a uniform mixture while chemical properties influences the performance of the thermal conversion system and output of the process including ash (residue). The co-firing of the EFB, MF, and PKS depends on the availability of the three biomass and at the right quantity, which is possible through an appropriate processing of FFB. Therefore, the availability of ready to use EFB, MF, and PKS is a precursor to their co-firing, which affects the value of ash produced on soil and cassava yield. Decision making on what type of ash is needed for a particular soil and crop potentially will influence the feedstock in biomass co-firing, which is the “bottom-up approach in biomass utilisation”. For FFB wastes,

the “bottom-up approach in biomass utilisation” will enhance decision making in FFB processing and thermal conversion when the appropriate utilisation of the residue (ash) generated is considered.



EFB-empty fruit bunch, MF-mesocarp fibre, PKS-palm kernel shell

Figure 7-1 Interconnection of the research questions and outcomes.

7.4 References

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8 Conclusions and Future Work

8.1 Conclusions

This study has attempted to present a comprehensive and consolidated account of the research on different FFB processing routes in Nigeria including an important insight on the limitations of using the EFB and its co-firing with the MF and PKS. The study also explored the influences of the intrinsic fuel analysis and the operational parameters on the outcome of the gasification processes. The basic idea underlying the co-gasification is to increase biomass utilisation and enhance the products especially quality ash and the benefits applying it to loamy sand for maximum cassava yield. The findings are summarised in relation to the specific objectives of this research.

Objective 1. To conduct a critical review of the prospects and challenges of co-FFB solid wastes and the utilisation as soil ameliorants. Therefore:

- Co-utilisation of the EFB, MF, and PKS provide a suitable option in effective management of the wastes, which would lead to valuable products including biochar, ash, and compost through pyrolysis, gasification, combustion, and composting (Chapter 2 and 3).
- A well-balanced utilisation of the FFB solid wastes could reduce the negative impacts of disposal of the wastes, including greenhouse gas emission, pest breeding, pressure on limited land space, wastes of potential soil ameliorants and the attendant economic losses, increase in energy sources and reduce dependency on fossil fuel (Chapter 2 and 3).

Objective 2. To evaluate the difference between industrial, small scale, and traditional routes of processing FFB for increased utilisation of the solid wastes for energy purposes. Therefore:

- The reviews demonstrate that EFB, MF, and PKS could be used as boiler fuels and the ash generated returned to the soil as amendments. However, 100 % more CPO, PK, MF, and PKS are lost in the industrial

route than the small-scale and traditional routes for every 1000 kg FFB processed, respectively. These losses are associated with low quality EFB for energy purposes. High quality EFB with little or no fruit can be co-fired with MF and PKS (Chapter 5).

- An estimated 6,670 tonnes carbon dioxide equivalent of methane and nitrogen oxide is released due to the disposal 29 000 tonnes of EFB from one palm oil mill (Chapter 2 and 4). The unavailability of ready to use EFB due to poor threshing as evidenced by the study on processing routes limits the co-firing with the MF and PKS and therefore the quality of ash for soil improvement and cassava yield (Chapter 6).

Objective 3. To evaluate the effects of the co-firing on the thermal behaviour of EFB, MF and PKS especially on the properties of the ash generated. Therefore:

- The availability of ready to use EFB through proper FFB processing would enable the co-firing with MF and PKS. The properties of ash from the co-gasification/co-firing of the EFB, MF, and PKS is influenced by the synergic reactions between the three biomass and therefore affect the availability of the individual nutrients especially potassium for agricultural purposes (Chapter 3 and 5).
- There was synergic reactions during co-gasification, which affected the syngas yield (Chapter 5).
- Smaller particle size of PKS increased the lower and higher heating values of the syngas by 0.13 and 0.14 MJ/m³, respectively, reduced the residue yield of 3.16 and 2.59 % and potassium/calcium ratio of 2.24 and 2.19 of the equal mixture of EFB, MF and PKS (Chapter 2, 3 and 4 and 5).
- The addition of EFB to MF and PKS led to reduced rate of agglomeration and a valuable ash for use as soil amendment (Chapter 3 and 5) against using only EFB, which potentially would lead to high agglomeration due to its high potassium content.

Objective 4. To determine the effects of ash from FFB solid wastes on selected soil properties and to increase cassava yield. Therefore:

- There are positive agronomic and environmental influences of the use of FFB solid waste streams as organic amendments in the soil (Chapter 2 and 6). The use of 40 tonnes/ha ash was 0.046 cmol+/kg more than the control, which contributed to 106 and 427 % more cassava tuber yield than the control in 2016 and 2017, respectively.
- The feedstock of the equal mixture of EFB, MF and PKS is more valuable for the generation of ash as soil amendment and cassava production providing evidence for the co-firing of the EFB, MF and PKS and improved efficiency of FFB processing (Chapter 2, 3 and 6).

Finally, the overall outcome above favours efficient processing of FFB, which will enable the recovery of almost all fruit, generate EFB ready to be used as fuel and reduce losses of MF and PKS. It also favours the co-firing of the EFB, MF and PKS, which potentially reduces methane and nitrogen oxide emissions due to EFB disposal by approximately 33 % and increase the quality of ash (36 % in potassium content) produced during the co-firing for soil improvement and increase in cassava yield.

8.2 Future work

The areas of research identified during this project for further studies are:

- Research into other ways of processing FFB is necessary to fully recover the fruits, reduce the particle size of EFB, and produce less moist waste. The use of hot air instead of steam in sterilising FFB, size reduction of FFB prior to sterilisation will potentially reduce the moisture content and particle size enabling fast drying of EFB and makes it ready to use as fuel within and outside the palm oil mills. The use of microwave in the sterilisation has been investigated by Sukaribin and Khalid (2009) and Cheng et al. (2011) with improvements on threshing efficiency and quality of CPO.

