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GENERATION AND CHARACTERISATION OF WASTEWATER IN THE SMALL-SCALE PALM OIL PROCESSING INDUSTRY IN GHANA: A STEP TOWARDS SUSTAINABLE MANAGEMENT SOLUTIONS

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ABSTRACT

The palm oil processing industry in Ghana is dominated by informal small-scale mills that produce 60 - 80% of the national production output. However, the operational conditions of the informal mills have received little attention in research, especially in terms of their water usage as well as wastewater generation rates, characteristics and potential environmental impacts. The aim of this research was to determine the sources and quantity of water used, quantity and quality of wastewater produced from small-scale palm oil processing mills in Ghana to guide sustainable management of the wastewater. Twenty-five (25) small-scale processing mills were selected for assessing the water sources and quantities, wastewater quantities and disposal practices. Then, wastewater samples were collected from four (4) of the processing mills in both lean and peak production seasons for characterization. Parameters measured were pH, total solids, TSS, TDS, BOD_5, COD, total nitrogen, phosphorus, potassium and oil and grease using standard analytical methods. Empty palm fruit bunch fibre was used for solids-liquid separation of wastewater and the sludge was sun-dried for potential use as soil conditioner or solid fuel. The effluent from the solid-liquid separation was subjected to column filtration using palm kernel shell and charcoal (particle size 1.18mm) as granular media. Boiling of fresh fruits, clarification of oil (optional), and cleaning of working tools were the unit processes which consumed fresh water and produced wastewater. Water was obtained from hand-dug wells, treated piped water, boreholes with handpumps and rivers/streams. Water consumption was influenced by the distance to the water source but not the price of water. For a litre of crude palm oil produced, 0.76-2.39 litres of water was consumed with a wastewater return factor of 68-82%. Characteristics of wastewater during the peak season were generally higher than the lean season except for pH and solids. The mean concentrations of 6 out of the 7 parameters were over 2-orders of magnitude higher than the Ghana effluent discharge standards. The current practice of disposing raw wastewater into the natural environment could be negatively affecting the environment. The nutrients content and calorific value of the sun-dried wastewater sludge was high showing their potential as sustainable soil conditioner or solid fuel. Open-air sun drying of palm oil mill sludge into biofuel and soil conditioner shows great potential as a renewable resource. In terms of effluent treatment, the performance of charcoal and palm kernel shell filters were creditable compared to the reference media (sand). However, charcoal and palm kernel shells show limited potential for use as granular filter media for treating high strength palm oil mill wastewater.

DEDICATION

This research work is dedicated to Charlotte Awere (My Lovely Wife), my sons (Mac-Donald and Nhyiraba) and my Parents (Paulina Amoah and the late Dominic Kwabena Awere)

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May God Almighty bless those I inadvertently omitted from this list.

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LIST OF ACRONYMS

AAKD - Abura Aseibu Kwamankese District
ANOVA - Analysis of Variance
ASTM - American Society for Testing and Materials
BOD - Biochemical Oxygen Demand
CCMA - Cape Coast Metropolitan Assembly
COD - Chemical Oxygen Demand
EFB - Empty Fruit Bunch
FAO - Food and Agricultural Organization
FFB - Fresh Fruit Bunch
GDP - Gross Domestic Product
GSS - Ghana Statistical Service
GWCL - Ghana Water Company Limited
ISO - International Organization for Standardization
MfM - Mfantseman Municipal Assembly
MICS - Multiple Indicator Cluster Survey
MMDA - Metropolitan, Municipal and District Assembly
PKS - Palm kernel shell
PM - Processing Mills
POME - Palm Oil Mill Effluent
PPF - Pressed palm fibre
TDS - Total Dissolved Solids
THLDD - Twifo Heman Lower Denkyira District
TS - Total Solids
TSS - Total Suspended Solids
USD - United States Dollar
WHO - World Health Organization

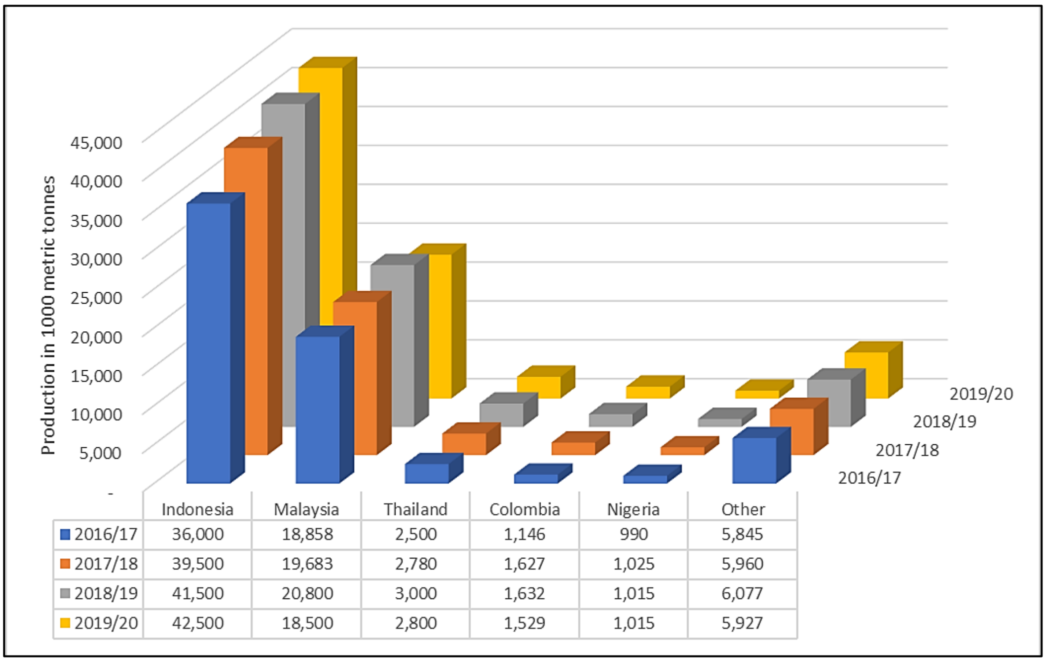
1 CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

1.1.1 Global palm oil production

Globally, oil palm (*Elaeis guineensis Jacq.*) is cultivated in Asia, Africa and Latin America. But the origin of oil palm is traced to the tropical rain forest region of Africa with the main belt running through the southern latitudes of Cameroon, Côte d'Ivoire, Ghana, Liberia, Nigeria, Sierra Leone and Togo into the equatorial region of Angola and the Congo (Poku, 2002). Traditionally, oil palm was harvested from the wild. Oil palm plantations were first established in Ghana in the 19th century (Angelucci, 2013). The same seeds and production techniques were then used to establish oil palm estates in another British colony, Malaysia. Asia is currently leading palm oil production with Indonesia, Malaysia and Thailand as the world's largest producers and exporters (USDA, 2020). Nigeria is Africa's leading producer while Ghana ranks 15th globally in terms of production quantity (Angelucci, 2013). Figure 1-1 shows the global palm oil production from 2016/17 – 2019/20.



	Indonesia	Malaysia	Thailand	Colombia	Nigeria	Other
🟦 2016/17	36,000	18,858	2,500	1,146	990	5,845
🟧 2017/18	39,500	19,683	2,780	1,627	1,025	5,960
⬜ 2018/19	41,500	20,800	3,000	1,632	1,015	6,077
🟨 2019/20	42,500	18,500	2,800	1,529	1,015	5,927

Figure 1-1. Palm oil production from 2016/17 to 2019/20

Adapted from USDA (2020)

Processing oil palm fruits for edible oil has traditionally been practiced in Africa for several years. The oil produced is an essential ingredient in much of the traditional West African cuisine. Palm oil is now an important domestic and industrial commodity worldwide. Palm oil is getting increasing attention on world commodity markets due to factors including the high yields of palm oil as compared to any other edible oil crops, high demand for domestic and industrial uses, use as biofuel (Ratanaporn et al., 2017, Angelucci, 2013) and the need for cheaper sources of oleo chemicals (Inyan, 2002). In 2019, palm oil production accounted for about 35% of global vegetable oil production (OECD/FAO, 2020). The current global palm oil production stands at 72.27 million metric tonnes (Shahbandeh, 2020a), increase of about 56% over the last decade. Figure 1-2 shows the global annual palm oil productions from 2007/08 to 2019/20.

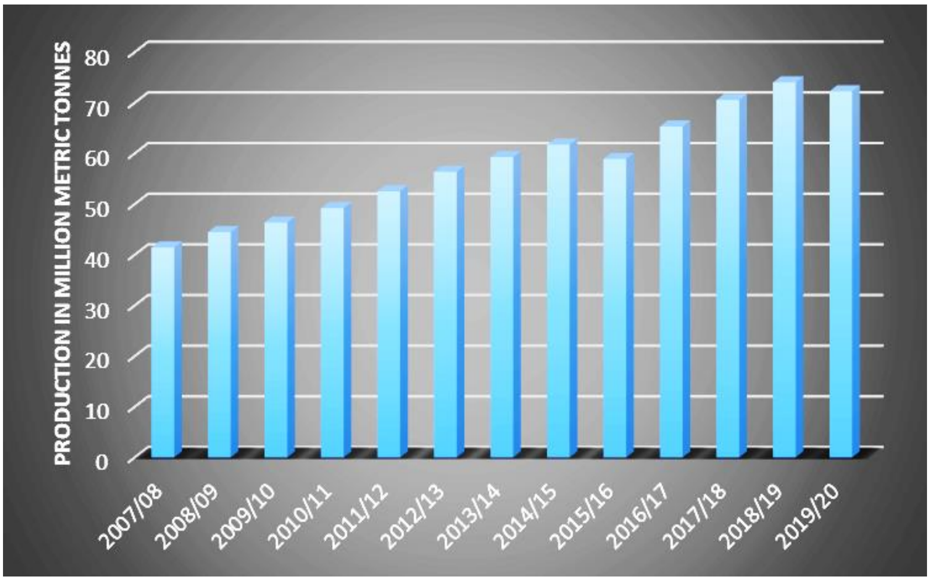


Figure 1-2. Global annual palm oil production from 2007/08 - 2019/20

Adapted from USDA (2020)

1.1.2 Palm oil production in Ghana

Even though oil palm is traced to Africa, in 2018, Africa’s palm oil production was only about 4% of the global output (FAOSTAT, 2019). The major palm oil production countries in Africa are Nigeria (43%), Cote d’lvoire (17%), Ghana (13%) and Cameroon (11%). Figure 1-3 shows the proportion of Africa’s 2018 palm oil output produced by country. This does not include countries with less than 2% output.

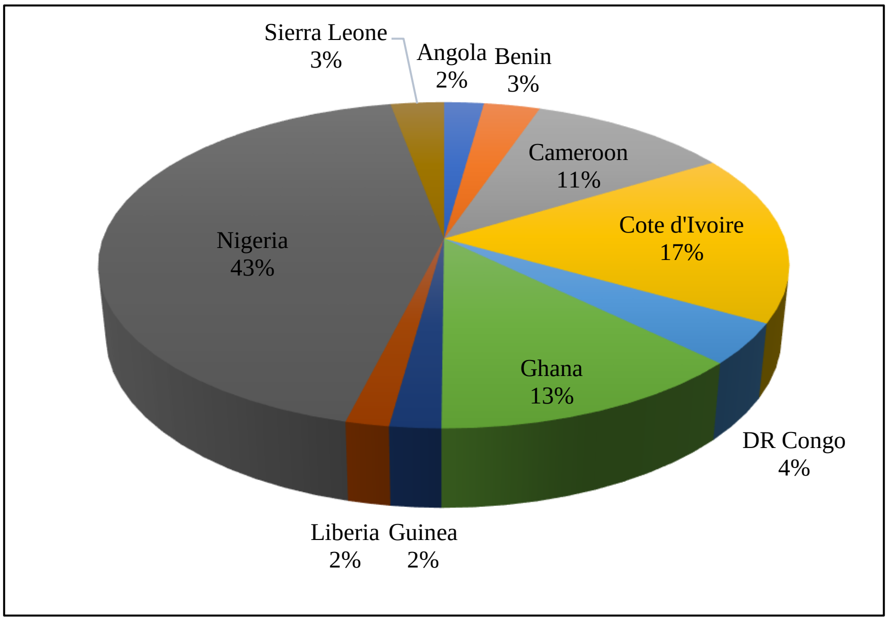


Figure 1-3. Proportion of palm oil production in Africa, 2018

Adapted from FAOSTAT (2019)

Palm oil is the most important edible oil in Ghana and in the West Africa region. Palm oil and palm kernel represented 2% of total agricultural production value of Ghana in 2010 (Angelucci, 2013). The processing of oil palm is a major source of income and employment to many women in the rural areas of the forest agroecological zone (Opoku and Asante, 2008). By 2015, the palm oil sector was employing over 2 million people mostly in rural areas (Yawson, 2015). Crude palm oil, particularly those produced by small-scale industry of Ghana, is used as vegetable oil in many local cuisines. Data from the 2008 Ghana Demographic and Health Survey shows that one out of every two households (54%) in the country and four out of five (80%) households in Central region used palm oil in food preparation (GSS et al., 2009). From analysis of palm oil production and consumption in Ghana between the year 2005 and 2010, Angelucci (2013) reported that the country produced a total of 120,000 tonnes of palm oil. As at 2019, the country's crude palm oil production had increased to 375,000 tonnes (IndexMundi, 2020a), doubling the production in a decade. The trend of palm oil production in Ghana from 2000 – 2018 is presented in Figure 1-4.

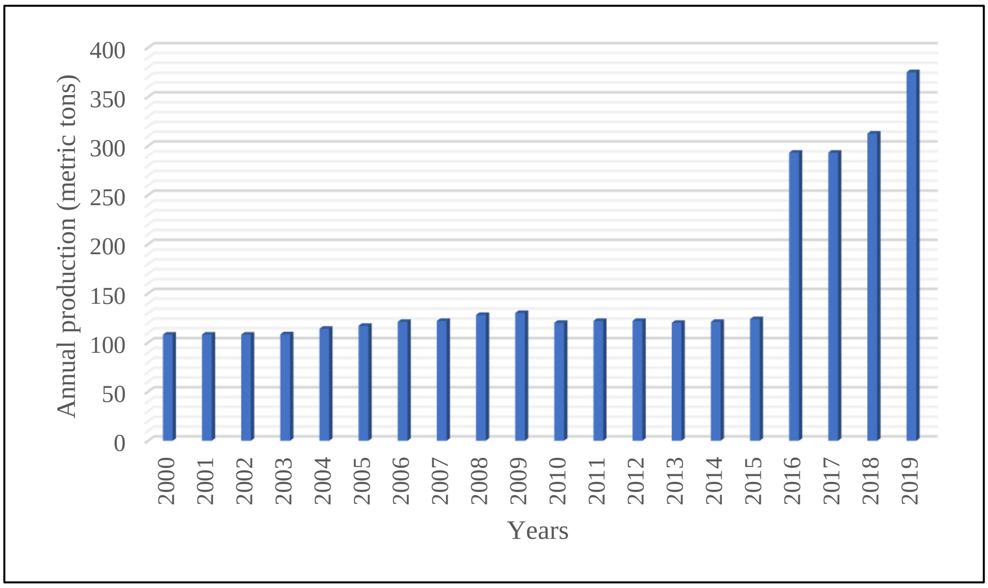


Figure 1-4. Annual crude palm oil production of Ghana, 2000 – 2019

Adapted from IndexMundi (2020a)

However, Ghana has an annual production deficit of about 30,000 tonnes which is estimated to reach 127,000 tonnes by 2024 (Commodafrica, 2018). Palm oil has a wide national geographical coverage as it is cultivated in ten (10) out of the sixteen (16) first level administrative regions of Ghana (Adjei-Nsiah et al., 2012). The most suitable areas for oil palm cultivation are said to be in the Western, Central and Eastern Regions (MASDAR, 2011).

1.1.3 Overview of imports and exports of palm oil in Ghana

Ghana is a net importer of crude palm oil even though the country exports crude palm oil to other neighbouring West African countries such as Senegal, Benin, Burkina Faso, Nigeria, and Niger. There has been a steady increase in exports and imports of crude palm oil but the trend is not consistent. Table 1-1 shows Ghana's crude palm oil exports and imports from 2005-2019. Figure 1-5 shows the trend of trade value of palm oil imports and exports for Ghana from 2005-2019.

Imports of crude palm oil reached 119,821 MT (Table 1-1) with a trade value of US$ 57.2million (Figure 1-5) in 2019. Countries from where Ghana imports palm oil are mainly Malaysia, Indonesia, Cote d'lvoire, Liberia, Singapore and Togo (TrendEconomy, 2021). On the other hand, exports for 2019 was significantly lower with only 15,392 MT with a trade value of US$ 11.1million, about one-fifth of the import value. For most of the years, imports were higher than exports except for 2012 and 2013 where crude palm oil exports far exceeded (31-69 times) the imports.

Within the past one-half decades (i.e., 2005-2019), there has been substantial imports of crude palm oil to meet domestic and industrial needs. From 2005-2019, Ghana imported about 1.1 million metric tonnes of crude palm oil with a trade value of about US$ 1.2billion. However, export quantity (in MT) within the same period was only about 18% of the total imports (see Table 1-1).

Table 1-1. Quantities of Export and Import of Crude Palm oils, Ghana (2005-2019)

Year	Export quantity (MT)	Import quantity (MT)
2019	15,392	119,821
2018	10,991	218,054
2017	1,160	339,704
2016	5,769	154,693
2015	22,453	*ND*
2014	15,674	*ND*
2013	3,016,513	97,630
2012	3,040,748	44,150
2011	8,913	19,013
2010	10,724	20,730
2009	5,370	22,407
2008	399	19,524
2007	940	12,963
2006	823	16,490
2005	*ND*	15,393

ND – No data reported

Source: United Nations (2021)

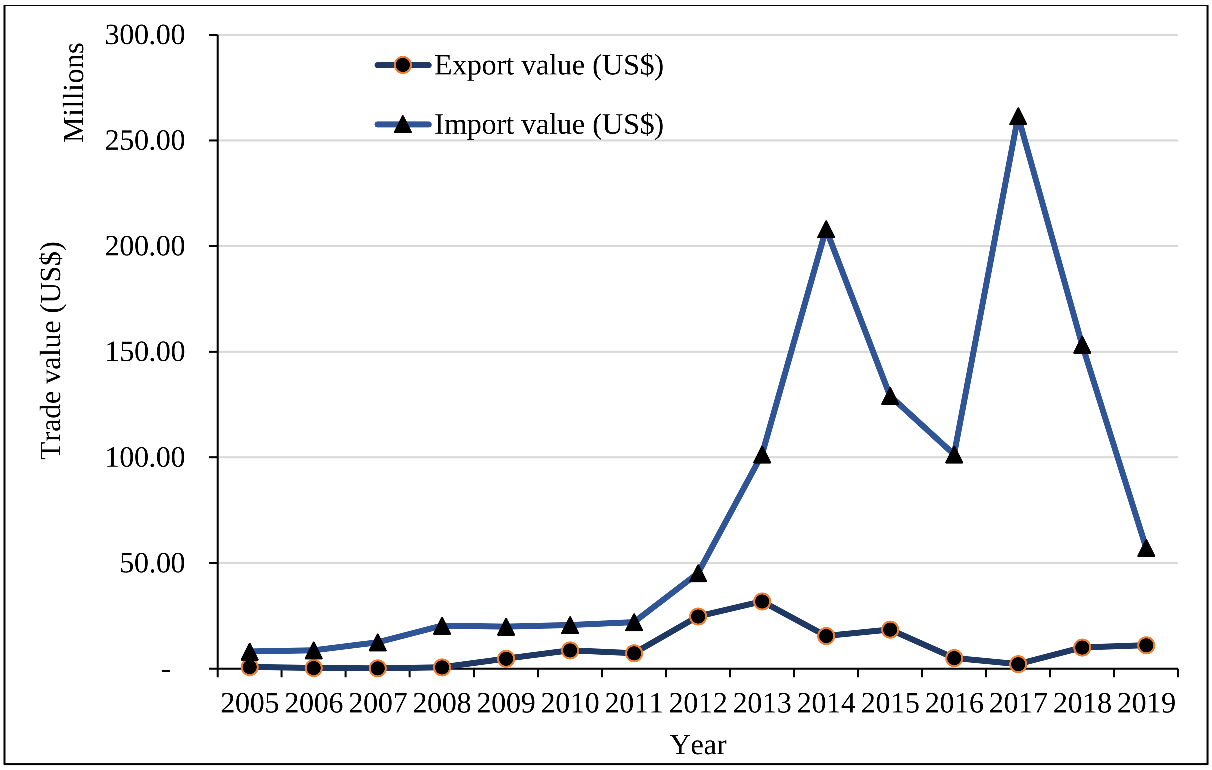


Figure 1-5. Trade value of Export and Import of Crude Palm oils, Ghana (2005-2019)

1.1.4 Palm oil processing characteristics

Palm oil is processed from fresh fruits using various techniques that differ in the level of mechanisation and interconnecting material transfer mechanisms. The scale of operations also differs at the level of processing. Palm oil processing in Ghana (like other West African countries) is undertaken by four (4) distinct groups of actors (Poku, 2002). These processing mills, according to their throughput and degree of complexity, are traditional, small-scale, medium-scale and large-scale mills. In terms of level of complexity, the traditional producers use methods which are basically manual with the use of rudimentary tools. The small-scale producers use a variety of low-efficiency machinery ranging from simple hand presses and other stand-alone machines to a very varied combination of machines which cater for the various unit processes in the processing. In terms of throughput, small-scale processing units handle up to 2 tonnes per hour of fresh fruit bunches (FFB) (Poku, 2002, MASDAR, 2011). The medium-scale and large-scale mills have technologically up-to-date machinery, established by agro-industrial complexes for the production of palm oil (Hassan et al., 2016) with production throughput of up to 60 tonnes of FFB per hour. The description of techniques for palm oil processing are detailed in Chapter 2 of this thesis. Characteristics of the different palm oil mills in Ghana is summarized in Table 1-2.

Table 1-2. Scale of palm oil processing mills in Ghana and their characteristics

Characteristic	**Large-scale Mills**	**Medium-scale Mills**	**Small-scale Mills**	**Artisanal Mills**
Plant Capacity	30 – 60 tons/hr	5 – 15 tons/hr	1 – 3 tons/hr	100 -1000 kg/day
Annual Production (FFB in tonnes)	70,000 – 140,000	15,000 – 30,000	2000 – 5000	2 – 70
Oil Extraction Rates (%)	16 – 23	12 – 15	12 – 13	8-10
Material Handling	Fully mechanised system in sequential processing steps	Semi mechanised system with few manual interventions	Semi mechanised system with more manual interventions	Manual process
Method of Oil Extraction	Uses mechanical press called ‘dry’ method	Uses mechanical press called ‘dry’ method	Uses batch system: material is placed in heavy ‘cage’ and metal plunger used. ‘Wet’ Process	Uses hot water to leach out oil from the mash called ‘wet’ process
Technology	Intermediate	Intermediate	Low	Very low
Power Supply	Self-generated electricity	Reliance on national grid or use of diesel generating set	Reliance on national grid or use of diesel generating set	Uses firewood and palm oil waste as source of fuel for cooking processes
Labour	High skilled artisans and labour	Mix of skilled and unskilled labour	Mainly unskilled labour	Laborious and unskilled.
Environment	Compliant with EPA	Non-compliant with EPA	Non-compliant with EPA	Non-compliant with EPA

	regulations and members of RSPO			
Health and Safety	Compliant with Factory, Offices and Shop Act of Ghana	Compliant with Factory, Offices and Shop Act of Ghana	Non-compliant with Factory, Offices and Shop Act of Ghana	Non-compliant with Factory, Offices and Shop Act of Ghana

Source: MASDAR (2011)

Though small-scale producers are characterized by weak milling capacity and low quality crude palm oil produced (Kajisa et al., 1997, Uckert et al., 2015), they occupy a greater share of the palm oil processing industry. Available data shows that there were more than 400 small-scale mills in Ghana as at 2002 (Poku, 2002) producing 60 – 80% of the national palm oil production (Angelucci, 2013, Osei-Amponsah et al., 2012). By 2015, they were employing over 2 million people mostly in rural areas (Yawson, 2015). The informal and wide-spread nature and high contribution of small-scale mills to Ghana’s palm oil production warrants attention and research.

1.1.5 Environmental regulations for palm oil processing mills

Environmental Permitting

The governmental institution mandated to regulate, coordinate and manage Ghana’s environment (air, land and water) is the Environmental Protection Agency (EPA). EPA was established on 30th December 1994 by an Act of Parliament (Act 490) (Government of Ghana, 1994). They have both regulatory and enforcement roles. Pursuant to Section 28 of Act 490, an Environmental Assessment Regulations (LI 1652) was made into force on 18th February 1999 by the Minister responsible for the Environment on the advice of the EPA Board (Ministry of Environment, 1999).

Regulation 1 of the Environmental Assessment Regulations, 1999 (LI 1652) requires undertakings specified in Schedule 1 to the Regulations (including oil and fats processing) to register with and obtain environmental permit from EPA prior to the commencement of the undertaking. In addition, existing undertakings, where EPA considers to have or is likely to have adverse effect on the environment or public health, are required to register with and obtain environmental permit in respect of the undertaking. Therefore, palm oil processing mills (including small-scale mills) are required to register with and obtain an environmental permit from EPA. However, small-scale processing mills belong to the informal where compliance of legal requirements is relatively weaker (Osei-Boateng and Ampratwum, 2011, Ministry of Employment and Labour Relations, 2014).

Section 13 of the Environmental Protection Agency (EPA) Act, 1994 (Act 490) states that “The EPA Board shall, where it considers that the activities of an undertaking pose a serious threat to the environment or to public health, serve on the person responsible for the undertaking, an enforcement notice requiring that person to take the steps stipulated by the Board to prevent or stop the activities”. The economic activities (in law or practice) of small-scale mills are not or insufficiently covered by formal arrangements including registration and regulation (Ministry of Employment and Labour Relations, 2014). Moreover, a study conducted by Gyamfi (2017) revealed that 70% of respondents from small-scale mills in Ashanti, Eastern, Central and Western regions of Ghana were either not aware or did not know how to comply with national environmental laws and regulations.

Water use

The Water Resources Commission (WRC) was established by the WRC Act 1996 (Act 522) as the overall body responsible for water resources management in Ghana (Government of Ghana, 1996). Section 13 of Act 522 prohibits the use of water resources without prior authorization and grant of water use rights from the WRC. Sections 1(e) of the Water Use Regulations 2001 (LI 1692) provides that a person may obtain a permit from the WRC for agricultural water use. Section 5 of LI 1692 prescribes that the WRC shall conduct investigation to establish whether the proposed water use is in accordance with policy and plan, and assess the potential environmental and social impacts, and the need for public participation in decision making on the application. Section 9 exempts any water use resulting from the abstraction of water (1) by manual means, and (2) for firefighting. Section 10 (1) provides that (a) water abstracted by mechanical means and used for any purpose where the abstraction level does not exceed five litres per second; and (b) subsistence agricultural water-use for land areas not exceeding one hectare are exempted from the permit requirement under regulation 2 but are required to register with the relevant District Assembly under Section 11.

Emission of gas

Section 2 (f) of the Environmental Protection Agency Act, 1994 (Act 490) authorizes the EPA “to issue environmental permits and pollution abatement notices for controlling the volume, types, constituents and effects of waste discharges, emissions, deposits or any other source of pollutants and of substances which are hazardous or potentially dangerous to the quality of the environment or a segment of the environment". Section 2 (h) of Act 490 mandates the EPA " to prescribe standards and guidelines relating to the pollution of air, water, land and any other forms of environmental pollution including the discharge of waste and the control of toxic substances". However, the informal and dispersed nature of the small-scale mills hinders the enforcement of these sections of Act 490.

1.1.6 Environmental pollution and management practices of palm oil processing mills

Irrespective of the scale of processing (as presented in Table 1-2), the following pollutants/ by-products are generated by the palm oil processing mills in Ghana. However, the way these pollutants are managed differs among the scale of palm oil processing mills.

1. Solid waste: these include empty fruit bunches (EFB), palm pressed fibre, palm kernel shell (PKS), ash and clinker from boiler furnaces (from large-scale mills). The high moisture content of EFBs prevents their use as solid fuel. At most small-scale mills, the EFB are heaped at the mill site to undergo decomposition. Unlike the small-scale mills, the large mills use the EFBs as mulch on the farms. Some small-scale mills dry and use EFBs and palm press fibres as solid fuel for boiling the palm fruits (Gyamfi, 2017). Most of the PKS are used as boiler fuel and the excess are used as road-fills (MASDAR, 2011) or sold for use as feed for piggeries (Gyamfi, 2017).
2. Liquid waste: the main liquid waste from the mills are palm oil mill effluent (POME), a mixture of water, unrecovered oils, cell debris and fibrous materials. POME from small-scale mills is hardly given any form of treatment before final disposal. Wastewater is discharged indiscriminately in surface water bodies or nearby bushes (Osei-Amponsah et al., 2012, Okwute and Isu, 2007, Gyamfi, 2017), polluting soil and water (Suarez et al., 2013). Research on the environmental impact of the indiscriminate disposal of POME on receiving soil and water bodies is very limited. But at the large-scale mills, such as Twifo Oil Palm Plantation (TOPP) and Ghana Oil Palm Development Company (GOPDC), POME is treated in ponds and pumped back into palm plantations to nourish the soil (MASDAR, 2011).
3. Smoke from burning of PKS, fibre or wood used for cooking are released into the atmosphere and hangs over mills and nearby communities causing discomfort to mill workers and community residents as noted by MASDAR (2011). The smoke is generated within the breathing zone of the mill workers which could potentially affect the health of the mill workers. Small-scale mills do not have in place measures and appropriate technology to control or manage smoke produced from their activities. To address this challenge associated with the activities of the small-scale mills, smoke and soot from boilers generated by large

mills are emitted through stacks with sufficient height to allow for adequate air dispersion of the smoke (Gyamfi, 2017).

4. Noise pollution. At the large mills (TOPP), noise is minimized by installation of silencers to exhaust and rubber-lining ducts and cyclones within the plant controlling noise levels. This notwithstanding, the noise levels at some points within TOPP still exceed 85 decibels but do not exceed 70 decibels on average at the factory edge (MASDAR, 2011). At the small-scale mills, there is no technology to control the noise generated by machinery used for processing.
5. Odour nuisance: unpleasant odour pervades the mills and downwind of the POME and EFB disposal sites. The odour is associated with rotting fruits, decomposition of EFB and POME. This environmental pollution is associated with all the different scales of palm oil processing mills.

1.1.7 *Effluent standard for palm oil mill industry*

The Ghana Standards Authority (GSA) is the National Statutory Body responsible for the development and promulgation of Ghana Standards. In 2019, GSA promulgated the Ghana Environmental Protection – Requirements for Effluent Discharge (GS 1212:2019) standard (GSA, 2019). The standard specifies the requirements for sector specific effluent quality and also gives guidelines for discharge of effluent into the environment. Table 1-3 shows the effluent discharge standard for oil and fat processing which includes the palm oil industry.

Table 1-3. Effluent standard for oil and fat processing industry in Ghana

Parameter	**Unit**	**Standard**
Colour	TCU	300
Conductivity	µS/cm	-
Temperature	^{o}C	≤ Above ambient
Turbidity	NTU	-
pH		6 – 9
TDS	mg/L	1000
TSS	mg/L	50
Alkalinity	mg/L	-
Ammonia as Nitrogen	mg/L	-
Nitrate as total Nitrogen	mg/L	-

BOD_5	mg/L	50
COD	mg/L	250
Oil and grease	mg/L	10
Pesticides, Total	mg/L	0.5
Phosphorus, Total	mg/L	2
Sulphide	mg/L	-
Copper	mg/L	-
Iron, Total	mg/L	-
Lead	mg/L	-
E-Coli	MPN/100ml	-
Coliforms, Total	MPN/100ml	400

Oil and fat processing industry includes oil and palm, shear butter, peanuts, coconut oil, palm kernel, etc.

Source: GSA, 2019

1.2 The Problem

Palm oil production in Ghana has doubled over the last two decades (FAOSTAT, 2019). However the industry is dominated by the informal small-scale mills (Angelucci, 2013, Osei-Amponsah et al., 2012). Available data indicates that there are more than 400 small-scale palm oil processing units in Ghana (Fold and Whitfield, 2012) most of which are sited in small towns and rural communities.

In processing fresh palm fruits into crude palm oil, high quantities of fresh water is reported to be consumed (Hassan et al., 2004), generating high quantities of wastewater (Chavalparit et al., 2006). For instance, to produce one tonne of crude palm oil, an estimated 5.0 – 7.5 tonnes of water is consumed out of which 50% returns as wastewater commonly called palm oil mill effluent (POME) (Ahmad et al., 2003). These estimates are reported for Southeast Asia where palm oil extraction is dominated by the large-scale industries employing more efficient processing techniques. The water and wastewater quantities are dependent on the processing method and level of technology employed. Consequently, the water consumption and wastewater production quantities could vary for the small-scale mills which are reported to use less efficient methods (Poku, 2002). The report of the masterplan study on the oil palm industry in Ghana recognized that large quantities of wastewater was produced during palm oil processing which require appropriate treatment before discharge into the environment (MASDAR, 2011). But, there is no available data in scientific literature on the quantities of water used and wastewater produced by the small-scale sector. Limited data on water consumption by such an important industry could lead to an underestimation of the water demand of the mostly rural communities in which the mills are situated and, consequently, competition between palm oil processing and other water uses. It is worth noting that, potable water supply to rural communities in Ghana is limited. About 68% of rural population in Ghana used basic drinking water service and over 50% depended on public standpipes or boreholes in 2018 (GSS, 2018).

Raw palm oil mill wastewater is reported to contain oxygen-consuming minerals (BOD_5 and COD) and solids contents (total solids, suspended solids, and total volatile solids), nutrients and unrecovered fats and oils (Lam and Lee, 2011) which could pollute the environment when disposed without treatment. In Ghana, small-scale palm oil processors have been cited for not adhering to any environmental protection practices (Poku, 2002). Moreover, Poku (2002) observed that, in Africa the small-scale mill operators empty their wastewater on the surrounding bushes, killing them slowly. This confirmed that POME from small-scale palm oil processing is very strong and could cause serious pollution and environmental problem. However, the quality of palm oil mill wastewater is reported to differ based on the processing techniques, processed batches or days, quality of the palm fruits, type of fruits (Ng et al., 1987), quality control of individual mills (Yusof and Ariffin, 1996), climate, condition of the palm oil processing (Liew et al., 2015), and cropping season of the oil palm (Wu et al., 2010). Characteristics of the wastewater and the potential environmental impact from the disposal of raw wastewater by small-scale processing mills have not adequately investigated. Studies on the palm oil processing industry in Ghana has focused on processing technology, profitability, institutional analysis, quality of crude palm oil, and gender roles.

Many technologies have been tested and applied to successfully treat palm oil mill wastewater mostly in Asia. These treatment technologies include anaerobic digestion, co-composting, adsorption, advanced oxidation, and membrane filtration systems. Detailed description of low-cost treatment methods are presented in Chapter 2 of this thesis. However, most of the technologies are expensive and may not be adaptable in a resource-constrained environment such as pertains in the small towns and villages where small-scale mills are located. In addition, downscaling some of the technologies to be applicable to informal small-scale mills could increase the unit cost of treatment and affect their acceptance. There is, therefore, an urgent need to conduct research into sustainable technologies for treating palm oil mill wastewater in resource-constraint settings such as resource-constrained environments such as small towns and villages where the small-scale mills are located. Particular focus must be placed on simple, low-cost, low energy technologies that utilizes local materials and resources especially “waste” products (such as palm kernel shells, charcoal and empty fruit bunches) from the palm oil processing industry. Moreover, the technology must, where practicable, lead to the recovery of essential resources and energy based on the circular economy principles.

1.3 Aim and Objectives of the Research

1.3.1 Research Aim

The aim of this research was to assess the sources and quantities of water used, generation rates and characteristics of wastewater produced from small-scale palm oil processing mills in Ghana to guide sustainable management of the wastewater.

1.3.2 Research Objectives

To achieve the general aim, the study focused on the following specific objectives: To

1. Determine the sources and quantity of water usage and wastewater return factors for small-scale palm oil processing.
2. Determine the seasonal and source characteristics of palm oil mill wastewater produced by the small-scale palm oil processing mills.
3. Assess the feasibility of solids-liquid separation, solar drying and reuse of palm oil mill wastewater sludge.
4. Assess the potential of using of palm kernel shell and charcoal as granular filter media for treating pre-filtered palm oil mill wastewater (from Objective 4).

1.4 Scope of the Research

In Ghana, suitable conditions for oil palm cultivation exist in the wetter southern part (Rhebergen et al., 2016) in the rainforest and semi-deciduous forest zones. Based on the agro-ecological zones, oil palm cultivation is best suited for the Western, Eastern, and Central Regions (Ofosu-Budu and Sarpong, 2013). Figure 1-6 is a map of southern Ghana showing suitable areas for oil palm production.