- Higher K/Ca ratio leads to higher agglomeration (Steenari et al., 2009) and therefore the use of smaller particle size for all the feedstock should be investigated since it can potentially reduce agglomeration during co-gasification without reducing the quality of ash as soil amendment.
- Further investigation on the effects of temperature, different gasifying agents, and equivalence ratio on the syngas yield, heating values, carbon conversion efficiency, residue yield, and K/Ca ratio during the co-gasification of the equal mixture of EFB, MF, and PKS. Further research can be extended into different ratios of EFB, MF, and PKS in the mixture.
- Additionally, the investigation can be extended into co-combustion, which potentially will enable the co-combustion of FFB solid wastes at relatively higher temperature.
- There were observed variations in properties of fly ash and bottom, which requires further investigation on the effects of fly ash and bottom ash from the feedstock of the equal mixture of EFB, MF and PKS on soil chemical and physical properties, and yield of cassava and other crops.

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Appendices

Appendix A Study of Oil Palm Fresh Fruit Bunch Processing in Nigeria

Table A-1 Quantity (kg) of CPO, PKS, MF, and PK recovered per 1000 kg of FFB processed in the Industrial route.

	Total weight of FFB	Total weight of fruit	CPO (10.9 % of fruit)	PKS (10 % of fruit)	MF (28.1 % of fruit)	PK (6.3 % of fruit)	CPO per 1000 FFB processed	PKS per 1000 FFB processed	MF per 1000 FFB processed	PK per 1000 FFB processed
	129.11	25.60	2.79	2.56	7.19	1.61	21.61	19.83	55.72	12.49
	189.15	42.80	4.67	4.28	12.03	2.70	24.66	22.63	63.58	14.26
	137.40	34.90	3.80	3.49	9.81	2.20	27.69	25.40	71.37	16.00
	113.50	26.80	2.92	2.68	7.53	1.69	25.74	23.61	66.35	14.88
	190.03	56.30	6.14	5.63	15.82	3.55	32.29	29.63	83.25	18.67
	199.33	58.20	6.34	5.82	16.35	3.67	31.83	29.20	82.05	18.40
	164.48	41.50	4.52	4.15	11.66	2.61	27.50	25.23	70.90	15.90
	137.20	47.40	5.17	4.74	13.32	2.99	37.66	34.55	97.08	21.77
	117.05	26.90	2.93	2.69	7.56	1.69	25.05	22.98	64.58	14.48
	170.50	55.20	6.02	5.52	15.51	3.48	35.29	32.38	90.97	20.40
Total	1547.74	415.60								
Average							28.93	26.54	74.59	16.72
Example calculation row 9. Quantity of MF produced: total quantity of fruit recovered * 0.281 = 13.32 Quantity produced per 1000 of FFB produced for PK: (13.32*1000)/137.2= 97.08										

CPO – crude palm oil, PKS – palm kernel shell, MF- mesocarp fibre, PK – palm kernel, FFB – fresh fruit bunch

Table A-2 Quantity (kg) of CPO, PKS, MF, and PK recovered per 1000 kg of FFB processed in the small-scale route.

	Total weight of FFB	Total weight of fruit	CPO (10.9 % of fruit)	PKS (10 % of fruit)	MF (28.1 % of fruit)	PK (6.3 % of fruit)	CPO per 1000 FFB processed	PKS per 1000 FFB processed	MF per 1000 FFB processed	PK per 1000 FFB processed
	236.2500	0.0096	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	318.9200	0.0056	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	168.0750	0.0101	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	180.7200	0.0144	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	240.5800	0.0064	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	180.3400	0.0160	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	263.2300	0.0134	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	294.5600	0.0134	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	297.7800	0.0158	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	178.8500	0.0086	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
Total	2359.3050									

Average

<0.0100 <0.0100 <0.0100 <0.0100

Example calculation row 2. Quantity of PKS produced: total quantity of fruit recovered * 0.1 = 0.001. Quantity produced per 1000 of FFB produced for PK: (0.00096*1000)/236.25= 0.004

CPO – crude palm oil, PKS – palm kernel shell, MF- mesocarp fibre, PK – palm kernel, FFB – fresh fruit bunch

Table A-3 Quantity (kg) of CPO, PKS, MF, and PK recovered per 1000 kg of FFB processed in the Traditional route.

Total weight of FFB	Total weight of fruit	CPO (10.9 % of fruit)	PKS (10 % of fruit)	MF (28.1 % of fruit)	PK (6.3 % of fruit)	CPO per 1000 FFB processed	PKS per 1000 FFB processed	MF per 1000 FFB processed	PK per 1000 FFB processed
52.7500	0.0001	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
93.5000	0.0018	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
50.4300	0.0011	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
121.6800	0.0072	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
54.0300	0.0009	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
90.0800	0.0014	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
60.7300	0.0026	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100

	85.8000	0.0032	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	119.3500	0.0048	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
	40.7300	0.0023	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
Total	769.0600		<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100	<0.0100
Average							<0.0100	<0.0100	<0.0100	<0.0100

Example calculation row 7. Quantity of PK produced: total quantity of fruit recovered * 0.063 = 0.0000882. Quantity produced per 1000 of FFB produced for PK: $(0.0000882 \times 1000) / 90.075 = 0.00098$

CPO – crude palm oil, PKS – palm kernel shell, MF- mesocarp fibre, PK – palm kernel, FFB – fresh fruit bunch

Table A-4 Lost energy values for mesocarp fibre. 1.19 multiplied each value of MF lost per 1000 kg FFB processed for the value in kWh.