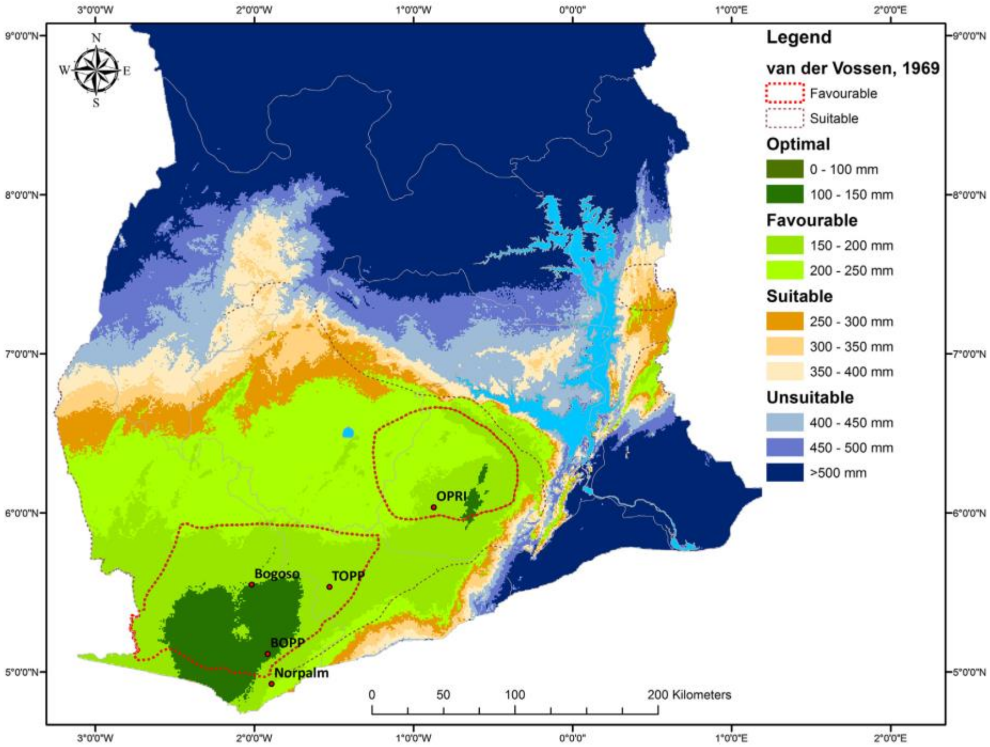


Figure 1-6. Map of southern Ghana showing suitable agro-ecological areas for oil palm production

Source: Rhebergen et al. (2016)

There is only one functional large-scale palm oil processing industry in the Central Region. This affords small-scale mills the opportunity for greater access to oil palm for processing. In addition, available data shows that four out of five (80%) households in Central region uses palm oil in food preparation (GSS et al., 2009). These reasons informed the choice of the Central Region as a case study.

All the four (4) scales of processing mills shown in Table 1-2 (i.e. traditional, small-scale, medium-scale and large-scale mills) exist in the Central Region. However, this study was limited to informal. palm oil processing mills because they are wide spread, and produce 60-80% of the national palm oil production (Angelucci, 2013, Osei-Amponsah et al., 2012). The informal and widespread nature of the activities of small-scale processers have affected enforcement of their compliance with environmental regulations. Moreover, the small-scale mills have been criticised for failing to adhere to waste management practices (Poku, 2002). Four (4) MMDAs (see Figure 1-7) namely Cape Coast Metropolitan Area (CCMA), Abura Aseibu Kwamankese District (AAKD), Twifo Hemang Lower Denkyira District (THLDD) and Mfantseman Municipality (MfM), were selected for the research to ensure agro-ecological balance. Thus, two (2) MMDAs (AAKD and THLDD) are in the forest zone and one each in the transition zone (MfM) and coastal savanna zone (CCMA).

1.5 Description of the Study Area

1.5.1 Overview of Ghana

Ghana is a Republic located on the West of Africa and lies within latitudes 4°44' N and 11°11' N and longitudes 3°11' W and 1°11' E. The total land area of the country is 238,533 square kilometres. Ghana shares boundaries in the north by Burkina Faso, the west by Côte d'Ivoire, the east by Togo and the south by the Gulf of Guinea. Figure 1-7 shows a map of Ghana and the Central Region.

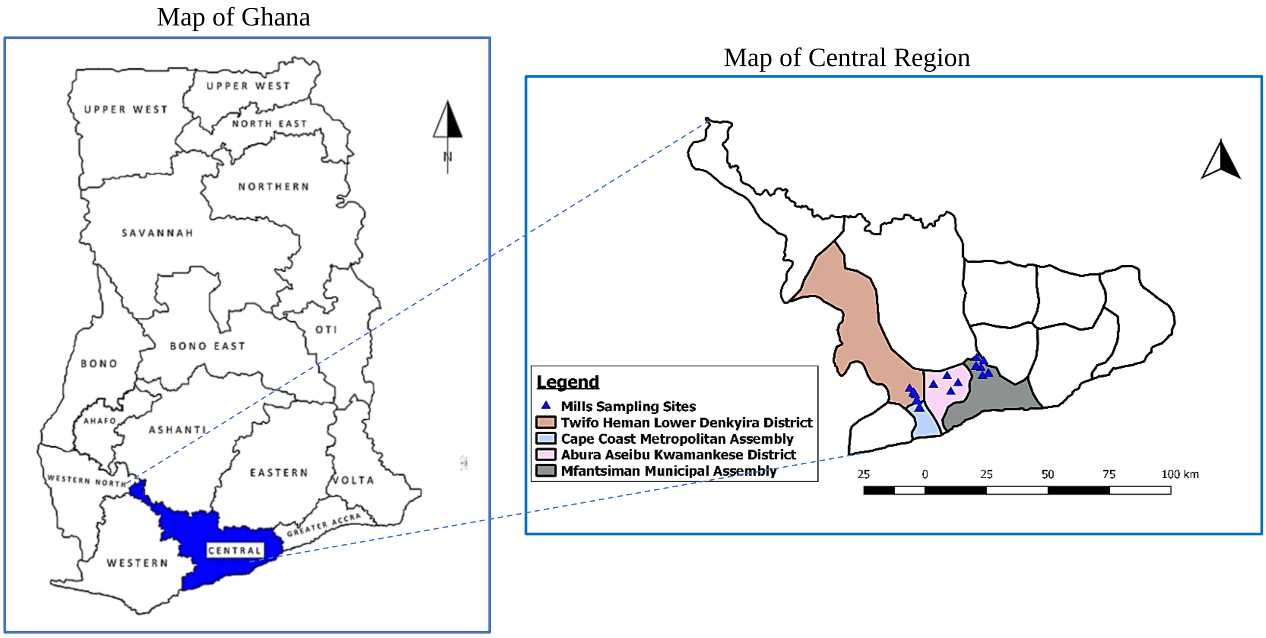


Figure 1-7. Map of the study area and sampling location

(The shaded part of the map of Central Region shows the study area)

The population was 30,417,856 at the end of 2019 with a growth rate of 2.19% and a population density of 127 persons/km^2 (Worldometer, 2020). The climate of Ghana is generally tropical, being warm and comparatively dry along the southeast coast, hot and humid in the southwest, and hot and dry in the north. The mean annual rainfall is estimated at 1,187 mm. Mean annual temperature ranges from 26.1°C near the coast to 28.9°C in the north. Rainfall distribution is bimodal in the forest, transitional and coastal zones. Agriculture accounted for about 19.7% of GDP in 2018 (GSS, 2019), 40% of export earnings and over 90% of the food needs of the country (FAO, 2020). It employs nearly half of the workforce and is the main source of livelihood for the majority of the country's poorest households (World Bank, 2017). The country's important cash crops are cocoa, oil palm, cotton and coconut (FAPDA, 2015).

In terms of local governance, the country is divided into sixteen (16) first-level government administrative units called Regions and 260 second-level administrative units classified as Metropolitan, Municipal and District Assemblies (MMDAs).

1.5.2 Overview of Central Region

The Central Region is one of the sixteen (16) first-level government administrative units of Ghana. The 2019 population of the region was estimated at 2,563,228 inhabitants (Citypopulation, 2019) with a population density of 260 inhabitants/km^2. The region is subdivided into twenty-two (22) MMDAs. Based on the climate, the region is divided into three agro-ecological zones namely coastal savanna, transitional and forest zones (MOFA, 2020). The average temperature ranges between 24^{o}C and 34^{o}C with a relative humidity of 50% to 85%. The region is characterized by bi-modal rainfall pattern with major and minor rainy seasons of March-July and September-November respectively (FAO, 2005).

In terms of palm fruit production, the peak and lean seasons are respectively February-June and July-January (Osei-Amponsah et al., 2012). The average annual rainfall ranges from 800mm in the Coastal Savanna to 1,500mm in the forest zone. The main economic activities are agriculture with 80% of the region’s total land area considered as cultivable (MOFA, 2020). The major tree crops cultivated in the region are cocoa, oil palm, citrus and coconut. The region’s land area for oil palm cultivation accounts for 16% of the total national area for oil production (MASDAR, 2011).

Access to basic drinking water in the region stands at 88%, higher than the national coverage of 79% (GSS, 2018). Water supply to communities in the region are through piped water by Ghana Water Company Limited (GWCL) or under the Community Water and Sanitation Agency’s (CWSA) small towns piped water supply systems. The GWCL supplies water to urban and peri-urban areas whiles the CWSA supplies water to small towns (population of 5,000 – 50,000) and rural areas (population of less than 5,000). In communities without piped water supply (mostly in rural areas), inhabitants obtain their water mainly from boreholes fitted with pumps, hand-dug wells (protected and unprotected) and untreated surface water.

1.6 Structure of the Study Report

The thesis is structured into Seven Chapters. Chapter 1 is this introductory Chapter and provides a background to the research including statement of the research problem, objectives of the study and description of the study area. Chapter 2 presents a review of literature relevant to the study. More specifically, Chapter 2 discusses the techniques for palm oil processing, the various wastes produced by the palm oil processing mills, characteristics of palm oil mill wastewater and low-cost treatment technologies for palm oil mill wastewater.

Chapters 3 - 6 are written in paper formats and address the five (5) Specific Objectives of the Study. Hence there is no specific chapter devoted to Materials and Methods. Chapter 3 reports on the specific study for Specific Objective 1 which address the water usage, wastewater generation and existing wastewater management practices implemented by the small-scale processing mills. Chapter 4 presents the seasonal and source characterization of palm oil mill wastewater (Specific Objective 2). In Chapter 5 is presented the study on solids-liquid separation and solar drying of palm oil mill wastewater sludge for potential reuse (Specific Objective 3). Chapter 6 reports on the bench-scale testing of palm kernel shell and charcoal as granular filter for treating pre-filtered palm oil mill wastewater (Specific Objective 4).

Finally, Chapter 7 summaries the conclusions from the various studies and the contribution to knowledge. The Chapter also discusses the implications of the study for policy, practice and future research direction.

2 CHAPTER TWO

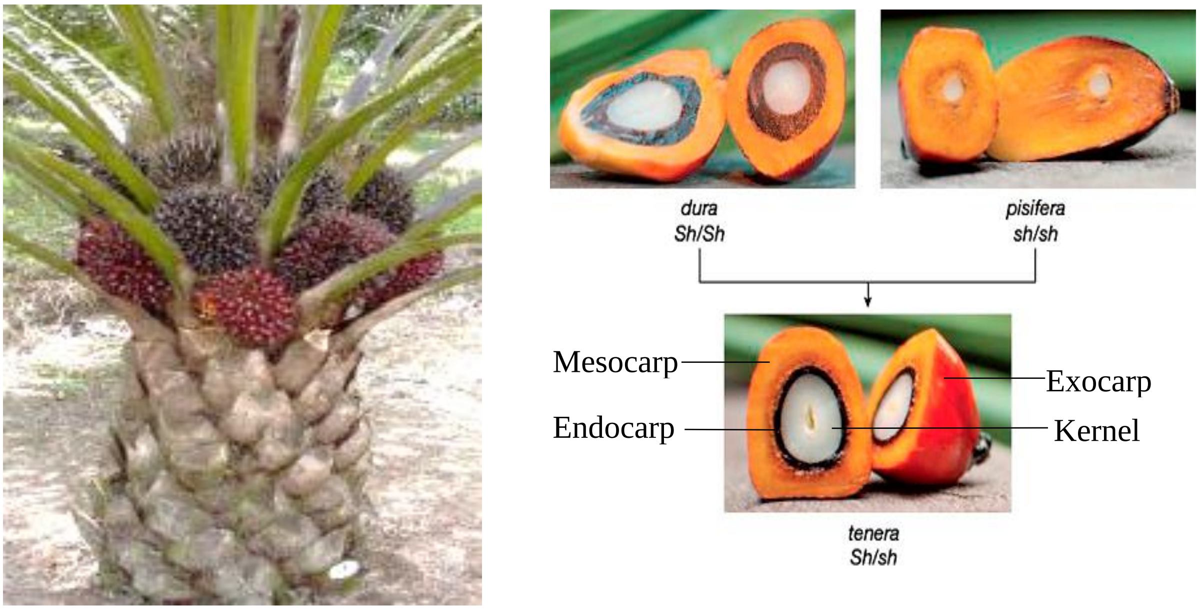
PALM OIL PROCESSING, WASTEWATER CHARACTERISTICS AND LOW-COST TREATMENT METHODS

2.1 Introduction

The chapter presents a review of literature relevant to the research. The review provides a description of the parts and types of oil palm fruits, processing methods used by both small-scale and large-scale mills highlighting the differences between the two processing methods. The chapter also gives an overview of the various waste from the processing. Finally, palm oil mill wastewater treatment technologies are discussed placing more emphasis on low-cost technologies.

2.2 Description and Varieties of Oil Palm Fruits

Oil palm fruits are harvested from the oil palm plant. The plant is single stemmed bearing a number of palm fronds in a simple head (Figure 2-1(a)). The fruits are obtained from a bunch containing 1500-2000 individual fruits and weighs 20-30 kg (Berger, 2003). A bunch of palm fruit consists of the fresh fruits, empty fruit bunches, and spikelets. Individual fruits comprises of an outer skin (exocarp), a pulp (mesocarp), a shell (endocarp) and a kernel (Poku, 2002). The mesocarp is a fibrous matrix containing the palm oil whiles the kernel contains the palm kernel oil.



(a) Oil palm tree with fruit bunches
(Credit: https://oilpalmblog.wordpress.com/)

(b) Varieties of oil palm fruits
(Adapted from Jiménez-Sánchez and Philp

Figure 2-1. Oil palm plant, fruit structure and varieties

According to Jiménez-Sánchez and Philp (2016), modern oil palm tree has three (3) varieties of palm fruits: *dura*, *pisifera* and *tenera*. The differences in the varieties are based on the thickness of the fresh covering the seed (see Figure 2-1 (b)). As described by Berger (2003) the *dura* has thin layer of fresh covering a hard-thick shell; the *pisifera* has a thick layer of fresh with a small kernel with very thin or no shell; and the *tenera*, which is a hybrid obtained by crossing *dura* and *pisifera*, have relatively thick flesh with a shell of intermediate size. Higher oil yields are obtained from the *tenera* than the *dura*. The oil content of *tenera* fruits averages 22.5% by weight which is about twice the oil content of the *dura* (8-12.5%) (Hyman, 1990). Moreover, the relatively thin shell of the *tenera* makes it easy to crack and release the nut. These advantages make the *tenera* a preferred choice for industrial/commercial cultivation.

In Ghana, *Dura* and *Tenera* are the two main oil palm varieties cultivated. But, the bulk of smallholder oil palm farms are the *Dura* because of the high level of unsaturation making it nutritionally preferred for local cuisine (Ofosu-Budu and Sarpong, 2013).

2.3 Palm Oil Production Processes

The processing of fresh palm fruits into oil involves series of unit processes. The activities of small-scale processing mills differ from the large-scale industries in terms of the technology used and the sequence of the processes. At most small-scale mills, the only mechanized operations are digestion of boiled fruits and pressing of digested fruits to extract the oil (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012). Table 2-1 describes the production processes employed by the small-scale and large-scale mills. The corresponding process flow diagrams for industrial scale and small-scale are respectively shown in Figure 2-2 and Figure 2-3.