S/N	Industrial route		Small-scale route		Traditional route	
	MF lost /1000 kg FFB	Value in kWh	MF lost /1000 kg FFB	Value in kWh	MF lost /1000 kg FFB	Value in kWh
1	55.72	66.30	<0.01	<0.01	<0.01	<0.01
2	63.58	75.66	<0.01	<0.01	<0.01	<0.01
3	71.37	84.94	<0.01	<0.01	<0.01	<0.01
4	66.35	78.96	<0.01	<0.01	<0.01	<0.01
5	83.25	99.07	<0.01	<0.01	<0.01	<0.01
6	82.05	97.64	<0.01	<0.01	<0.01	<0.01
7	70.90	84.37	<0.01	<0.01	<0.01	<0.01
8	97.08	115.53	<0.01	<0.01	<0.01	<0.01
9	64.58	76.85	<0.01	<0.01	<0.01	<0.01
10	90.97	108.26	<0.01	<0.01	<0.01	<0.01
Average		88.76		<0.01	<0.01	<0.01

MF- mesocarp fibre, FFB – fresh fruit bunch

Table A-5 Lost energy values for palm kernel shell. 1.16 multiplied each value of PKS lost per 1000 kg FFB processed for the value in kWh.

S/N	Industrial route		Small-scale route		Traditional route	
	PKS lost /1000 kg FFB	Value in kWh	PKS lost /1000 kg FFB	Value in kWh	PKS lost /1000 kg FFB	Value in kWh
1	19.83	23.00	<0.01	<0.01	<0.01	<0.01
2	22.63	26.25	<0.01	<0.01	<0.01	<0.01
3	25.40	29.46	<0.01	<0.01	<0.01	<0.01
4	23.61	27.39	<0.01	<0.01	<0.01	<0.01
5	29.63	34.37	<0.01	<0.01	<0.01	<0.01
6	29.20	33.87	<0.01	<0.01	<0.01	<0.01
7	25.23	29.27	<0.01	<0.01	<0.01	<0.01
8	34.55	40.08	<0.01	<0.01	<0.01	<0.01
9	22.98	26.66	<0.01	<0.01	<0.01	<0.01
10	32.38	37.56	<0.01	<0.01	<0.01	<0.01
Average		30.79		<0.01		<0.01

PKS – palm kernel shell, FFB – fresh fruit bunch

Table A-6 Calculations for energy value of empty fruit bunch, mesocarp fibre, and palm kernel shell.

Calculation of energy values for each of empty fruit bunch, mesocarp fibre and palm kernel shell	Reference
KWh per unit of fuel = Fuel heat content (in Btu per physical unit)/heat	Energy Information Administration (2012)

<hr/>		<hr/>	
rate (in Btu per kWh)			
Representative heat rate for biomass		Mayhead (2010)	
= 15 000 Btu/kWh = 15825 kJ/kWh			
Empty fruit bunch			
(14499*1.06)/15825	0.97 kWh		
Mesocarp fibre			
(17846*1.06)/15825	1.19 kWh		
Palm kernel shell			
(17336*1.06)/15825	1.16 kWh		
<hr/>		<hr/>	

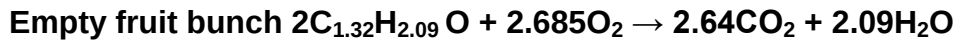
Appendix B Co-gasification of Nigerian biomass in a pilot scale downdraft gasifier

Table A-7 Detailed calculations for the different parameters.

Parameter		MP	EMP1	EMP2
Fuel feed rate (kg/hr)		2.80	2.80	2.80
Air feeding rate (l/min)		160	160	160
Air feeding rate (m ³ /hr)		9.60	9.60	9.60
Air feeding rate (kg/hr)	air feeding rate in m ³ /hr*1.225(Density of air)	11.76	11.76	11.76
Air fuel ratio actual	Air feeding rate kg/hr/Fuel feed rate kg/hr	4.20	4.20	4.20
Air fuel ratio stoichiometric		7.72	7.15	7.15
Equivalence ratio	Air fuel ratio actual/Air fuel ratio stoichiometric	0.54	0.59	0.59
Gas flow rate (l/min)		258	412	390
Volumetric flow (m ³ /hr)		9.72	13.50	12.89
Yield gas (m ³ /kg)	Volumetric flow m ³ /hr/Fuel feed rate kg/hr	3.47	4.82	4.60
HHV _{biomass} (kJ/kg)	Average values of the biomass used	21720	19940	19940
LHV _{gas} (kJ/m ³)	$((12.64 \cdot \text{CO}\%) + (35.82 \cdot \text{CH}_4\%) + (10.8 \cdot \text{H}_2\%))/100$	780	650	780
Carbon conversion efficiency	$((12 \cdot \text{Yield gas in m}^3/\text{kg}) \cdot ((\text{CO}\% + \text{CH}_4\% + \text{CO}_2\%)/(22.4 \cdot 52.2))) \cdot 100$	34.18	56.30	61.65
HHV _{gas} (kJ/m ³)	$((12.75 \cdot \text{H}_2\%) + (12.63 \cdot \text{CO}\%) + (39.82 \cdot \text{CH}_4\%))/100$	840	690	830
Cold gas efficiency	$(\text{Yield gas m}^3/\text{kg} \cdot \text{HHV}_{\text{gas}}/\text{HHV}_{\text{biomass}} \text{ kJ/kg}) \cdot 100$	13.37	16.79	19.23

Weight of biomass		16.80	21.40	13.50
Yield of ash (wt.%)	(weight of ash/weight of biomass)*100	1.55	3.16	2.59
Yield of slag (wt.%)	(weight of slag/ weight of biomass)*100	0.39	1.67	1.35
Yield of char (wt.%)	(weight of char/ weight of biomass)*100	2.14	0.00	0.00
Yield of solid residues (wt. %)	Sum of ash, slag, and char yields	4.08	4.84	3.94

B-1 Stoichiometric air fuel ratio



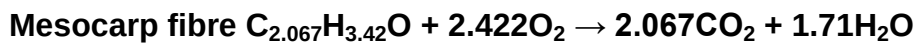
1 mole of empty fruit bunch = 67.87 kg = amount of fuel

1 mole of O_2 = 32 kg = 2.685×32 = amount of air

Oxygen/fuel = $85.92/67.87 = 1.266$

Using 23.2 % of oxygen in air

$1.266 \times 100/21 = 6.03$ kg



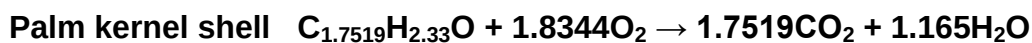
1 mole of mesocarp fibre = 44.224 kg = amount of fuel

1 mole of O_2 = 32 kg = 2.422×32 = amount of air

Oxygen/fuel = $77.504/44.224 = 1.75$

Using 23.2 % of oxygen in air

$1.75 \times 100/21 = 8.33$ kg



1 mole of palm kernel shell = 39.3528 kg = amount of fuel

1 mole of O_2 = 32 kg = 1.8344×32 = amount of air

Oxygen/fuel = $58.7008/39.3528 = 1.49$

Using 23.2 % of oxygen in air

$1.49 \times 100/21 = 7.10$ kg

MP = palm kernel shell + mesocarp fibre

Average stoichiometric air fuel ratio = 7.72

EMP1 = palm kernel shell + mesocarp fibre + empty fruit bunch

Average stoichiometric air fuel ratio = 7.15

EMP2 = palm kernel shell + mesocarp fibre + empty fruit bunch

Average stoichiometric air fuel ratio = 7.15

B-2 Volumetric flow m³/hr

(Ambient temperature + 273/temperature of flame + 273)/ Gas flow rate in m³/hr

	Flare temperature °C	Ambient temperature °C	Gas flow rate (l/min)	Gas flow rate (m³/hr)	Volumetric flow (m³/hr) considering temperature difference	yield m³/kg	
MP	263.6	20	0.546031	258	24.72	13.49788	3.018769
EMP1	259.1	20	0.550648	412	23.4	12.88517	4.861439
EMP2	193.6	20	0.627947	390	15.48	9.720617	5.651522

Appendix C Variations in ash properties affecting soil and cassava yield in south East Nigeria

The total concentration of elements in the soil are presented in Table A-8 for both experiments I (2015 and 2016) and II (2016). There were significant increases in total iron and total aluminium in 2016 compared to 2015 values for experiment I.

Table A-8 Mean ($\pm$ standard error) concentrations of elements in the soil for experiments I and II.

Parameter (mg/kg)	Experiment I Initial data (2015)		Experiment I after a year (2016)		Experiment II Initial data (2016)	
	0- 0.3 m	0.3-0.6 m	0- 0.3 m	0.3-0.6 m	0- 0.3 m	0.3-0.6 m
Total Calcium	8.78 $\pm$ 2.35	4.69 $\pm$ 0.36	18.41 $\pm$ 1.24	31.36 $\pm$ 5.31	23.06 $\pm$ 1.1	21.97 $\pm$ 0.82
Total potassium	103.01 $\pm$ 4.04	115.94 $\pm$ 8.31	140.53 $\pm$ 9.45	39.38 $\pm$ 17.30	82.6 $\pm$ 3.49	89.83 $\pm$ 6.22
Total magnesium	8.06 $\pm$ 1.06	9.69 $\pm$ 0.63	18.83 $\pm$ 2.48	41.93 $\pm$ 9.51	9.43 $\pm$ 0.95	8.6 $\pm$ 0.7
Total phosphorus	24.32 $\pm$ 1	24.17 $\pm$ 1.05	32.91 $\pm$ 2.52	45.16 $\pm$ 5.84	19.71 $\pm$ 0.89	20.57 $\pm$ 0.67
Total nickel	13.93 $\pm$ 1.27	15.8 $\pm$ 0.82	19.06 $\pm$ 0.87	15.76 $\pm$ 1.06	18.41 $\pm$ 0.45	13.41 $\pm$ 1.9
Total manganese	31.8 $\pm$ 1.69	26.46 $\pm$ 1.4	37.58 $\pm$ 1.61	45.99 $\pm$ 3.20	35.39 $\pm$ 1.27	32.09 $\pm$ 1.8
Total copper	3.66 $\pm$ 0.21	3.61 $\pm$ 0.24	2.48 $\pm$ 0.26	5.46 $\pm$ 0.53	0.92 $\pm$ 0.12	4.52 $\pm$ 0.56
Total iron	4959.61 $\pm$ 322.64	6250.73 $\pm$ 823.21	10879.22 $\pm$ 250.07	9184.78 $\pm$ 501.97	8917.27 $\pm$ 293.63	10825.93 $\pm$ 588.19

Total aluminium 11520.79±480.92 11418.5±1058.37 14068.79±515.34 12190.4±1169.76 7136.61±441.91 13845.24±1205.67

Table A-9 Some physical and chemical properties of the soil and cassava tuber yield of the treatments replicates and soil depths for experiment I in 2016.