Table 2-1. Descriptive comparison of small-scale and large-scale palm oil production processes

Unit operation	**Method used by the small-scale**	**Method used by the large scale**
Receipt of Fresh fruit bunches	The fresh fruit bunches are brought to the mills in baskets carried on the head or in small trucks. At the small-scale level, harvesting, and postharvest transportation and handling of fresh fruit bunches lead to	The fresh fruits are received in bunches at the factory. The fruits are processed within 24 hours of harvesting (Hassan et al., 2004) to prevent enzymatic action.

	much of the fruits been bruised (Poku, 2002).	
Splitting of bunches	At most mills, the FFBs are divided into small parts (splitting/quartering) using cutlass or axe. The aim is to obtain smaller sizes for easy handling during stripping. This activity is mostly performed by men. During quartering, the bunches are placed on the bare ground or concrete platform which leads to fruit bruises.	Not applicable
Storage	After splitting, they are stored on the bare floor with or without covering for 3-7days (Nkongho et al., 2014, Taiwo et al., 2000, Osei-Amponsah et al., 2012, Adjei-Nsiah et al., 2012). Coverings mostly used are palm fronds, jute bags or plastic sheets. The aim is to allow enough time for the tissue holding the fruit and bunches together to wilt and facilitate loosening of the fruits from the bunches. The storage allows the formation of free fatty acids (FFA) which affects the quality of the crude palm oil produced. Storage reduces the moisture content of the fruits and consequently the wastewater quantity (Adjei-Nsiah et al., 2012).	Not applicable
Stripping / loosening	The fruits are manually separated from the bunches using sticks, blunt side of cutlass or handpicking. The stripping equipment used (sticks and blunt side of cutlass) further leads to fruit bruising. ***Waste product:*** fresh empty fruit bunches which are sometimes dried and used as	Stripping of fruits from the bunches is undertaken after sterilization. This process is carried out using rotary drum threshers. ***Waste product:*** Sterilized empty fruit bunches which are used:

	solid fuel. But many of the empty fruit bunches are left unused at the processing site.	- As fertilizers on plantations - To generate heat for the factory - As solid fuel
Fermentation (optional)	This is an optional activity and so not all processers perform this activity. The loosened fresh fruits are heaped in baskets for 1-4 weeks (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012) to allow fermentation to take place. The duration of storage depends on the end-use of the crude palm oil (food-grade or soap-grade). For food-grade oils, fermentation period does not exceed 1 week (Adjei-Nsiah et al., 2012). On the other hand, the boiled fruits are fermented for 2-5 days to reduce the moisture content before pressing (Anyaoha et al., 2018).	Not applicable
Sterilization / boiling	The fermented or unfermented fruits are submerged in water in metal drums or cooking pots and boiled over open fires. The fires are set and maintained by using firewood, dried coconut branches, empty palm fruit bunches and fibre or waste lorry tires (Osei-Amponsah et al., 2012). During boiling, the fruits are covered with jute bags or palm fronds to minimize heat loss. Boiling takes 1-4 hours depending on the quantity of fruits and burning efficiency (Taiwo et al., 2000, Osei-Amponsah et al., 2012). The objectives of fruit boiling, according to Poku (2002) are to:	Fresh fruit bunches are sterilized in batches in a steam sterilizer. The temperature and duration for sterilization varies among factories but are typically 120-140°C and 50-120 minutes respectively (Hosseini and Abdul Wahid, 2015, Department of Environment, 1999, Singh et al., 2010). The process is undertaken to, among other things: - Deactivate the enzymes responsible for free fatty acid (FFA) build-up

	• Deactivate the enzymes responsible for free fatty acid (FFA) build-up • Softens and prepare the fruit mesocarp for digestion • Detach kernels from the shells and to prevent the kernels from breaking during pressing and nut cracking The nature of the fire produces smoke which could affect the health of processers. In addition, processers are exposed to the heat from the hot fruits and wastewater during manual scooping and transfer of fruits to the digester. ***Waste product:*** boiler wastewater	• Soften and loosen the fruits from the bunches to facilitate stripping of the fruits from the bunches • Softens and prepare the fruit mesocarp for subsequent processing • Detach kernels from the shells and to prevent the kernels from breaking during pressing and nut cracking • Remove external impurities (Hassan et al., 2004) ***Waste product:*** Steam condensate which accounts for 17-36% of the total palm oil mill effluent (Nasution et al., 2018a, Prasertsan and Prasertsan, 1996).
Digestion	This is one of the mechanized processes. The boiled fruits are manually scooped and conveyed into a mechanical digester. The digestion process breaks the exocarp and oil-bearing mesocarp to enhance oil extraction. This operation is undertaken while the boiled fruits are still hot in order to reduce the viscosity of the oil (Poku, 2002). The most common mechanical digesters in use are horizontal and vertical digesters (Taiwo et al., 2000).	The sterilized fresh fruits are mashed using the rotating arms or mechanical digesters under steam-heat. A digester temperature of about 90°C are maintained for effective digestion. The heat may either be produced by steam jacket around the digester or through direct live steam injection (Department of Environment, 1999). The process breaks the oil-bearing mesocarp and together with the steam facilitate oil extraction.

Oil extraction and clarification	Extraction of oil is accomplished using mechanical presses. The process separates the oil from the mash. Depending on the required quality of the oil (food-grade or soap-grade), two methods of oil extraction exist, i.e. 'dry' and 'wet'. The dry method uses mechanical presses to squeeze out the oil but in the wet method hot water is used to leach out the oil, (Poku, 2002). The oil produced from the dry method is mostly soap-grade. In the dry method, boiled fruits are fermented to reduce the moisture content. Then mechanical press is used to squeeze out the oil which contains very minimal sludge. The oil is kept for 2-3 hours for the sludge to settle before the clear oil is scooped from the top. The sludge, which mostly contains a thin layer of oil, is boiled for about 15 minutes after which the residual oil is scooped from the top (Osei-Amponsah et al., 2012). In the wet method, the boiled fruits are squeezed to produce a mixture of oil, cell debris, fibrous materials, and water. Hot water is added in the ratio of 3:1 (Poku, 2002). The mixture is then kept on fire under low heat for 1-2 hours (Osei-Amponsah et al., 2012) for the oil to flow to the surface. The clear oil is skimmed manually from the surface into a storage tank. Food-grade oil is produced from the wet method.	The wet extraction method is commonly used. The mashed fruits are pressed at reasonable pressure to separate the oil and the pressed cake (nuts and palm fibre). Typically, a twin screw press is used. High oil recovery is achieved using hot water. The oil extracted consists of a mixture of palm oil (35-45%), water (45-55%) and fibrous materials (Department of Environment, 1999). The palm oil is separated from the impurities (water and fibrous materials) using a centrifuge in a process called clarification. The oil is continuously skimmed from the top of the clarification tank. The clarified oil is 99.9% and 99.99% free of moisture and dirt respectively (Department of Environment, 1999). ***Waste product:*** • Pressed cake which comprises of palm fibre and nuts. • Separator sludge or clarification wastewater. This is the major source of palm oil mill effluent and it accounts for 60-75% of the total palm oil mill effluent (Nasution et al., 2018a, Prasertsan and

	Waste product: • Pressed cake which comprises of palm fibre and nuts • Clarification wastewater	Prasertsan, 1996). About two-thirds of the suspended solids originate from clarification (Department of Environment, 1999, Hosseini and Abdul Wahid, 2015).
Nut and fibre separation	The palm kernels are separated from the fibre. The sorted fibre is covered for 1-3 days and allowed to undergo internal exothermic reaction after which it is pressed to obtain soap-grade oil (Poku, 2002, Osei-Amponsah et al., 2012). ***Waste product:*** • Pressed palm fibre which is dried and used to start fire at the processing mills • Palm kernels (nuts and shells) which are dried and sold to palm kernel oil processers	The pressed cake is transferred to the depericarper for fibre and nut separation. The separation is achieved by strong air current induced by a suction fan or using a mechanical separator (Hosseini and Abdul Wahid, 2015). ***Waste product:*** • Pressed fibre which is used as boiler fuel • Palm nuts which is sent to a nut cracking machine or ripple mill.
Nut Cracking and processing	This is part of palm kernel oil processing	The nuts are cooled, dried and cracked using nutcracker. In factories where ripple mill is used for nut cracking, drying of the nuts becomes unnecessary. The mixture of shells and kernels are separated using a clay bath, salt solution with specific gravity 1.12 or hydrocyclone (used by most factories) (Department of Environment, 1999). The palm kernels are transferred to the palm kernel mill for palm kernel oil extraction.

		Waste product: Hydrocyclone wastewater (4-8% of total palm oil mill effluent) (Prasertsan and Prasertsan, 1996, Nasution et al., 2018a). The palm kernel shells are sent to the boiler for steam and power generation.

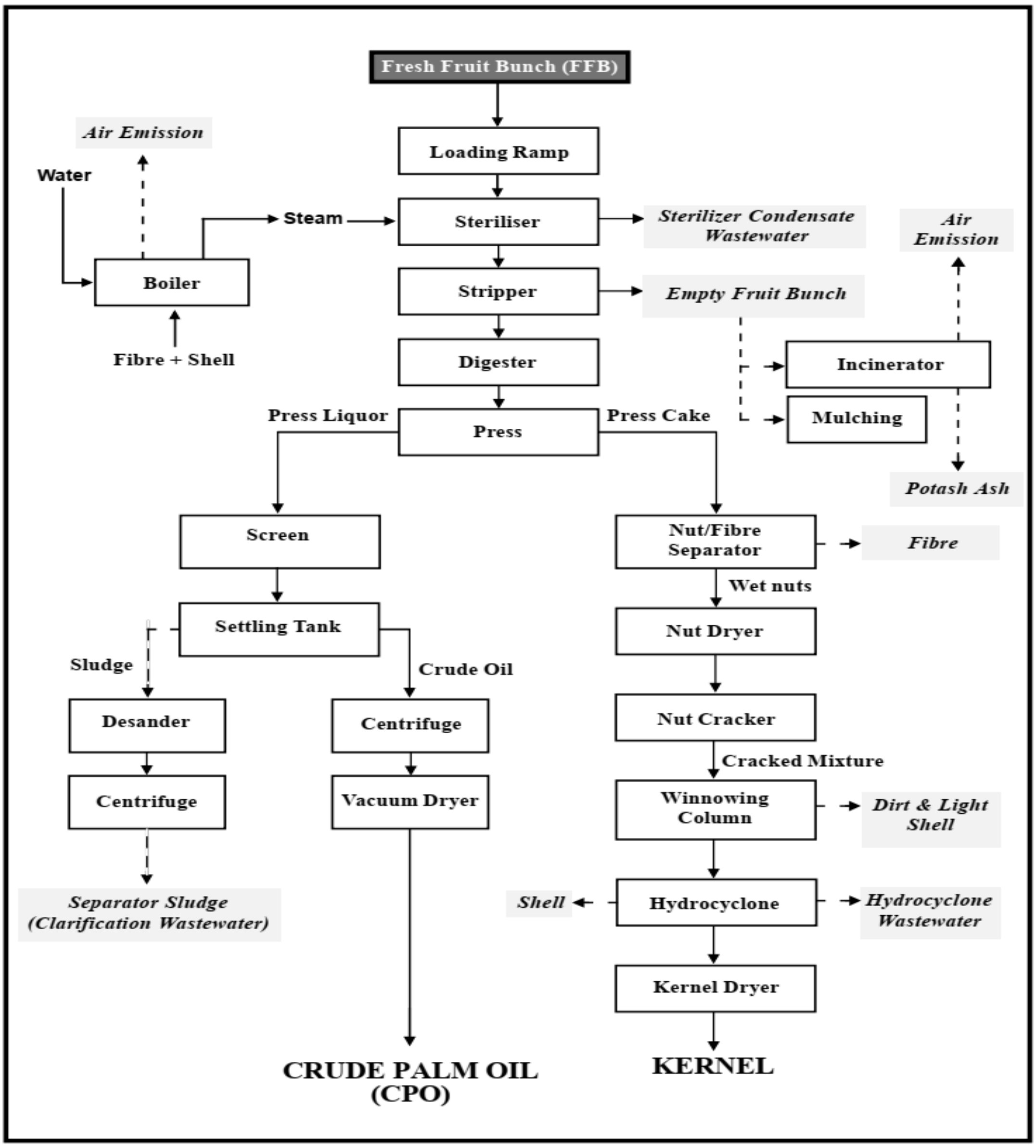
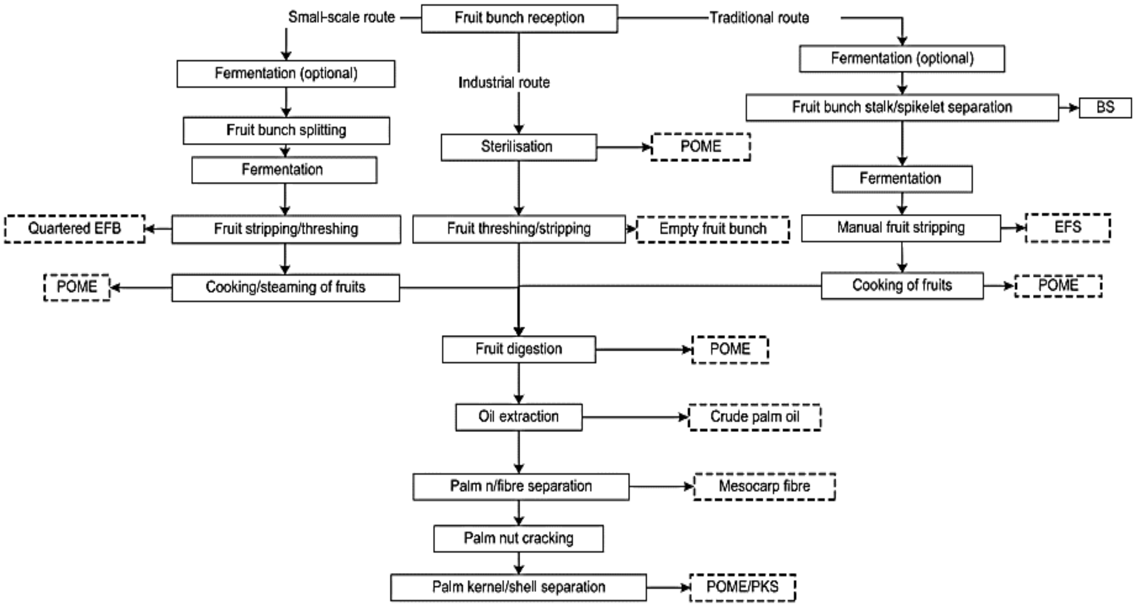


Figure 2-2. Conventional palm oil extraction process at industrial scale

Source: Department of Environment (1999)



Notes: solid box = process; dashed box = waste/output; EFB = empty fruit bunch; POME = palm oil mill effluent; BS = bunch stalk; EFS = empty fruit spikelet; and PKS = palm kernel shell.

Figure 2-3. Process flow diagram for palm oil processing at Industrial, small-scale and traditional routes

Source: Anyaoha et al. (2018)

2.4 Waste Streams from Small-Scale Palm Oil Processing

During the processing of fresh palm fruit bunches into crude palm oil, various categories and varying quantities of waste is generated. The main waste categories are solid, liquid, and gaseous wastes.

2.4.1 Solid wastes

Generally, the solid wastes are generated from various processing operations such as stripping/threshing, pressing and kernel cracking. The solid wastes generated include empty fruit bunch (EFB), palm press fibre (PPF), chaff and palm kernel shell (PKS) and palm kernel cake (Ohimain and Izah, 2013, Rupani et al., 2010). The proportions of solid wastes produced are dependent on the variety of oil palm fruit (*Dura* or *Tenera*) but generally they are in the order EFB > PPF > PKS > chaff. For each kg of crude palm oil extracted about 1 kg of wet EFB is produced (Sulaiman et al., 2010). Moreover, a tonne of FFB is made up of 230‑250 kg of EFB, 130‑150 kg of fibre, 60–65 kg of shells, 55–60 kg of kernels and 160–200 kg of unrefined oil (Ahmad et al., 2003).

Unlike the large-scale mills, a very small proportion of the solid wastes generated by the small-scale mills are utilized. Part of the solid waste is utilized as sources of fuel. This reduces the dependence on firewood, which increases the rate of deforestation. But in Ghana, the major source of fuel for palm oil processing is fibre/PKS (Figure 2-4).

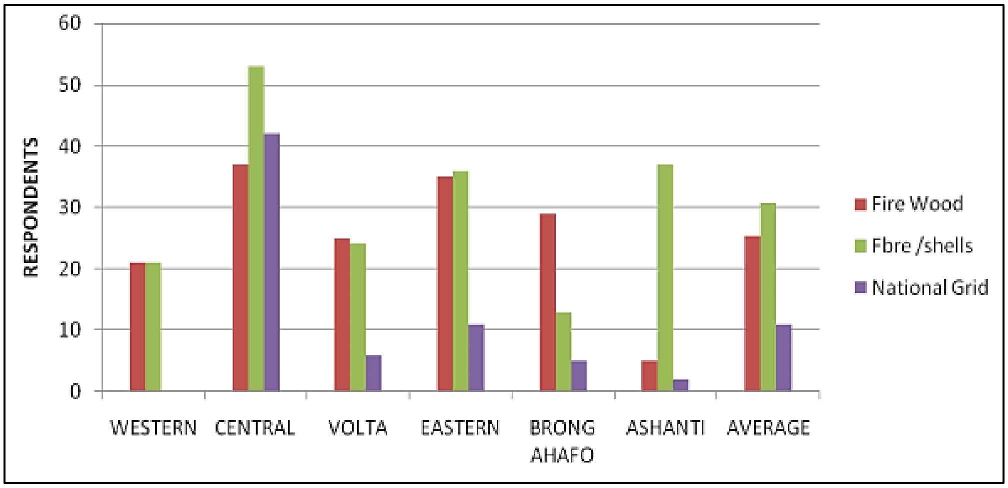


Figure 2-4. Types of fuel for palm oil processing in Ghana

Source: MASDAR (2011)

EFB, PPF and PKS are used as solid fuels for boilers (Ohimain and Izah, 2014). But due to the high moisture content (over 60%) (Sulaiman et al., 2010), EFB must be dried before use. Moreover, Palm press fibres are dried and used to start fire in most small-scale processing mills. The presence of unrecovered oil in PPF enhances their combustibility and consequently their use in starting fires. In small mills, up to 70% of PPF are disposed as waste (Prasertsan and Prasertsan, 1996). The ash from PPF are rich source of phosphorus, potassium, and calcium. Aside their use as fuel, EFB and PPF are potential source of soil conditioner when de-oiled. The local furnaces used by the small-scale industries are designed for solid fuels from the palm oil processing other than PKS. Only few local mills utilize a small quantity of the PKS. The rate of biological decomposition of PKS is very slow and this affect their use as soil conditioner. They are thus left unused or used as filling materials for surfacing of floors or untarred roads. The output from the furnace is ash with a very high mineral content. It is estimated that combustion of a tonne of EFB produces 4kg of boiler ash (Prasertsan and Prasertsan, 1996). Unlike the large-scale mills, a very small proportion of the solid wastes generated by the small-scale mills are utilized. The excess wastes are piled up at the processing mills.

2.4.2 Liquid wastes

Processing of oil palm requires large quantity of water and consequently generates high amount of wastewater. At the small-scale mills, the wastewater is generated during boiling of fresh fruits and clarification of crude palm oil. The characteristics of the wastewater from the various unit processes differ. In extracting one tonne of crude palm oil, it is reported that 2.5 – 3.8 tonnes of wastewater is produced (Ahmad et al., 2003, Ho et al., 1984, O-Thong et al., 2012). In Nigeria, 72-75% of water used by small-scale mills returns as wastewater (Ohimain and Izah, 2013). In terms of FFB, processing of one tonne consumes 5.0 – 7.5 tonnes of water, out of which 50 – 79% end up as POME (Ohimain and Izah, 2013, Singh et al., 2010, Chavalparit et al., 2006). Raw palm oil mill wastewater contains high organic matter content (10250-43750 mg/l BOD_3 and 15000-100000mg/l COD) and solids contents (11500-79000mg/l total solids; 5000-54000mg/l suspended solids, and 9000-72000mg/l total volatile solids) (Lam and Lee, 2011). POME consists of 2% unrecovered oil, 2-4% suspended solids and 94-96% water (Ma et al., 1994). The suspended solids emanate from the fibrous mesocarp of the palm fruits. Additionally, wastewater contains plant nutrients (such as nitrogen, phosphorus, potassium), heavy metals (zinc, copper, iron, etc.) (Ohimain et al., 2012). At the small-scale mills, wastewater is discharged on land, in nearby bushes or surface water bodies (Osei-Amponsah et al., 2012, Okwute and Isu, 2007). In Africa, Poku (2002) reported the use of POME as herbicides to control weeds around the processing mills. Other forms of liquid wastes are the palm oils and fuels for machinery that spill on the land around the processing mills. Even though very small compared to POME, spilled fuel and palm oil contribute to land and water pollution.

2.4.3 Gaseous Emission

Gaseous pollutants at the processing mills originates from different unit processes such as boiling of fresh fruits, digestion of boiled fruits, and clarification of crude palm oil. Smoke originates from inefficient local fires and digesters/pressers used for digestion and pressing of boiled fruits.

Whereas most industrial scale oil palm processing use electricity, conventional diesel machines are used for fruits digestion at the small-scale mills in West Africa. Some of the commonly used equipment that emits gaseous emission during oil palm processing is presented in Figure 2-5.

Figure 2-5. Gaseous emission sources from smallholder oil palm processing mill

Photo credit: Izah et al. (2016)

The smoke has negative impacts not only on mill workers but also on people living and working close to the mills. Diesel exhaust fumes contribute significantly to combustion-derived particulate matter air pollution (Ohimain and Izah, 2013). In addition to the smoke, the noise from the machines could potentially affect the health of the workers. In Nigeria, Ohimain and Izah (2013) measured CO, SO_2, NO_2, NH_3, VOCs, H_2S, suspended particulate matter (SPM), and noise level at small-scale palm oil processing mills in Elele, Rivers State. They found elevated concentrations of the parameters measured (CO, SO_2, NO_2, NH_3, VOCs, H_2S, suspended particulate matter (SPM) with most of them above the Nigerian Ambient Air Quality standards. Noise levels were however within permissible limits of 90dB. Another source of air emission is biogas produced from digestion of POME. As has been mentioned already, at the small-scale mills, wastewater is discharged into the natural environment without treatment. The wastewater undergoes anaerobic digestion releasing methane gas and odour into the environment.

2.5 Characteristics of Palm Oil Mill Effluent

The main sources of palm oil mill wastewater are sterilizer condensate (17-36%), separator sludge (60-75%) and hydrocyclone wastewater (4-8%) (Nasution et al., 2018a, Prasertsan and Prasertsan, 1996, Department of Environment, 1999). In general terms, palm oil mill effluent (POME) is a mixture of wastewater from sterilization, clarification and hydrocyclone. POME is a non-toxic, viscous brownish, colloidal slurry composed of water, oil and fine suspended particles. Raw POME is discharged at 75-95°C (Zinatizadeh et al., 2006, Wu et al., 2010, Bhatia et al., 2007, Lee et al., 2019). In terms of percentage proportions, palm oil mill wastewater is a colloidal suspension with 95-96% water, 0.6-0.7% oil and 2-4% suspended solids (Ma, 1999). POME also contains high organic substances (BOD and COD), high quantities of total solids and oil & grease (Wang et al., 2015). The presence of high degradable organic matter content of POME has been attributed in part to the unrecovered palm oil content (Ahmad et al., 2003). The wastewater is generally acidic due to the presence of organic acids in complex forms that could be utilized as carbon sources (Md Din et al., 2006). In addition, POME contains appreciable quantities of plant nutrients in the form of nitrogen, potassium, magnesium, phosphorus and calcium (Ohimain and Izah, 2017). Table 2-2 shows the general characteristics of POME reported in literature. The characteristics of the individual wastewater streams is presented in Table 2-3. The particulate matter comprises of organic plant cell debris and fragments with low ash content (Wu et al., 2010). The characteristics of palm oil mill wastewater is reported to differ based on the processing techniques, processed batches or days, quality of the palm fruits, type of fruits (Ng et al., 1987), quality control of individual mills (Yusof and Ariffin, 1996), climate, condition of the palm oil processing (Liew et al., 2015), and cropping season of the oil palm (Wu et al., 2010). The general characteristics of raw POME suggests the need to subject it to appropriate treatment before discharge into the environment.

Table 2-2. Characteristics of POME from literature

Parameter	**Wood et al. (1979)**	**Department of Environment (1999)**	**Najafpour et al. (2006)**	**Zinatizadeh et al. (2006)**	**Choorit and Wisarnwan (2007)**	**Wong et al. (2009)**
pH	-	3.4-5.2	3.8-4.4	4.05	4.24-4.66	4.15-4.45
TS	29,600-55,400	11,500-79,000	-	-	68,854-75,327	33,790-37,230
TDS	15,500-59,000	-	-	-	-	-
TSS	14,100-26,400	5,000-54,000	16,500-19,500	19,780	44,680-47,140	15,660-23,560
BOD_5	17,000-26,700	10,000-44,000*	23,000-26,000	22,700	62,500-69,215	21,500-28,500
COD	42,900-88,250	16,000-100,000	42,500-55,700	44,300	95,465-112,023	45,500-65,000
Total Nitrogen	500-800	180-1,400	500-700	780	1,305-1,493	300-410
Phosphorus	94-131	180	-	-	-	-
Potassium	1,281-1,928	2,270	-	-	-	-
Oil and grease	4,400-8,000	150-18,00	4,900-5,700	4,850	8,845-10,052	1077-7582

All values are in mg/l except pH *BOD_3 at 30°C

TS-total solids; TDS-total dissolved solids; TSS-total suspended solids

Table 2-3. Characteristics of individual wastewater streams in Malaysia

Parameter	**Sterilizer condensate**	**Oil clarification wastewater**	**Hydrocyclone wastewater**
pH	5.0	4.5	-
Suspended solids	5,000	23,000	7,000
Dissolved solids	34,000	22,000	100
BOD_3 at 30°C	23,000	29,000	5,000
COD	47,000	64,000	15,000
Total nitrogen	500	1,200	100
Oil and grease	4,000	7,000	300

All values are in mg/l except pH

Source: Ma and Ong (1985)

2.6 Low-cost POME Treatment Technologies for Resource-Constrained Communities

Many technologies have been tested and applied to successfully treat palm oil mill wastewater mostly in Asia. These treatment technologies include anaerobic digestion (Yacob et al., 2005, Ohimain and Izah, 2017), aerobic systems (Vijayaraghavan et al., 2007), co-composting (Hasanudin et al., 2015), adsorption (Alkhatib et al., 2015), advanced oxidation (Ng and Cheng, 2016, Bashir et al., 2017), and membrane filtration system (Wang et al., 2015). Detailed description of different the treatment methods can be found in the works by Liew et al. (2015), Iskandar et al. (2018) and Ohimain and Izah (2017). However, most of the technologies are expensive and may not be adaptable in a resource-constrained environment such as pertains in small towns and villages where small-scale mills are located. In addition, downscaling some of the technologies to be applicable to informal small-scale processing mills could increase the unit cost of treatment and affect their acceptance. Therefore, for resource constrained countries, low-cost technologies (such as ponding systems, anaerobic digesters, co-composting, vermicomposting and sludge extraction, drying and reuse) must be explored.

2.6.1 Ponding system

Ponding systems are the commonest technology for treating POME. The use of pond systems is favoured by reasons such as: low-cost, low maintenance, process and operational simplicity, easy of expansion and ability to withstand hydraulic loads (Liew et al., 2015). This technology is used by more than 85% of palm oil processing mills in Malaysia (Ma and Ong, 1985). The ponding system consists of series of ponds involving cooling ponds, acidification ponds, anaerobic ponds, facultative ponds, and algae aerobic ponds (Liew et al., 2015). The number of ponds depends on the production capacity of the mill (Hassan et al., 2004) and the quantity of wastewater produced. The treatment of POME in ponds is achieved by microorganisms in a suspended growth process. The microorganisms are affected by temperature. The temperature of raw POME is therefore reduced from 75-95°C (Lee et al., 2019) to <35°C in cooling ponds (Thanh et al., 1980). The anaerobic ponds, facultative ponds and aerobic ponds are distinguished by their depths. The optimum depths are 5-7 m for anaerobic ponds, 1.0-1.5 m for facultative ponds and 0.5-1.0 m for aerobic ponds (Hassan et al., 2004). The ponding systems are capable of achieving 22% COD (Hosseini and Abdul Wahid, 2015), 99.7% BOD, 99% suspended solids, 91% total nitrogen and 25% ammoniacal nitrogen (Ma and Ong, 1985) reductions. Figure 2-6 shows the flow diagram of a ponding system for POME treatment.

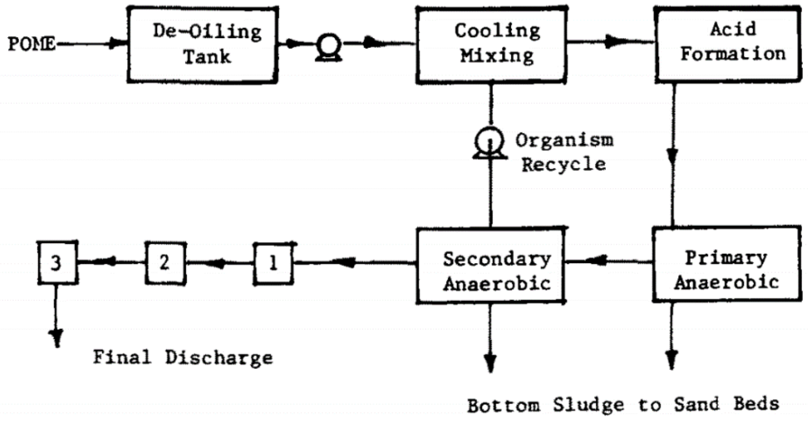


Figure 2-6. Ponding system for POME treatment

Source: Ma and Ong (1985)

The major drawbacks with ponding systems are their large land requirement and long hydraulic retention times (HRT). Thanh et al. (1980) reported a land area requirement of 1.0-5 ha and HRT of 40-200 days for ponding systems. However, a much lower HRT for anaerobic ponds, facultative ponds and aerobic ponds of 45 days, 20 days and 14 days respectively (Hassan et al., 2004) have been reported in recent times. In addition, formation of scum and sludge accumulation are challenges with pond systems. The scum is formed when bubbles release unrecovered oil and grease to the surface. However, the sludge could be removed periodically (normally every 5years when the capacity of the pond reduces significantly) and dried for use as soil conditioner (Ma and Ong, 1985). The anaerobic digestion process in open ponds emits methane gas into the environment. It is reported that an anaerobic pond has the potential to generate up to 70% methane gas (by composition) (Yacob et al., 2006).

2.6.2 Composting systems

Composting is the decomposition of organic residues into manure using a consortium of microorganisms (bacteria, actinomycetes and fungi) in a controlled environment. The high organic solids and appreciable nutrients content of POME (Wang et al., 2015, Ahmad et al., 2003, Ohimain and Izah, 2017) makes them potential substrates for compost production. In composting, bulking agents are important to maintain the moisture, carbon-to-nitrogen ratio, pH and supply air (Manish et al., 2013). But for wet substrates such as POME, low moisture bulking agents are required (Imbeah, 1998, Gea et al., 2007). POME may therefore be co-composted with bulking agents such empty palm fruit bunches and sawdust. Raw or partially digested POME from anaerobic tanks and ponds could be utilized for co-composting. The composting process is influenced by temperature, water content, oxygen concentration in the composting matrix, porosity and free air space (Gea et al., 2007). Co-composting of POME with empty fruit bunches or saw dust has shown considerable success both at the laboratory and field scale.

At a field-scale, Baharuddin et al. (2009) co-composted partially treated POME from anaerobic pond with shredded empty fruit bunches at a ratio of 1:3. The composting method used was windrows. The final compost was achieved in 60 days with a turning frequency of 1-3 times per week. The characteristics of the final compost showed considerable amounts of nutrients (carbon, nitrogen, phosphorus, potassium, calcium, magnesium, sulphur, and iron), trace amounts manganese, zinc, and copper but very low levels of heavy metals. In a related study, palm oil mill sludge was co-composted with sawdust (1.86:1) over 90-day period in an in-vessel system made from cylindrical polyethylene vessel with 2 cm diameter holes to aid aeration (Zahrim et al., 2007). Their composting process was verified to follow first order kinetic equation with degradation rate, k of 0.014/day and maximum degradation rate of 51%. Through a pot experiment, the compost improved the growth of pseudostems of *Cymbopogon citratus* cultivated in a sandy soil.

Co-composting of raw POME and empty fruit bunches have been found to produce compost with inconsistent quality due to the variable characteristics of POME (Yoshizaki et al., 2013). Co-composting of POME significantly reduces the emission of greenhouse gases due to the aerobic decomposition process employed (Hasanudin and Haryanto, 2018, Barik, 2019).

2.6.3 Vermicomposting systems

An alternative to the conventional composting which uses consortium of microorganisms is vermicomposting which uses earthworms. Vermicomposting have been found to exhibit a higher rate of organic degradation and produce nutrient-rich compost with finer texture (Lee et al., 2019). The composting period could be 50% of the time required by conventional composting systems. Composting of POME using earthworms have shown great potential. Syirat et al. (2014) used epigeic earthworms (*Eudrillus eugeniae*) to decompose POME sludge in a closed system within 60 days. They obtained a compost of high nutrient content compared with compost produced from EFB-POME sludge and mesocarp fibre-POME sludge. Similarly, Rupani et al. (2017) used *Lumbricus rubellus* for vermicomposting POME-palm pressed fibre (1:1) over 30days. The resulting compost showed significant improvement in nitrogen, phosphorus, and potassium content with 75% vermicompost extract enhancing germination of mung bean. In another study, various compositions of empty fruit bunches and POME solid (100, 90, 80, 70, 60, 50% EFB) were vermi-composted using *Eisenia fetida* earthworms for 84 days (Nahrul Hayawin et al., 2012). A significant increase in total Kjeldhal nitrogen (0.4-1.7 mg/kg), total phosphorus (0.2-1.4 mg/kg) and total potassium (0.06-0.5 mg/kg) was recorded for all vermicompost with the highest increase recorded for 1:1 EFB-POME solid combination. Other researchers composted EFB and POME with various organic wastes. Hau et al. (2020) analysed the final macronutrient and physical properties of vermicompost produced from mixed-composting of EFB + POME (weight ratio of

1:1) with fishmeal (N source), bonemeal (P source), bunch ash (K source) and sawdust in different compositions using *Eisenia Fetida*. The compost which matured in 40 days, had a porous structure to support aeration and increased nitrogen (18 to 62%), phosphorus (125 to 906%) and potassium (262 to 294%) content.

It has been found that vermicompost possess higher essential nutrients (N, P, K, Mg, etc.) and retains nutrients for a longer time than conventional compost (Sinha et al., 2009). Vermicomposting produces two (2) important end products: manure/compost and earthworm biomass. The latter could be processed into protein source in poultry and fish (Parolini et al., 2020).

2.6.4 Evaporation

Evaporation is the process of removing water from solution through the application of heat energy using low-pressure steam (Kandiah and Batumalai, 2013). The process requires the use of evaporator of suitable material and adequate amount of latent heat of vaporization. Evaporation has been used to remove water from aqueous solutions for several years. But its application in POME treatment is very limited. Ma (1997) used a 200 L single-effect evaporator based on the principle of rapid heating at a temperature and pressure of 80^{o}C and 600 mmHg respectively to recover 85% of water from the POME. Two significant benefit of using the evaporation technology proposed by Ma (1997) to process POME are (1) the distillate possesses sufficient quality (20mg/L BOD) and quantity to be used as boiler feedwater (2) there is zero liquid discharge. In order to reduce the production of POME, Kandiah and Batumalai (2013) proposed and piloted a new multi-step process including single-effect forced circulation evaporator system for palm oil clarification. According to the authors, the new clarification process could reduce the amount of liquid effluent by 83% compared to the conventional oil clarification process while achieving about 75% rise in oil content.

The major consideration for evaporation systems is the energy requirement. For single-effect evaporator, Ma (1999) recommends specific energy consumption of one kg of steam per kg water evaporated for design of evaporation systems. But for multiple-effect evaporator, the energy requirement is only about 25% (Tan and Lim, 2019). The high temperature (75-95^{o}C) of fresh POME could be utilized to reduce the amount of heat required for evaporation.

3 CHAPTER THREE

WATER USAGE AND WASTEWATER RETURN FACTORS FOR SMALL-SCALE PALM OIL PROCESSING IN GHANA

3.1 Abstract

The palm oil processing sector in Ghana is dominated by informal and unregulated small-scale processers. This study was aimed at assessing the water usage, wastewater return factor and wastewater management practices by small-scale palm oil processing mills in the Central Region of Ghana. Twenty-five (25) small-scale processing mills were selected from four palm oil processing Metropolitan, Municipal and District Assemblies to ensure agro-ecological balance. Data was collected through in-depth interviews, structured observation, and field measurements. A pre-tested interview guide was used to obtain information on the sources, distances, and cost of water as well as wastewater management practices from managers and processers. The water usage, wastewater and crude palm oil production were obtained through field measurement. Structured observation was used to triangulate the findings from the interview. Boiling of fresh fruits, clarification of oil (optional), and cleaning of working tools were the unit processes which consumed fresh water and produced wastewater. Water was obtained from hand-dug wells, treated piped water, boreholes with handpumps and rivers/streams which were located within 200m from the processing mills. Eighty percent (80%) of the water sources were from Basic Service level. For a litre of crude palm oil produced, 0.76-2.39 litres of water was consumed generating 0.57-1.89 litres of wastewater which are disposed on the land and nearby bushes without treatment. In terms of wastewater return factors, 68-82% of the water used in the extraction industry returned as wastewater. There were no significant differences in the water consumption and wastewater production between the wet and dry processing methods. The wastewater produced could generate 10.4-34.4 litres of methane gas. The current disposal of untreated wastewater on land could be impacting negatively on the environment.

Keywords: Ghana, palm oil processing, small-scale, water usage, wastewater return factor

3.2 Introduction

Processing oil palm fruits into edible oil has traditionally been practiced in Africa. The oil produced is an essential ingredient in much of the traditional West African cuisine. Palm oil is now an important domestic and industrial commodity worldwide. On the world commodity markets, palm oil is gaining increasing attention due to factors such as the high yields of oil palm as compared to any other edible oil crops, high demand for domestic and industrial uses, use as biofuel (Angelucci, 2013, Ratanaporn et al., 2017) and the need for cheaper sources of oleo chemicals (Inyan, 2002). Whiles palm oil processing is traced to West African origins, current production levels in the subregion are significantly low. In 2013 for example, West Africa's palm oil output was 2.2 million metric tonnes (MT), equivalent to 3.5% of global production (Hassan et al., 2016). The major production centres have shifted to Southeast Asia with Indonesia, Malaysia and Thailand as the world's leading producers (IndexMundi, 2020b). In West Africa, the main palm oil producing countries are Nigeria, Ivory Coast, Ghana, Benin, Guinea, Liberia, Sierra Leone and Togo.