Soil depth (m)	Treatment (tonne/ha)	Total Al (mg/kg)	Total Ca (mg/kg)	Total K (mg/kg)	Total Ni (mg/kg)	Total Mn (mg/kg)	Total Cu (mg/kg)	Total Fe (mg/kg)	Total P (mg/kg)	Electrical conductivity (µS/cm)
0 - 0.3	160	11254.5	49.7	173.1	12.6	51.1	6.8	7995.6	62.7	40.3
0 - 0.3	0	20275.9	5.6	139.2	15.2	43.4	6	12595.1	26.1	66.3
0 - 0.3	40	12927.4	17.6	118	11.6	38.4	5	9057.8	35.6	73
0 - 0.3	80	14223.2	41.8	208.4	16	50.6	7.4	10105.6	51.8	51
0 - 0.3	160	9150.2	57.2	157.8	11.8	49.8	5.6	7310.1	90.8	65.4
0 - 0.3	80	2269.5	5.6	43	8.8	25.8	3.2	5450.5	30.3	64.8
0 - 0.3	40	11783.6	26.4	123.8	14.4	37.6	4.6	8090	35.2	46.4
0 - 0.3	0	14775.6	15.2	115.8	11.8	43.1	4.4	10043.7	30.7	37.5
0 - 0.3	80	11703.4	70.3	199.8	13.2	56.1	8.4	8795.2	60.2	48.8
0 - 0.3	0	2426.9	9.6	5.6	24.6	20	1.4	5873.3	2.5	68.1
0 - 0.3	160	18138.4	16	142.4	21	51.2	5.4	12567.1	73.8	42.7
0 - 0.3	40	11701.4	36.3	106.8	17	45.3	4	8849.3	27.8	84.4
0 - 0.3	160	12376.8	69.3	317	17.8	77.6	10.6	9484.6	106.7	52.7

0 - 0.3	80	13337.3	33	140	21.4	50.4	5	9899.6	46.4	156.9
0 - 0.3	40	13613.3	28.8	125.4	15.8	44.8	5	9767.6	40.2	66.6
0 - 0.3	0	15089	19.4	114	19.2	50.6	4.6	11071.4	27.8	58.7
0.3 - 0.6	160	16490.7	19	202.2	14.2	37	3.2	11471.3	40.2	38.9
0.3 - 0.6	0	17004.6	14.6	121	15.4	43.8	2.6	12183.2	24.9	33.9
0.3 - 0.6	40	16206.8	15.8	143.2	20.6	40.8	4.2	12169.2	29.8	36.8
0.3 - 0.6	80	11475.7	13.4	107.2	13.6	27.6	2.6	9653.7	19.1	33.7
0.3 - 0.6	160	14683.1	21.2	209.6	22.4	37.4	3.6	11511.3	41.4	51
0.3 - 0.6	80	13441.3	14.8	114.4	22.6	32.4	3.2	10551.5	25.3	39.5
0.3 - 0.6	40	13093.4	29.6	110.6	20.4	50	3	10455.5	29	33.2
0.3 - 0.6	0	15340.9	15	121.4	21.6	32.6	3.6	11213.4	22.4	35.5
0.3 - 0.6	80	14203.2	20.2	175.6	16.6	34.8	1.4	10925.4	40.2	38.4
0.3 - 0.6	0	16134.8	14.6	113	20	32.8	3	11867.2	22.8	30.7
0.3 - 0.6	160	12019.6	24.8	179.8	25.2	48.8	2	10193.6	51	44.2
0.3 - 0.6	40	14547.1	17.2	127	21.6	42.6	1.8	11303.3	36.1	34.2
0.3 - 0.6	160	11713.7	27.2	185.2	14.2	37.8	1.8	9679.7	51.8	55.5
0.3 - 0.6	80	16098.2	17.4	141.3	20.8	39.9	2.2	12067.7	38.2	47.2
0.3 - 0.6	40	12087.6	16.2	107.4	17.6	30.2	1.4	9727.7	28.6	33.3
0.3 - 0.6	0	10559.9	13.6	89.6	18.2	32.8	0	9093.8	25.7	36.2
Soil	Treatment	Total N	Total C	C/N ratio	Total	Available	Available	pH	Bulk	Cassava

depth (m)	(tonne/ha	(%)	(%)		OC (%)	P (mg/kg)	K (mg/kg)		Density (kg/m3)	tuber yield (tonne/ha)
0 - 0.3	160	0.07	1.91	25.71	1.78	7.60	48.2	5.6	0.8	10.7
0 - 0.3	0	0.1	1.42	14.24	1.42	0.30	11.0	3.7	1.2	7.3
0 - 0.3	40	0.07	1.34	17.95	1.02	4.30	20.6	4.6	1.2	15.4
0 - 0.3	80	0.09	2.08	23.04	2.03	6.30	57.9	4.2	1	14.2
0 - 0.3	160	0.09	2.67	30.1	2.62	7.40	63.9	4.9	1	11.3
0 - 0.3	80	0.09	1.72	19.12	1.6	4.70	32.1	4.9	1.3	10.4
0 - 0.3	40	0.09	1.79	20.14	1.42	5.30	43.1	3.8	1.5	13.4
0 - 0.3	0	0.09	1.45	16.04	1.44	0.30	7.5	4.5	1.4	4.3
0 - 0.3	80	0.1	3.72	38.26	3.71	10.00	60.2	5.6	1.3	11.2
0 - 0.3	0	0.08	1.34	16.75	1.26	0.50	20.8	4.5	1.3	8.3
0 - 0.3	160	0.07	1.23	16.93	1.14	13.80	23.4	3.7	1.1	15.9
0 - 0.3	40	0.08	1.48	18.65	1.43	3.80	23.2	4.8	1.2	10.6
0 - 0.3	160	0.1	4.32	43.85	4.24	15.90	16.3	6.2	1.0	6.3
0 - 0.3	80	0.08	1.55	18.61	1.53	3.80	26.2	4.7	1.3	11.3
0 - 0.3	40	0.09	1.76	20.32	1.53	3.80	29.2	4.7	1.0	11.7
0 - 0.3	0	0.09	1.5	16.42	1.4	3.10	17.0	3.6	1.1	4.9
0.3 - 0.6	160	0.04	1.1	25.97	0.85	4.70	106.7	4.8		
0.3 - 0.6	0	0.06	0.97	16.38	0.9	0.10	9.9	3.7		

0.3 - 0.6	40	0.06	1.02	17.86	0.96	0.60	16.2	4.6
0.3 - 0.6	80	0.05	0.88	19.44	0.87	1.90	37.6	4.5
0.3 - 0.6	160	0.06	1.05	16.79	0.91	0.10	102.3	3.8
0.3 - 0.6	80	0.06	0.96	16.29	0.94	0.70	20.1	3.7
0.3 - 0.6	40	0.04	0.78	17.59	0.75	5.00	16.0	4.5
0.3 - 0.6	0	0.05	0.84	17.85	0.74	0.00	6.6	3.8
0.3 - 0.6	80	0.06	1.36	21.72	1.22	3.10	80.6	4.7
0.3 - 0.6	0	0.05	0.87	18.30	0.84	0.09	15.1	4.6
0.3 - 0.6	160	0.06	1.24	19.27	1.15	4.50	84.4	4.6
0.3 - 0.6	40	0.06	1.03	16.47	1.03	1.10	32.8	4.6
0.3 - 0.6	160	0.06	1.46	24.22	1.45	7.90	104.4	4.9
0.3 - 0.6	80	0.05	1.06	22.43	1.06	2.00	35.0	4.6
0.3 - 0.6	40	0.04	1.00	25.48	0.94	0.70	38.9	4.6
0.3 - 0.6	0	0.05	0.76	16.33	0.73	0.00	12.1	4.6

Al – aluminium, Ca – calcium, K –potassium, Ni – nickel, Mn – manganese, Cu –copper, Fe – Iron, P – phosphorus, N – nitrogen, C – carbon, OC – organic carbon, C/N – carbon-nitrogen ratio

Table A-10 Some physical and chemical properties of the soil and cassava tuber yield of the treatments replicates and soil depths for experiment I in 2017.

Soil depth (m)	Treatment (tonne/ha)	CEC (cmol+/kg) (2016)	Exch. K (cmol+/kg) (2016)	Exch. Ca (cmol+/kg) (2016)	Exch. Mg (cmol+/kg) (2016)	Exch. Na (cmol+/kg) (2016)	CEC (cmol+/kg) (2017)	Exch. K (cmol+/kg) (2017)	Exch. Ca (cmol+/kg) (2017)
0 - 0.3	160	13.2	0.17	1.69	1.97	0.31	7.05	0.08	1.09
0 - 0.3	0	8.21	0.05	0.51	0.78	2.08	9.87	0.10	0.15
0 - 0.3	40	10.7	0.08	0.75	3.14	0.99	14.51	0.10	0.42
0 - 0.3	80	16.4	0.20	1.18	3.30	0.63	8.46	0.14	0.75
0 - 0.3	160	11.1	0.34	2.05	2.36	0.31	13.11	0.06	0.98
0 - 0.3	80	16.8	0.13	1.13	3.22	0.67	9.16	0.03	0.92
0 - 0.3	40	12.1	0.15	1.00	3.04	0.80	29.18	0.03	0.27
0 - 0.3	0	8.93	0.05	0.42	0.53	1.09	13.08	0.01	0.19
0 - 0.3	80	10.4	0.2	1.98	2.17	0.16	17.00	0.04	0.6
0 - 0.3	0	16.1	0.07	0.59	1.11	0.93	22.35	0.03	0.34
0 - 0.3	160	14.6	0.24	2.61	2.29	0.04	13.46	0.23	2.92
0 - 0.3	40	15.7	0.10	1.38	3.63	0.82	9.52	0.05	0.76
0 - 0.3	160	19.6	0.31	2.51	2.61	0.03	23.82	0.49	1.52
0 - 0.3	80	7.86	0.09	0.98	3.28	1.19	14.89	0.19	1.21
0 - 0.3	40	6.07	0.10	0.80	2.88	1.10	17.71	0.05	1.33

0 - 0.3	0	12.1	0.07	0.42	0.93	1.03	11.70	0.13	0.35
0.3 - 0.6	160	12.9	0.35	0.44	3.18	0.95	11.66	0.14	0.79
0.3 - 0.6	0	20.4	0.04	0.18	0.43	1.00	10.94	0.34	0.15
0.3 - 0.6	40	14.3	0.07	0.37	1.01	1.03	13.79	0.10	0.11
0.3 - 0.6	80	12.1	0.12	0.21	0.78	0.95	17.04	0.09	0.25
0.3 - 0.6	160	7.07	0.29	0.35	2.31	0.98	11.30	0.26	0.21
0.3 - 0.6	80	13.9	0.09	0.31	1.03	1.27	12.37	0.15	0.25
0.3 - 0.6	40	19.3	0.10	0.17	0.36	1.01	23.11	0.10	0.08
0.3 - 0.6	0	11.4	0.03	0.17	0.35	1.03	4.89	0.03	0.12
0.3 - 0.6	80	16.1	0.25	0.53	3.17	0.93	14.92	0.09	0.30
0.3 - 0.6	0	13.9	0.06	0.21	0.62	1.03	8.82	0.11	0.21
0.3 - 0.6	160	16.4	0.25	0.68	4.17	1.10	14.21	0.14	1.20
0.3 - 0.6	40	18.9	0.08	0.51	1.56	0.94	6.69	0.09	0.34
0.3 - 0.6	160	16.4	0.28	0.65	3.70	0.58	5.60	0.07	0.38
0.3 - 0.6	80	14.6	0.08	0.28	0.90	0.66	13.46	0.25	0.28
0.3 - 0.6	40	17.9	0.09	0.46	1.61	1.06	14.21	0.08	0.49
0.3 - 0.6	0	15.7	0.04	0.19	0.59	1.13	11.68	0.17	0.26