Ghana is ranked 13th in the world and 3rd in West Africa in terms of production quantities (IndexMundi, 2020a). As in many other West African countries, palm oil is the most important edible oil in Ghana. Palm oil and palm kernel represented 2% of total agricultural production value of Ghana in 2010 (Angelucci, 2013). From analysis of palm oil production and consumption in Ghana between the year 2005 and 2010, Angelucci (2013) reported that the country produced a total of 120,000 tonnes of palm oil. As at 2019, the country's crude palm oil production had increased to 375,000 tonnes (IndexMundi, 2020a). However, Ghana has an annual production deficit of about 30,000 tonnes which is estimated to reach 127,000 tonnes by 2024 (Commodafrica, 2018). Processing of oil palm is a major source of income and employment to many women in the rural areas of the forest agro-ecological zone of Ghana (Opoku and Asante, 2008). Palm oil has a wide geographical coverage and cultivated in six out of the 10 administrative regions of Ghana (Adjei-Nsiah et al., 2012). The most suitable areas for oil palm cultivation are in the Western, Central and Eastern Regions.

Palm oil is processed from fresh fruits using various techniques that differ in the level of mechanisation and interconnecting material transfer mechanisms. The scale of operations also differs at the level of processing. Unlike in South-East Asia where the processing of crude palm oil is entirely undertaken by agro-industries in high-technology well-equipped mills, palm oil processing in Ghana (like other West African countries) is undertaken by four (4) distinct groups of actors (Poku, 2002). These processing mills, according to their throughput and degree of complexity, are traditional, small-scale, medium-scale and large-scale mills. In terms of level of complexity, the traditional producers use methods which are basically manual with the use of rudimentary tools. The small-scale producers use a variety of low-efficiency machinery ranging from simple hand presses and other stand-alone machines to a very varied combination of machines which cater for the various unit processes in the processing. In terms of throughput, small-scale processing units handle up to 2 tonnes per hour of fresh fruit bunches (FFB) (Poku, 2002, MASDAR, 2011). The medium-scale and large-scale mills have technologically up-to-date machinery, established by agro-industrial complexes for the production of palm oil (Hassan et al., 2016) with production throughput of up to 60tonnes of FFB per hour. Detailed description of the various processing mills in Africa can be found in Poku (2002). Poku (2002)'s description of small-scale oil palm process is applicable to the mills that were involved in this study.

Though small-scale producers are characterized by weak milling capacity (Kajisa et al., 1997, Uckert et al., 2015), they occupy a greater share of the West African palm oil processing sector. In the West African subregion, up to 83% of the palm oil is produced by the small-scale industry (Hassan et al., 2016). Available data shows that there were more than 400 small-scale mills in Ghana as at 2002 (Poku, 2002) producing 80% of the national palm oil production (Angelucci, 2013, Osei-Amponsah et al., 2012). By 2015, they were employing over 2 million people mostly in rural areas (Yawson, 2015). The informal and wide-spread nature and high contribution of small-scale mills to Ghana's palm oil production warrants attention and research. However, studies on the palm oil processing industry in Ghana has focused on processing technology, profitability, institutional analysis, quality of crude palm oil, and gender roles. Research on water consumption and wastewater quantities, characteristics, and treatment from small-scale palm oil processing mills in Ghana is very limited.

In processing fresh palm fruits into crude palm oil, high quantities of fresh water is reported to be consumed (Hassan et al., 2004), generating high quantities of wastewater (Chavalparit et al., 2006).

The water and wastewater quantities are dependent on the processing method and level of technology employed. For instance, to produce one tonne of crude palm oil, an estimated 5.0 – 7.5 tonnes of water is consumed out of which 50% returns as wastewater commonly called palm oil mill effluent (POME) (Ahmad et al., 2003). These estimates are reported for Malaysia and Indonesia where the palm oil extraction industry is dominated by the large-scale industries employing more efficient processing techniques. The water consumption and wastewater production quantities could vary for the small-scale palm oil processing mills which use less efficient methods (Poku, 2002). The informal and widespread nature of the activities of small-scale processers have affected enforcement of compliance with environmental regulations. Small-scale processing mills in Ghana have therefore been criticised for failing to adhere to waste management practices (Poku, 2002).

This study was aimed at quantifying the water consumption and wastewater production and management practices by small-scale processing mills in Ghana.

3.3 Materials and Methods

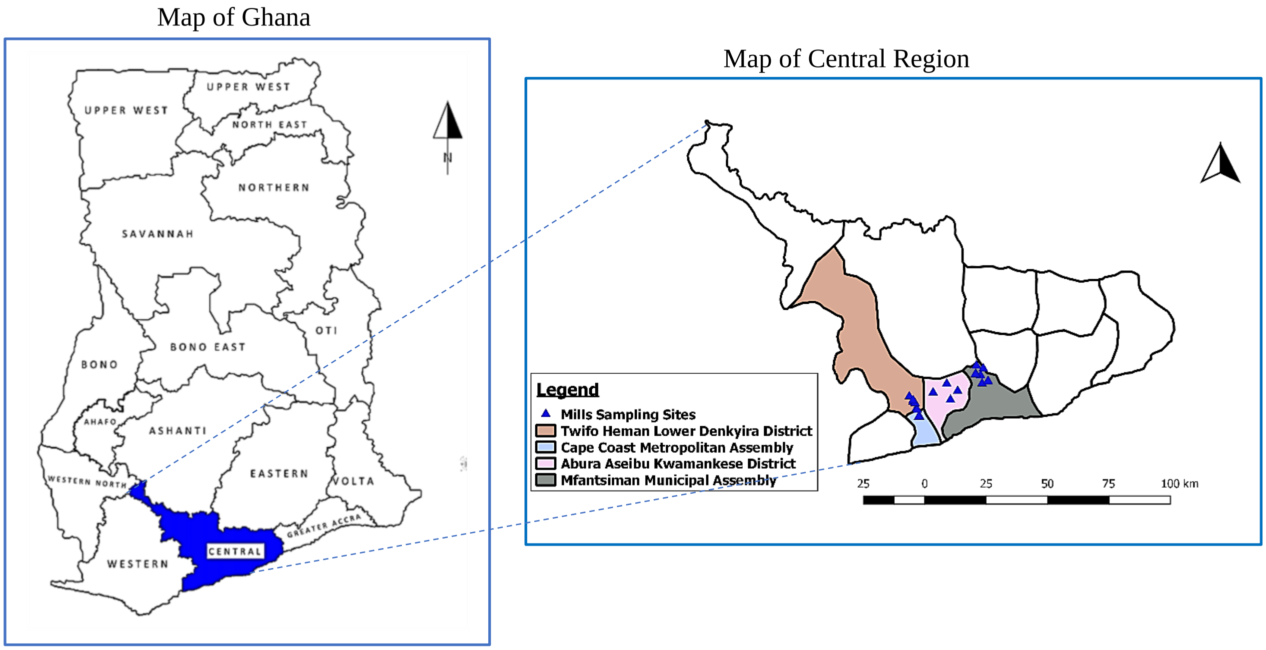
3.3.1 Study Setting

The study was conducted in the Central Region of Ghana. The Central Region is one of the sixteen (16) first-level government administrative units of Ghana. The 2019 population of the region is estimated at 2,563,228 inhabitants (Citypopulation, 2019) with a population density of 260 inhabitants/km^2. The region is subdivided into seventeen second-level administrative units classified as metropolitan, municipal or district assemblies. Based on the climate, the region is divided into three agro-ecological zones namely coastal savanna, transitional and forest zones (MOFA, 2020). The average temperature ranges between 24^{o}C and 34^{o}C with a relative humidity of 50% to 85%. The region is characterized by bi-modal rainfall pattern with major and minor rainy seasons of March-July and September-November respectively (FAO, 2005). In terms of palm fruit production, the peak and lean seasons are respectively February-June and July-January (Osei-Amponsah et al., 2012). The average annual rainfall ranges from 800mm in the Coastal Savanna to 1,500mm in the forest zone. The main economic activities are agriculture with 80% of the region's total land area considered as cultivable (MOFA, 2020). The major tree crops cultivated in the region are cocoa, oil palm, citrus and coconut. The region's land area for oil palm cultivation accounts for 16% of the total national area for oil production (MASDAR, 2011).

Access to basic drinking water in the region stands at 88%, higher than the national coverage of 79% (GSS, 2018). Water supply to communities in the region are through piped water by Ghana Water Company Limited (GWCL) or under the Community Water and Sanitation Agency (CWSA) small towns piped water supply systems. The GWCL supplies water to urban and peri-urban areas whiles CWSA supplies water to small towns (population of 5,000 – 50,000) and rural areas (population of less than 5,000). In communities without piped water supply (mostly in rural areas), inhabitants obtain their water mainly from boreholes fitted with pumps, hand-dug wells or untreated surface water.

3.3.2 Selection of Processing Mills

Four (4) MMDAs namely Cape Coast Metropolitan Area (CCMA), Abura Aseibu Kwamankese District (AAKD), Twifo Hemang Lower Denkyira District (THLDD) and Mfantseman Municipality (MfM), were selected. The MMDAs were strategically selected to ensure agro-ecological balance. Thus, two (AAKD and THLDD) are in the forest zone and one each in the transition zone (MfM) and coastal savanna zone (CCMA). An initial list of eighteen (18) small-scale palm oil processing mills were obtained from the offices of the Business Advisory Centres (BAC) in the MMDAs. Snowball sampling method was used to identify additional seven (7) processing mills for inclusion in the study. Preliminary visits were conducted to all the processing mills to obtain basic information about the mills. A review of literature shows that both dry and wet methods of palm oil extraction are used by small scale processing mills in Ghana (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012, Poku, 2002). The method of palm oil extraction influences the quantity of water demand and wastewater generated. Through the preliminary visits, it was identified that six (6) of the processing mills employed dry extraction method whilst the remaining nineteen (19) mills uses the wet extraction method. A map showing the study area and location of the selected small-scale processing mills is presented in Figure 3-1.


Map of Ghana

Map of Central Region

Figure 3-1. Map of the study area and sampling location

3.3.3 Study Design

The study was designed to:

- Qualitatively assess the processing techniques employed by small-scale palm oil processing mills and to ascertain the stages where water is used and wastewater generated.
- Quantitatively measure the water usage and wastewater generation for each unit operation
- Qualitatively assess the wastewater management practices implemented by the small-scale palm oil processing mills.

3.3.4 Data Collection Methods

Data for the study was collected through interviews, personal observation and field measurements. These data collection methods were applied to all the 25 small-scale palm oil processing mills selected for this study.

3.3.4.1 In-Depth Interviews

Through literature review, an interview guide (Appendix A) was designed and pre-tested for use in the study. For each of the processing mills, the manager and a worker were interviewed using the interview guide. Interviews were used to document the various stages where water is used, and wastewater generated. In addition, information on the sources, costs and distance of water from the processing mills were obtained. Existing wastewater management practices implemented by the mills were also obtained through the interviews.

3.3.4.2 Structured Observation

The personal observation technique was employed to corroborate the information obtained from the mill operators through the interviews. Specifically, processing techniques, stages of water usage and wastewater generation, distance from water source, sources of water and wastewater disposal practices were observed.

3.3.4.3 Field Measurements

Field measurements were used to obtain the quantity of water used and wastewater generated for each processing cycle. While some researchers (Muyibi et al., 2014) reports on the quantity of water consumed and wastewater produced in palm oil processing, review of available literature did not reveal any reported methodology for quantifying the water-use and wastewater production. To obtain the quantity of water and wastewater, the researcher followed the palm oil processing activities right from the receipt of fresh fruit bunches to the final stage of palm oil processing. Graduated plastic tanks were provided to separately store fresh water and wastewater. The tank for water storage were filled and the processers were monitored to only fetch water from this tank. An 18-litre graduated plastic bucket was used to fetch water from the tank thereby tracking the quantity of water used at different stages of the process. The volume of water used for each production cycle and the quantity of palm oil produced were recorded in a logbook.

As was done for the water usage, wastewater generated was kept in different graduated storage tanks. Separate tanks were used to collect and measure the amount of wastewater from different processing activities (unit processes). For example, wastewater from the boilers were not mixed with the wastewater from the clarification tanks. After measuring the volume of wastewater generated, the processers were allowed to dispose the wastewater using their existing management practices. This was observed and documented as the existing wastewater management practice employed by the mills. For each processing site, water consumption, volume of oil produced, and rate of generation of wastewater were measured for three (3) production cycles in order to find an average and reduce accidental errors in measurement.

3.3.5 Data analysis

Data was analysed using Microsoft Excel. All data set were tested for normality with Shapiro-Wilk test at 95% significance level. Descriptive statistics of mean and standard deviation were recorded for the 25 processing mills and separately for dry and wet processing methods. Depending on the number of parameters tested, a *t*-test or one-way ANOVA test (α=0.05) was used to test for statistically significant differences.

3.4 Results and Discussions

3.4.1 Processing Operations, Stages of Water Usage and Wastewater Production

The unit processes used by processers in this study area were receipt of fresh fruit bunches, quartering of FFB, Storage of quartered FFB, stripping of fruits from bunches, cleaning, storage of fruits (optional), boiling of fresh fruits, storage of boiled fruits (optional), digestion of boiled fruits, extraction of oil/pressing, clarification (optional) and cleaning of working tools. Figure 3-2 is a flow chart showing the sequence of operations employed by small-scale processing mills in the Central Region of Ghana.

The processing practices of small-scale palm oil producers in parts of Ghana and Nigeria have been studied and reported in scientific literature (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012, Taiwo et al., 2000). There were no significant differences between the unit processes reported in literature and those employed by processers in the current study area. However, other optional operations were introduced depending on the method of oil extraction (whether wet or dry method). As has also been reported in other studies (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012), the only mechanized operations were the digestion of boiled fruits and pressing of the digested fruits to extract the oil. Both wet and dry methods of palm oil extraction were employed among small-scale processing mills in the Central Region of Ghana. Six (6) of the processing mills studied used the dry method of processing. In the dry method, oil is squeezed out of the boiled fruits using mechanical presses but in the wet method, water is mixed with the digested fruits to make a slurry which is kept on low heat to leach out the oil as reported by Kandiah et al. (2006) and Poku (2002).

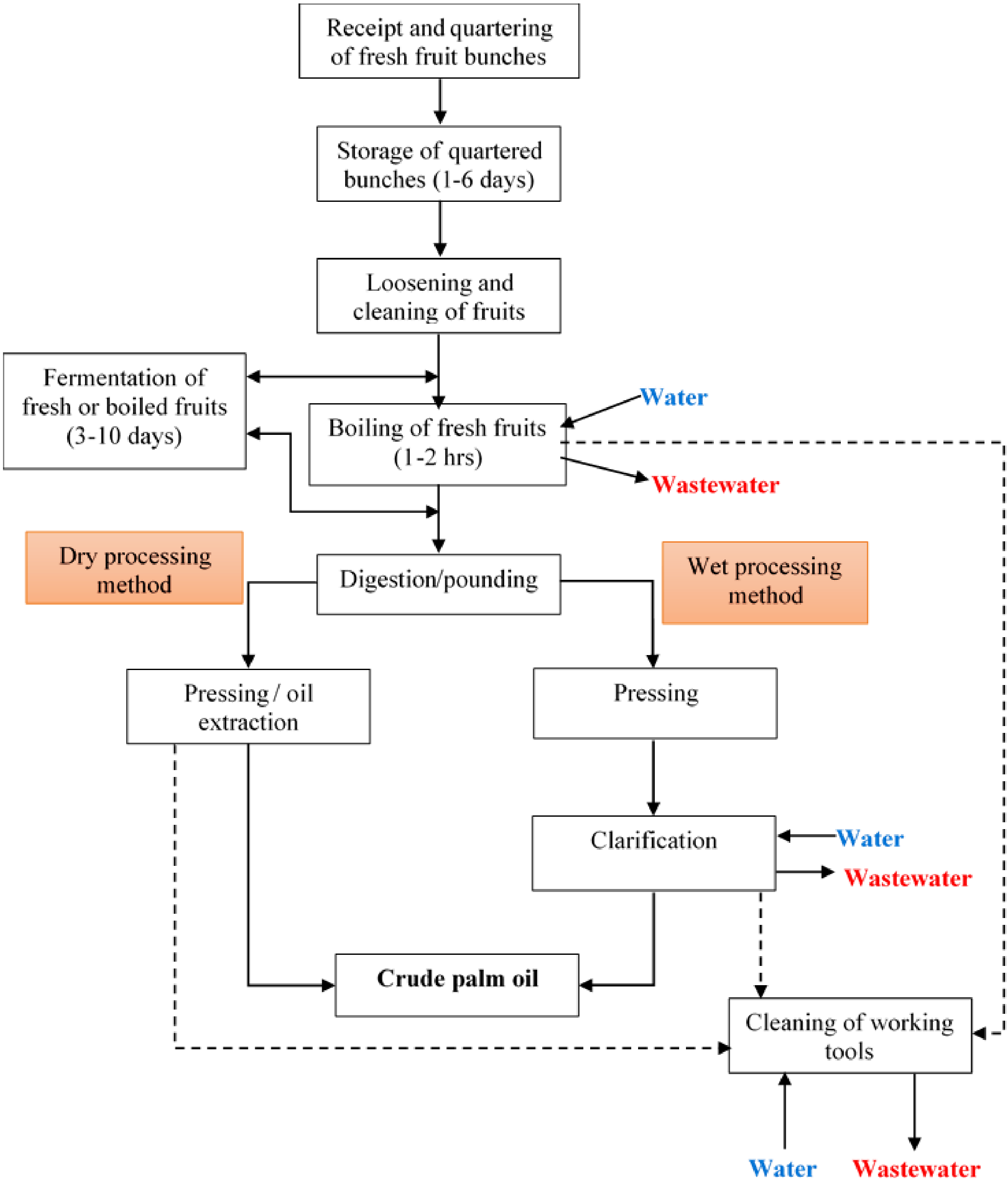


Figure 3-2. Process flow chart for small-scale palm oil extraction

The unit processes which required fresh water were boiling of fresh fruits, extraction of oil (optional), and cleaning of working tools. Similarly, the unit processes which produced wastewater were boiling of fresh fruits, clarification of oil (optional), and cleaning of working tools. Storage as a unit operation, among other functions, reduces the moisture content of the fruits (Osei-Amponsah et al., 2012). Among the small-scale processing mills assessed, there were disparities in the level and stage of fruit storage. Fresh fruit bunches were stored for 2-6 days and boiled fruits for 1-3 days. The pericarp of palm fruits contains about 25% moisture (Prasertsan and Prasertsan, 1996). In the dry extraction method, processers reduced the moisture content of the boiled fruits by drying for 3-10 days before digestion. The length of storage of fruits whether fresh or boiled greatly influences the moisture content of the fruits and ultimately the quantity of water used, and wastewater produced. The wet method potentially requires more water for processing and generates higher wastewater quantities compared to the dry method.