Soil depth (m)	Treatment (tonne/ha)	pH	Dry matter (%)	Water content (%)	Organic matter (%)	Available potassium (mg/kg)	Electrical conductivity (µS/ cm)	Cassava tuber yield (tonne/ha)	Bulk density (kg/m3)
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0 - 0.3	160	6.29	99.3	0.7	3.2	41.37	24.7	9.95	1.4
0 - 0.3	0	4.79	99.4	1.7	2.4	12.67	17.76	1.55	1.8
0 - 0.3	40	5.04	99.3	0.7	3.4	15.97	12.85	7.55	1.6
0 - 0.3	80	5.39	99.2	0.8	3.4	47.42	27.60	4.70	1.6
0 - 0.3	160	5.45	99.4	0.7	3.5	18.37	20.30	6.60	2.1
0 - 0.3	80	5.63	99.4	0.7	2.7	11.82	16.10	10.50	1.6
0 - 0.3	40	4.97	98.7	1.3	3.5	12.12	17.06	7.60	1.7
0 - 0.3	0	4.75	99.2	0.8	3.5	8.42	44.10	0.95	1.8
0 - 0.3	80	5.24	99.4	0.6	3.5	13.67	11.30	13.65	1.8
0 - 0.3	0	4.95	99.2	0.8	3.7	17.57	18.50	1.70	1.9
0 - 0.3	160	6.50	99.2	1.8	5.1	41.97	17.82	4.90	1.7
0 - 0.3	40	5.59	99.4	0.7	5.0	29.32	12.12	21.45	1.8
0 - 0.3	160	5.99	99.4	0.7	3.8	22.87	13.03	9.85	1.8
0 - 0.3	80	5.67	99.5	0.6	3.9	34.32	13.15	11.50	1.9
0 - 0.3	40	5.59	99.2	0.8	3.8	20.62	11.97	11.60	1.7
0 - 0.3	0	5.24	99.4	0.7	3.5	21.32	13.59	4.95	1.8
0.3 - 0.6	160	6.12	99.2	0.8	6.6	76.62	126.30		
0.3 - 0.6	0	4.85	99.4	0.7	8.5	14.97	19.50		
0.3 - 0.6	40	4.79	99.2	0.8	2.4	10.42	20.40		
0.3 - 0.6	80	5.22	99.0	1.1	3.2	35.27	13.64		

0.3 - 0.6	160	5.16	99.3	0.7	3.2	23.87	25.50	
0.3 - 0.6	80	5.09	99.3	0.7	3.3	8.17	22.70	
0.3 - 0.6	40	4.65	99.4	0.7	1.7	7.47	19.39	
0.3 - 0.6	0	4.69	99.2	0.8	3.1	8.77	16.59	
0.3 - 0.6	80	4.92	98.7	1.3	3.9	11.17	17.76	
0.3 - 0.6	0	4.91	99.2	0.9	2.5	12.92	19.14	
0.3 - 0.6	160	6.26	99.4	0.6	2.6	21.97	22.20	
0.3 - 0.6	40	5.42	99.2	0.9	2.1	15.67	13.80	
0.3 - 0.6	160	5.47	99.2	0.8	3.3	27.87	25.00	
0.3 - 0.6	80	5.05	99.2	0.8	4.4	12.97	16.30	
0.3 - 0.6	40	5.72	99.2	0.8	3.2	18.52	18.47	
0.3 - 0.6	0	4.99	99.4	0.6	6.6	12.87	13.34	

Exch. Exchangeable, Ca – calcium, CEC – cation exchangeable capacity, Na, sodium, Mg – magnesium, K –potassium

Table A-11 Some physical and chemical properties of the soil and cassava tuber yield of the treatments replicates and soil depths for experiment II in 2017.

Soil depth (m)	Ash type	Electrical conductivity (μS/cm)	Available potassium (mg/kg)	pH	Dry matter (%)	Water Content (%)	Organic matter (%)	Bulk density (kg/m³)	Cassava tuber yield (tonne/ha)
0 - 0.3	EMPC	11.1	104.3	5.4	99.3	0.7	3.5	7.5	1.7
0 - 0.3	MPMN	11.6	29.4	5.1	99.5	0.5	3.2	2.7	1.8
0 - 0.3	MPBN	11.5	39.7	4.8	99.3	0.7	3.8	2.4	1.9
0 - 0.3	MPC	20.9	103.2	5.6	99.5	0.5	3.1	4.6	1.8
0 - 0.3	MPFN	48.3	38.1	5.4	99.3	0.7	3.2	2.0	1.9
0 - 0.3	MPBN	15.1	45.0	5.3	99.6	0.4	2.8	1.3	1.8
0 - 0.3	MPMN	11.3	28.5	5.1	99.5	0.5	3.1	3.0	1.8
0 - 0.3	EMPC	12.8	132.4	5.3	99.3	0.7	3.7	5.5	1.6
0 - 0.3	MPFN	14.9	40.6	4.9	99.4	0.6	3.2	2.6	1.8
0 - 0.3	MPC	18.9	97.3	5.2	99.3	0.7	3.7	2.0	1.8
0 - 0.3	EMPC	15.6	263.0	4.8	99.5	0.5	3.5	4.3	1.9
0 - 0.3	MPC	19.1	95.2	6	99.4	0.6	3.4	3.5	1.9
0 - 0.3	MPBN	12.5	33.2	4.7	99.5	0.6	3.2	2.5	1.6
0 - 0.3	MPMN	12.2	43.0	5.1	99.5	0.5	3.3	3.0	1.8
0 - 0.3	MPFN	18.2	28.8	4.8	99.4	0.6	3.5	2.0	1.7
0.3 - 0.6	EMPC	17.7	90.4	5.3	98.6	1.4	4.4		