3.4.2 Sources, location, and cost of water

3.4.2.1 Sources of water

The sources of water were rivers/streams, hand-dug wells, mechanized boreholes and treated piped water from public standpipes. The proportion of mills using water from each of the sources is shown in Table 3-1.

Table 3-1. Sources of water for small-scale palm oil processing in central region, Ghana

Water Source	**Frequency (N)**	**Percentage (%)**	**Remark**
Treated piped water	5	20	*80% from Basic service level**
Borehole with handpump	4	16	
Hand-dug well (Protected)	11	44	
Hand-dug well (Unprotected)	3	12	
River/stream	2	8	
Total	25	100	

*Based on WHO/UNICEF definition under SDG 6.1

The 2010 Ghana Population and Housing Census (PHC) puts the proportion of the population using the various sources of water in the four (4) MMDAs at 15.2-32.9% (public standpipes/taps), 0.5-44% (boreholes/pump/tube wells), 0.3-5.9% (protected wells), 0-1.7% (unprotected wells) and 0.1-15.6% (rivers/streams) (GSS, 2013). These results of the water sources used by the processing mills largely reflect the sources of drinking water available to inhabitants in the study area. The proportion of the various water sources for palm oil processing are consistent with the 2010 PHC results. Most small-scale palm oil processing mills are sited in villages and small towns where piped water supply may not be available. In villages, boreholes fitted with handpumps and hand-dug wells (protected and unprotected) serve as the source of water to the inhabitants (Armah, 2014). Water from boreholes fitted with handpumps were available to users at a fee, mostly charged per bucket of water. However, to eliminate the need to always pay for water or travel longer distances to access water for their operations, most people (including small-scale and cottage industries) construct hand-dug wells at their premises. This accounted for the high dependence on hand dug wells (56%) by the small-scale palm oil processing mills. The masterplan study on the oil palm industry in Ghana (MASDAR, 2011) observed similar sources of water usage by small-scale palm oil processing mills. Moreover, the Ghana Multiple Indicator Cluster Survey (MICS) 2017/2018 reported the proportion of the population in the Central Region using basic drinking water services as 88.4% as against a national coverage of 79.4% (GSS, 2018). Eighty percent (80%) of the water sources used by processers in this study area were from Basic Service level as per the WHO/UNICEF definition under the SDGs 6.1 (WHO/UNICEF, 2017). This is a positive sign as the use of unimproved water sources has been associated with causes and transmission of water-related diseases (Fewtrell and Bartram, 2001, Hunter, 1997).

3.4.2.2 Location of water sources

The results of water consumption by distance to water source and cost of water for the small-scale palm oil processing mills are summarised in Table 3-2. Majority of the processing mills (48%) had their water sources on their premises. The mean water consumption increased when the source was nearer as reported by WEDC (2017). Processing mills that obtained their water from the remotest water source of 100 - 200m consumed less water.

Table 3-2. Water consumption by distance to water source and cost of water for small-scale palm oil processing in Central Region, Ghana

Typologies	**N**	**Water consumption (litres per litre of oil produced)**	
		Mean (SD)	**F-statistic (*p*-value)**
Distance to water source from mill			
On premises	12	1.887 (0.352)	F=13.705 (*p=0.000*)**
Less than 100m	8	1.678 (0.285)	
100-200m	5	1.041 (0.162)	
Total	25		
Price of Water (in USD/18-litre bucket)			
Not paying	16	1.731 (0.453)	F=4.945 (*p=0.017*)*
0.032	4	1.112 (0.047)	
0.052	5	1.825 (0.131)	
Total	25		

SD – standard deviation, USD – United States Dollar,N – number in sample, 1USD = GH¢ 5.77

* Significant at 2% level

** Significant at 1% level

The distance to the water source significantly influenced the water consumption. The differences in the mean water consumption among the various distances were statistically significant at 1% level. On-plot water sources encouraged greater quantity of water usage as also reported by Overbo et al. (2016).

3.4.2.3 Price of water

Majority of the mills (16 mills out of 25) did not pay for water due to their dependence on hand-dug wells mostly owned by the processing mills (see Table 3-2). For those mills which paid for water, the price of water ranged between 0.032USD and 0.052USD per 18-litre bucket. The price of 0.052 USD was paid for water obtained from treated piped water sources while the 0.032 USD was for water obtained from boreholes with hand pumps. The price of water influenced the mean water consumption, but the pattern was not consistent. Surprisingly, the processing mills that paid more for water (0.052USD/18-litre) rather consumed higher quantity of water than those that did not pay for water. However, the differences in the mean water consumption among the various price categories were significant at 2% level. A Post-hoc test revealed statistically insignificant differences in the mean consumption between those not paying and those paying the 0.052USD/18-litre. In obtaining water from boreholes with hand pumps and hand-dug wells, greater human effort is needed as compared to piped water sources and this may have encouraged water-use efficiency. The price of water paid by small-scale processing mills in the study area was the same as the price paid by householders who fetched water for domestic use. This price range is within the price of 18-litre bucket of domestic water reported across small towns in Ghana (Kumasi, 2018). But the price of water paid by the mills are about 20 times lower than the price of urban and peri-urban domestic water (1.02 USD for 18 litres) charged by the Ghana Water Company Limited (PURC, 2020). For industrial use, the price of water should be relatively higher than for domestic use to reduce competition and encourage water-use efficiency and recycling by the industries.

3.4.3 Water usage and wastewater production

The results of the water usage and wastewater production for small-scale palm oil processing is summarised in Table 3-3. The results are presented as quantity (in litres) of water used or wastewater produced per litre of crude palm oil produced.

Table 3-3. Water-use and wastewater production by small scale processing mills (N=25)

Characteristic	**Mean (SD)**	**Minimum**	**Maximum**	**p-value (Shapiro-Wilk)**
Water used per litre of oil produced	1.651 (0.437)	0.760	2.391	*0.501*
Wastewater generation per litre of oil produced	1.261 (0.353)	0.568	1.888	*0.591*
Wastewater return factor[a] (%)	76.1 (3.0)	67.8	81.6	*0.464*

SD – standard deviation [a]Wastewater generation as a fraction of water used

The test for normality using Shapiro-Wilk test at 5% significance level showed that all the data were normally distributed. Water usage and wastewater production characteristics for the two processing methods (i.e. dry and wet) are presented in Table 3-4.

Table 3-4. Water usage and wastewater production characteristics for different processing methods by small scale processing mills in Central Region, Ghana

Characteristics	**Mean (SD)**		**Differences in processing methods**[b]	
	Dry method (N=6)	**Wet method (N=19)**	**Percentage**	**P-value**
Quantity of water used per litre of oil produced	1.629 (0.643)	1.658 (0.373)	*2*	*0.919*
Wastewater generation per litre of oil produced	1.224 (0.501)	1.273 (0.309)	*4*	*0.831*
Wastewater return factor[a] (%)	74.7 (3.6)	76.5 (2.7)	*2*	*0.304*

SD – standard deviation [a]Wastewater generation as a fraction of water used

3.4.3.1 Water usage

The study revealed that small-scale palm oil mills consume 0.76 – 2.39 litres (mean=1.65L, SD=0.437) of water in extracting one litre of crude palm oil (Table 3-3). Using crude palm oil density of 879 kg/m^3 (determined at the laboratory), the quantity of water used by small-scale processers in the study area translates into 0.86 – 2.72 tonnes (mean=1.88) for a tonne of crude palm oil produced. A similar small-scale/cottage industry in Ghana is the shear butter production industry. It is estimated that to process one tonne of shear butter in the Northern and Upper West Region of Ghana, 4.8-5.9 tonnes of water is required (Jasaw et al., 2015). In Malaysia, Ahmad et al. (2003) reported water consumption of 5.0 – 7.5 tonnes for a tonne of crude palm oil extracted. The water consumptions figures recorded in this study are lower than water consumption for shear butter processing in Ghana and palm oil production in Malaysia. The range of water consumption reported for Malaysia are 2.8-5.8-folds higher than what was recorded in this study. The wide differences could be attributed to the different processing technologies employed. As previous mentioned, small-scale mills use manual methods with few mechanized unit processes as opposed to large scale mills which predominantly employ fully mechanized methods of palm fruits processing.

In estimating water demand for small towns in Ghana, the CWSA’s design guidelines specify a per capita water consumption of 20 litres/capita/day for standpipes (CWSA, 2010a). The water consumption per litre of oil extracted by the small-scale mills is about 3.8-12% of the daily per capita water consumption from public standpipes in small towns and rural areas in Ghana. An average daily water demand by the small-scale mills of 624.64 litres is equivalent to the domestic water demand of thirty-one (31) people in small towns and rural areas of Ghana (Appendix B). The relatively high water usage by small-scale palm oil processing mills necessitates the need to factor this informal cottage industry in the design of rural and small towns water supply systems.

To better appreciate the differences in water consumption reported in this study and that of literature, it is important to analyse the contribution of different unit processes to the total water consumption (shown in Figure 3-3).

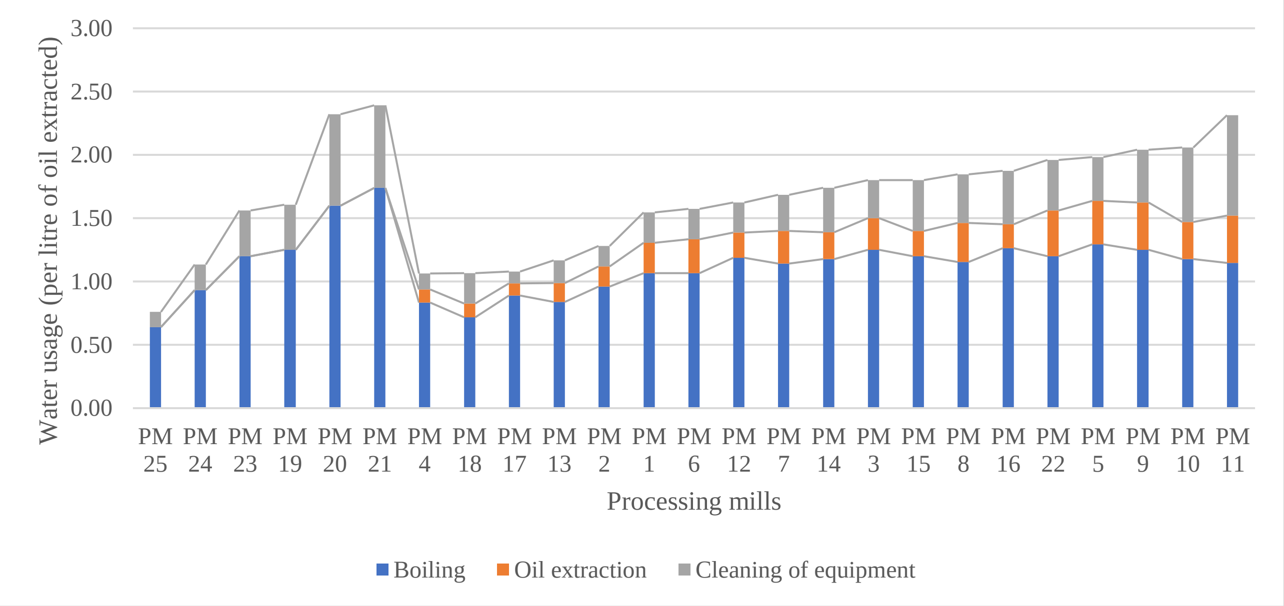


Figure 3-3. The proportion of water used for various operations

The unit operation demanding the highest quantity of water was boiling (50-84%; mean=70%; SD=8%) followed by cleaning of working tools (9-34%; mean=20%; SD=6%) and finally oil extraction (0-18%; mean=11%; SD=7%) (Figure 3-3). Less quantity of water was required for oil extraction at the small-scale mills because most mills eliminate clarification to reduce operational costs (Osei-Amponsah et al., 2012). The wide variation (50-80%) in the quantity of water from boiling could be as a result of the absence of a standard mode of measuring water at the small-scale mills. There were no laid down criteria for measuring the volume of water for the different unit processes. Different processers use water quantities based on the quantity of fruits to be processed and experience of the processer. Moreover, the manual and tedious nature of the clarification process by the small-scale mills may have contributed to its limited use and consequently less amount of water usage as opposed to the large-scale industries. Considering that an average of 70% of the total water consumption was for boiling, a shift from the current method of boiling by submerging the fruits in water as also observed in Kwaebibirim District of Ghana by Osei-Amponsah et al. (2012) to steam sterilization practiced by the large scale industries (Mba et al., 2015) could significantly reduce the amount of water used for this operation.

3.4.4 Wastewater generation

For each litre of crude palm oil produced, 0.57 – 1.89 (mean=1.26, SD=0.353) litres of wastewater is generated by the small-scale mills in the study area as shown in Table 3-3. The densities of the crude palm oil and wastewater were determined in the laboratory to be 879 kg/m^3 and 1,036 kg/m^3 respectively. Using the measured densities, the quantity of wastewater generated by the small-scale processing activities were 0.67 – 2.23 tonnes (mean=1.49) for a tonne of crude palm oil produced.

However, literature reports that for each tonne of crude palm oil extracted, 2.5 - 3.8 tonnes of wastewater is generated (Ahmad et al., 2003, Ho et al., 1984, O-Thong et al., 2012). The wastewater production quantities by the small-scale mills in this study are about 27-59% of the wastewater production quantities reported in literature for large-scale mills. This may be attributed to the lesser number of unit processes that generate wastewater at the small-scale mills. Wastewater from small-scale mills was generated mostly from boiling of fresh fruits, cleaning of working tools and, in some cases, during clarification. At the large-scale mills, the greatest proportion of wastewater originates from clarification condensate (Department of Environment, 1999, Prasertsan and Prasertsan, 1996, Nasution et al., 2018a). In the small-scale mills, fresh fruits were boiled for up to 4 hours in metal tanks and covered with jute sacks as has also been reported by Osei-Amponsah et al. (2012) with much of the vapour evaporating into the air. This consequently reduces the wastewater generation. More so, storage of fresh fruits and drying of boiled fruits reduced the moisture content and consequently the wastewater generation rate. The relatively low wastewater quantities produced by the small-scale mills as compared to the large-scale mills reveals the possibility to adopt small-scale treatment systems tailored to suit individual processing mills. But, the average daily wastewater generation rate by the small-scale mills (474.27 litres) is equivalent to the domestic wastewater production of thirty (30) people in small towns and rural areas of Ghana (see Appendix B).

In terms of contribution from individual unit processes, Figure 3-4 shows the proportion of wastewater generated from different unit processes.

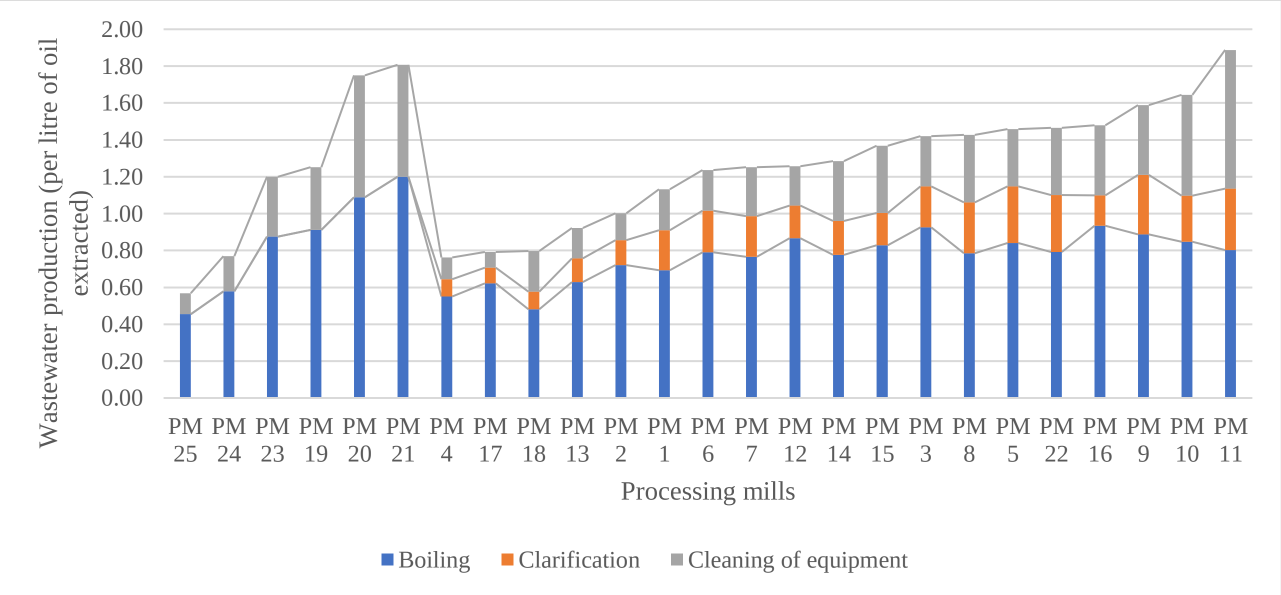


Figure 3-4. Proportion of wastewater from various unit processes

The unit processes generating the highest quantity of wastewater was boiling (42-80%; mean=64%; SD=9%) followed by cleaning of working tools and equipment (11-40%; mean=24%; 7%) and clarification (0-21%; mean=12%; SD=8%). In terms of unit processes and percentage proportions, the average results obtained in this study differ from those obtained in Malaysia, Indonesia and Thailand. In Malaysia (Department of Environment, 1999) and Indonesia (Nasution et al., 2018b) the wastewater generation for different unit processes are in the order: clarification (60%), sterilization (36%) and hydrocyclone (4%). But in Thailand, the proportion for clarification was relatively higher (clarification-75%, sterilization-17%, hydrocyclone-8%) (Prasertsan and Prasertsan, 1996). The differences in our results (small-scale mills) and that obtained from literature could be due to the differences in the level of technology used. At the large-scale mills fresh fruit bunches are sterilized before stripping (Hassan et al., 2004), allowing the empty fruit bunches to absorb and retain some of the wastewater as opposed to stripping before boiling practiced by the small-scale mills. The high amount of wastewater from boiling at the small-scale mills as against clarification condensate at the large-scale mills could lead to differences in the characteristics of the wastewater (POME) produced by these industries. Knowing the wastewater quantities and the characteristics from different unit processes will enable the selection of appropriate treatment technologies for different wastewater streams. For example, wastewater from boilers could be treated for reuse while wastewater from clarification tanks could be targeted for biogas production because of the high organic solid residues as suggested by Hassan et al. (2004).