0.3 - 0.6	MPMN	12.1	16.4	4.8	98.8	1.3	3.7
0.3 - 0.6	MPBN	15.8	18.4	5.2	98.3	1.8	4.6
0.3 - 0.6	MPC	9.7	63.5	4.8	98.7	1.3	4.0
0.3 - 0.6	MPFN	13.8	32.5	4.6	99.3	0.8	3.3
0.3 - 0.6	MPBN	10.9	17.8	4.9	98.6	1.4	3.8
0.3 - 0.6	MPMN	11.0	20.0	4.8	99.1	0.9	3.2
0.3 - 0.6	EMPC	16.3	48.6	4.6	99.0	1.0	3.6
0.3 - 0.6	MPFN	18.3	19.9	5.0	99.0	1.1	3.5
0.3 - 0.6	MPC	18.4	74.0	5.0	98.7	1.4	3.6
0.3 - 0.6	EMPC	15.9	110	4.5	99.1	0.9	3.5
0.3 - 0.6	MPC	21.0	58.3	6.1	99.0	1.0	3.3
0.3 - 0.6	MPBN	16.5	26.3	4.5	99.1	0.9	3.0
0.3 - 0.6	MPMN	15.1	18.8	4.8	99.4	0.7	3.1
0.3 - 0.6	MPFN	13.0	29.3	4.8	98.7	1.4	4.0

Table A-12 Some physical and chemical properties of the soil and cassava tuber yield of the treatments replicates and soil depths for experiment II in 2017.

Soil depth (m)	Ash type	Available phosphorus	Exchangeabl e potassium (cmol+/kg)	Exchangeable calcium (cmol+/kg)	Cation exchangeable capacity (cmol+/kg)	Total Nitrogen (%)	Total Carbon (%)
0 - 0.3	EMPC	19.67	0.08	0.50	14.18	0.07	1.01
0 - 0.3	MPMN	28.93	0.05	0.31	10.27	0.07	1.02
0 - 0.3	MPBN	31.40	0.07	0.00	12.78	0.07	0.96
0 - 0.3	MPC	6.28	0.01	0.01	11.34	0.06	0.96
0 - 0.3	MPFN	59.34	0.05	0.77	12.72	0.06	0.95
0 - 0.3	MPBN	22.81	0.02	0.14	9.87	0.06	0.88
0 - 0.3	MPMN	8.26	0.13	0.24	9.52	0.07	1.13
0 - 0.3	EMPC	7.60	0.05	0.25	11.68	0.07	0.99
0 - 0.3	MPFN	11.74	0.02	0.36	9.54	0.08	1.11
0 - 0.3	MPC	7.11	0.07	0.12	12.39	0.08	1.03
0 - 0.3	EMPC	5.62	0.01	0.12	10.61	0.08	1.09
0 - 0.3	MPC	6.61	0.00	0.01	9.18	0.07	0.97
0 - 0.3	MPBN	4.30	0.12	0.01	6.32	0.06	0.83
0 - 0.3	MPMN	3.97	0.00	0.20	10.99	0.08	1.13
0 - 0.3	MPFN	16.03	0.10	0.14	12.42	0.09	1.24
0.3 - 0.6	EMPC	13.06	0.37	0.07	8.80	0.06	0.91
0.3 - 0.6	MPMN	8.60	0.01	0.00	7.38	0.06	0.87

0.3 - 0.6	MPBN	5.79	0.03	0.01	11.70	0.06	0.87
0.3 - 0.6	MPC	2.48	0.01	0.01	10.94	0.06	0.82
0.3 - 0.6	MPFN	23.14	0.09	0.43	13.79	0.06	0.90
0.3 - 0.6	MPBN	7.27	0.01	0.01	8.82	0.05	0.81
0.3 - 0.6	MPMN	2.81	0.04	0.01	10.25	0.05	0.68
0.3 - 0.6	EMPC	2.31	0.10	0.03	11.66	0.04	0.76
0.3 - 0.6	MPFN	2.98	0.14	0.01	9.16	0.06	0.90
0.3 - 0.6	MPC	4.13	0.12	0.01	10.96	0.06	0.72
0.3 - 0.6	EMPC	3.97	0.06	0.18	9.91	0.07	0.98
0.3 - 0.6	MPC	2.48	0.07	0.01	15.25	0.05	0.74
0.3 - 0.6	MPBN	1.98	0.01	0.01	11.32	0.05	0.73
0.3 - 0.6	MPMN	2.48	0.03	0.01	9.87	0.07	1.10
0.3 - 0.6	MPFN	12.07	0.06	0.31	12.75	0.09	1.21



Figure A-1 Pictures from the experimental site in Nigeria (A) during initial soil sampling, (B) after bed (plots) preparation, (C) during cassava stem planting, (D) before harvest in 2016, (E) after the cassava tuber harvest in 2016.

Appendices references

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