3.4.4.1 Wastewater return factor

The wastewater return factors for the 25 small-scale palm oil processing mills is presented in Figure 3-5. In the Ghanaian small-scale mills, 68-82% (mean=76%, SD=3%) of the water used returns as wastewater.

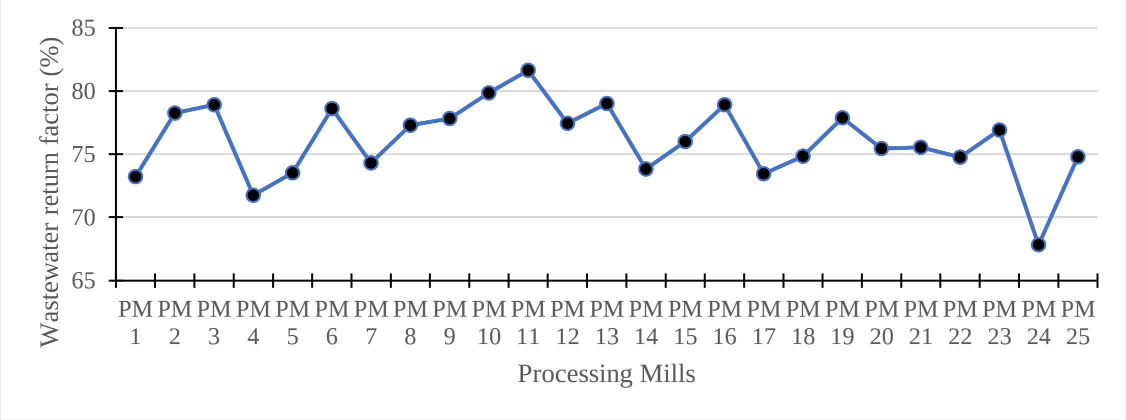


Figure 3-5. Wastewater return factors for the small-scale palm oil processing mills

In Malaysia, Ahmad et al. (2003) reports that more than 50% of water used in the extraction process returns as wastewater. Assessment of the wet process in Thailand revealed that 50-79% of the water used in palm oil extraction returns as wastewater (Chavalparit et al., 2006). Similarly, 72-75% of water used by small-scale mills returns as wastewater in Nigeria (Ohimain and Izah, 2013). It could be observed that the wastewater return factors obtained in this study (for 23 mills) are generally comparable to those reported by the other researchers. But, two (2) of the mills (PM 10 & 11) recorded return factors higher (80-82%) than those generally reported in literature. However, the results for the two processing mills are within the range of wastewater return factors of 80-90% reported for domestic sources (Mara, 2013). In the palm oil extraction industry, the wastewater return factor is based on characteristics of the processing method (small-scale, medium scale or high scale), and the extraction system employed. The potentially high organic loads of palm oil mill effluent (Lam and Lee, 2011) brings to the fore, the need to explore environmentally friendly and appropriate technologies for wastewater treatment and reuse in the palm oil industry. It is therefore necessary to assess the quality of wastewater produced by the small-scale mills.

3.4.5 Variation of water usage and wastewater production with processing method

The amount of water used differed with the processing technique employed. The mean water usage, wastewater production and wastewater return factor were higher for the wet processing method than the dry method (refer to Table 3-4) as observed by Poku (2002). In the dry method, no water was required for clarification. However, the differences in the mean water consumption and wastewater production by the dry and wet methods were not greater than 4%. The wastewater return factor for the dry method (mean=74.7, SD=3.6) and wet method (mean=76.5, SD=2.7) are within the range of values reported in literature (Chavalparit et al., 2006, Ohimain and Izah, 2013). The results from ANOVA test (α=0.05) reveals that the differences in the mean characteristics between the dry and wet methods are not statistically significant (p=0.143-0.839). Even though literature (Poku, 2002) reports higher water usage and wastewater production by the processing mills using the wet method, the findings from this study do not support such reports. In this study, the water usage and wastewater production characteristics are relative to the volume of crude palm oil produced but the report by Poku (2002) was based on the actual quantity of water used and wastewater generated irrespective of the quantity of oil obtained.

The major water-consuming and wastewater-producing unit process of boiling is common to both processing methods. The unit operation which distinguishes the dry method from the wet is clarification (refer to Figure 3-2). But, the contribution of oil extraction to the mean water consumption and clarification to wastewater production were 11% (SD=7%) (Figure 3-3) and 12% (SD=8%) (Figure 3-4) respectively. This explains why the water consumption and wastewater production between the two processing methods were not different. It may be inferred from the results that regardless of the processing method employed at the small-scale industry in Ghana, the quantities of water used and wastewater generated are significant from a developing country context. The statistically similar water usage and wastewater production quantities for wet and dry processing methods implies that similar capacities of wastewater treatment technology could be selected for the small-scale processing mills employing either wet or dry methods.

3.4.6 Wastewater Disposal Practices and their Potential Problems

None of the twenty-five (25) small-scale processing mills had a wastewater treatment system in place. Untreated wastewater generated from the extraction processes were discharged on the land or through drains to nearby bushes (Figure 3-6). The findings from this study confirms a report that small-scale palm oil processers in Ghana do not adhere to any environmental protection practices (MASDAR, 2011, Poku, 2002). This study has revealed that for each litre of oil extracted, an average of 1.65 litres of water is used of which about 76% returns as wastewater. Therefore, large quantities of untreated wastewater is currently discharged into the environment.

Figure 3-6. Pictures showing wastewater disposal practices (Photo credit: Authors)

Similar environmentally unfriendly wastewater disposal practices by small scale mills have been reported in Nigeria (Okwute and Isu, 2007). Contrary to other observations (Osei-Amponsah et al., 2012), none of the mills assessed in this study disposed their wastewater directly into streams or rivers. The current wastewater disposal practices are exacerbated by the limited enforcement of environmental regulations on informal small-scale industries. Raw palm oil mill wastewater contains high organic matter content (10.25-43.75 g/L BOD_3 and 15,000-100 g/L COD) and solids contents (11.5-79 g/L total solids; 5-54 g/L suspended solids, and 9-72 g/L total volatile solids) (Lam and Lee, 2011). Disposal of wastewater on land could be washed into surface water bodies by runoff. When washed into water bodies, the high organic content of the wastewater could deplete the oxygen content of the receiving water bodies (Ahmad et al., 2003, Khalid and Mustafa, 1992) and affect the life of their aquatic organisms (Saari et al., 2018). Excessive fats and oils may form scam (Bi et al., 2015) on the surface of waterbodies further depriving the water body of dissolved oxygen.

Disposal of the untreated wastewater has detrimental effects on the receiving land and vegetation (Singh et al., 2011). In most of the mills assessed in this study, the areas where wastewater is disposed have lost their vegetation (see Figure 3-6). This confirms observations in Africa by Poku (2002) that the bushes at the small-scale mill wastewater disposal areas die slowly. Moreover, the untreated wastewater pollutes the air through odour production as reported by (Ahmad and Ghufran, 2019) and Loh et al. (2013). Aside the odour, the degradation of the wastewater could generate biogas with over 60% methane content (Loh et al., 2013, Tan and Lim, 2019). Anaerobic digestion of $1m^3$ of POME has been reported as generating $28m^3$ of biogas with 65% methane content (Quah and Gillies, 1983). Based on these data, extraction of 1 litre of crude palm oil by the small-scale industry in Ghana produces wastewater capable of generating 10.4-34.4 litres of methane gas which are released into the environment. Methane gas is considered one of the potent green house gases and contributes 25 times to global warming compared to CO_2 (Loh et al., 2017). The current wastewater disposal practices employed by the small-scale mills could be adversely affecting the environment and this calls for urgent attention.

3.5 Conclusions

This study was aimed at assessing the water usage and wastewater return factors by small-scale palm oil processing mills in Central Region of Ghana. Water for processing was sourced from protected hand dug wells, piped water from public standpipes, boreholes with handpumps, unprotected hand-dug wells and rivers/streams. The proportion of water sources used by the mills reflect the water sources available to the inhabitants in the study communities. Eighty percent (80%) of the water sources were from Basic Service level. The price of water ranged between 0.023 – 0.052USD for an 18-litre bucket. The distance to the water source influenced the water consumption with higher consumption for on-plot water sources. But not paying for water did not influence water consumption. For a litre of crude palm oil produced, 0.76-2.39 litres of water were used generating 0.57-1.89 litres of POME. In terms of wastewater return factors, 68-82% of the water used in the extraction industry returned as wastewater. Boiling of fresh fruit as a unit operation consumed the greatest quantity of water (42-80%) and generated the highest quantity of wastewater (40-80%). The processing method (dry or wet) did not influence the water consumption and wastewater production. Wastewater produced by the processing activities were discharged on the bare land without treatment. Therefore, the small-scale palm oil processing mills do not comply with environmental regulations and wastewater discharge standards. Whiles Government of Ghana is seeking to increase palm oil production, greater quantities of water for processing will be required and consequently generating higher quantities of wastewater. Particular attention should be paid to the small-scale processing mills which dominates the palm oil production sector. There is an urgent need to develop a national policy to formalize and regulate the activities of the small-scale palm oil processers. Research must be directed towards finding appropriate wastewater treatment technologies for use by the small-scale industry. Enforcement of environmental regulations should be extended to the small-scale (cottage) industries to ensure compliance.

4 CHAPTER FOUR

SEASONAL AND SOURCE CHARACTERIZATION OF PALM OIL MILL WASTEWATER FROM INFORMAL SMALL-SCALE PROCESSING MILLS IN GHANA

(Part of this chapter is published by Springer as a Book Chapter: Awere, E. Bonoli, A. and Obeng, PA. (2021). Qualitative Assessment of palm oil mill wastewater from small-scale processing mills in Ghana. In: J. N. Mojekwu et al. (Eds.): Sustainable Education and Development, Springer Nature, pp. 1-11. Doi: 10.1007/978-3-030-68836-3_29)

4.1 Abstract

Palm oil production in Ghana is dominated by informal small-scale mills that produce about 80% of the national production. These mills have been criticised for failing to adhere to environmental regulations. However, the extent of potential environmental damage caused by the disposal of wastewater by the small-scale mills is unknown. This research was aimed at determining the seasonal and source characteristics of palm oil mill wastewater produced by small-scale mills in Ghana to inform the selection of appropriate management technologies for optimum resource recovery. Four processing mills were selected from Abura Aseibu Kwamankese District of Ghana. Wastewater samples were collected from each of the four processing mills in August 2019 (lean production season) and March 2020 (peak production season). Samples were collected in opaque plastic containers and stored under 4°C. All analysis was performed following standard analytical methods. Parameters measured were pH (3.7-4.7), total solids (2034-5327 mg/l), TSS (1355-5106 mg/l), TDS (211-1575 mg/l), BOD_5 (16172-31194 mg/l), COD (50391-65673 mg/l), total nitrogen (160-473 mg/l), phosphorus (21-90 mg/l), potassium (126-224 mg/l) and oil & grease (266-1186 mg/l). The mean concentrations of 6 out of the 7 parameters were over 2-orders of magnitude higher than the Ghana effluent discharge standards. Characteristics of wastewater produced during the peak season were generally higher than the lean season except for pH and solids (total and suspended). The differences were significant for pH, TDS, total nitrogen, and potassium but statistically insignificant for total solids, TSS, BOD_5, COD, phosphorus and oil & grease. For both production seasons, the pH, TDS BOD_5 and COD of the wastewater after boiling were higher than

after clarification. The current practice of disposing raw wastewater into the natural environment by the small-scale processing mills could be negatively affecting the environment.

Keywords: Characterisation, Ghana, palm oil mill wastewater, small-scale palm oil processing

4.2 Introduction

The palm oil processing industry of Ghana is dominated by informal small-scale mills which account for about 80% of the national palm oil production (Angelucci, 2013, Osei-Amponsah et al., 2012). Available data indicates that there are more than 400 small-scale palm oil processing units in Ghana (Fold and Whitfield, 2012) most of which are sited in small towns and rural communities. The small-scale processing mills have weak milling capacity (Uckert et al., 2015, Fold and Whitfield, 2012) and thus are able to process only up to 2 tonnes of fresh fruit bunches per hour (Poku, 2002, MASDAR, 2011). This is partly due to the extensive use of manual processes. As observed during the field survey and also reported by other researchers (Adjei-Nsiah et al., 2012, Osei-Amponsah et al., 2012), the only mechanized processes at the small-scale mills are digestion of boiled fruits and pressing of digested fruits to extract the oil. Unlike the large-scale mills that use technologically up-to-date processes and machinery, the small-scale mills employ low-efficiency stand-alone machines (Poku, 2002, MASDAR, 2011) for fruit digestion and pressing.

Irrespective of the level of mechanization of the techniques employed, processing fresh palm fruits into crude palm oil requires high quantities of fresh water (Hassan et al., 2004) and produces significant quantities of wastewater (Chavalparit et al., 2006). In Malaysia for example, an estimated 5.0 – 7.5 tonnes of water is consumed to produce one tonne of crude palm oil, out of which 50% returns as wastewater (Ahmad et al., 2003). However, findings from field measurements at twenty-five (25) small-scale processing mills (Chapter 3 of this thesis) showed comparatively lower quantities of water usage and wastewater production. In processing one tonne of crude palm oil, 0.86-2.72 tonnes of water was consumed but resulted in a relatively higher wastewater return factor of 68-82%. At the large scale mills in Southeast Asia, the palm oil mill wastewater originates from sterilization (17-36%), clarification (60-75%) and hydrocyclone (4-8%) (Nasution et al., 2018a, Prasertsan and Prasertsan, 1996, Department of Environment, 1999).

But at the small-scale mills in the study area, the proportions of wastewater from different processes were 42-80% for boiling, 21% for clarification and 11-40% for cleaning.

Many studies have characterized palm oil mill wastewater produced mostly in Southeast Asia (Malaysia, Indonesia and Thailand) where palm oil processing is undertaken by at large-scale industry. Review of related literature showed disparities in the results of characterisation of palm oil mill wastewater. For instance, raw palm oil mill wastewater is reported to contain high organic matter content (10.25-43.75 g/L BOD_3 and 15-100 g/L COD) and solids contents (11.5-79 g/L total solids; 5-54 g/L suspended solids, and 9-72 g/L total volatile solids) (Lam and Lee, 2011). In terms of percentage proportions, palm oil mill wastewater is a colloidal suspension with 95-96% water, 0.6-0.7% oil and 2-4% suspended solids (Ma, 1999). Palm oil mill wastewater is composed also of high organic substances (Wang et al., 2015), making them suitable substrate for biological treatment.

The quality of palm oil mill wastewater is reported to differ based on the processing techniques, processed batches or days, quality of the palm fruits, type of fruits (Ng et al., 1987), quality control of individual mills (Yusof and Ariffin, 1996), climate, condition of the palm oil processing (Liew et al., 2015), and cropping season of the oil palm (Wu et al., 2010). Hence, the differences in wastewater production quantities, proportions of wastewater from different processing operations and technological differences in processing techniques between the large and small scale could lead to variations in the characteristics of the wastewater produced.

The small-scale palm oil processing mills in Ghana have been noted for their non-compliance with environmental regulations (Poku, 2002, MASDAR, 2011). Besides, raw palm oil mill wastewater is reported to be discharged into the environment without treatment. However, to the best of the author (s) knowledge, no study has been conducted in Ghana to assess the quality of palm oil mill wastewater produced at the small-scale level. Consequently, there has not been any scientific evaluation of the potential environmental damage caused by the operations of the small-scale processing mills. As a result, there is inadequate knowledge to inform the selection of ‘appropriate’ treatment technologies to derive beneficial materials and energy (methane gas, manure/compost, biofuel) and ensure compliance with environmental regulations. This study was aimed at assessing the characteristics of palm oil mill wastewater produced by small-scale palm oil processing mills in Ghana to address the knowledge gap highlighted above.

4.3 Materials and Methods

4.3.1 Study Context

The study was conducted in the Central Region, which is one of the sixteen (16) first-level government administrative units of Ghana. The current population of the region is estimated at 2,563,228 inhabitants (Citypopulation, 2019) with a population density of 260 inhabitants/km^2. The region is subdivided into twenty-two second-level administrative units classified as metropolitan, municipal or district assemblies. Based on the climate, the region is divided into three agro-ecological zones namely coastal savanna, transitional and forest zones (MOFA, 2020). The average temperature ranges between 24^{o}C and 34^{o}C with a relative humidity of 50% to 85%. The region is characterized by bi-modal rainfall pattern with major and minor rainy seasons of March-July and September-November respectively (FAO, 2005). In terms of palm fruit production, the peak and lean seasons are respectively February-June and July-January (Osei-Amponsah et al., 2012). The average annual rainfall ranges from 800mm in the Coastal Savanna to 1,500mm in the forest zone. The main economic activities are agriculture, with 80% of the region's total land area considered as cultivable (MOFA, 2020). The major tree crops cultivated in the region are cocoa, oil palm, citrus and coconut. The region's land area for oil palm cultivation accounts for 16% of the total national area for oil production (MASDAR, 2011).

4.3.2 Sampling and Sample Sources

Four (4) small-scale palm oil processing mills employing wet oil extraction method were selected from Abura Aseibu Kwamankese District, Ghana. The processing mills were part of twenty-five (25) small-scale processing mills selected for assessing their water consumption and wastewater return factors in Chapter 3 of this thesis. The choice of processing mills using wet extraction method was based on their popularity in the study area as observed during field visits in February to August 2019. Samples were taken from each of the processing mills in the peak palm oil production season (March 2020) and lean production season (August 2019). For each of the processing mills and production seasons, samples were collected separately from boiling and clarification tanks. Samples were collected in opaque plastic containers and labelled appropriately before transport.

4.3.3 Sample Preservation

The initial wastewater temperatures of 80 – 85°C were cooled to reach room temperature before transporting to the Environmental Quality Engineering laboratory of the Cape Coast Technical University, Ghana for analysis. During transportation to the laboratory, the samples were protected from light to ensure that the bioactivity of the samples was not altered. At the laboratory, samples were stored under 4°C in a refrigerator to inhibit microbial activities (Choo et al., 2015) before use in the experiment. Prior to characterization, wastewater samples were kept out of the refrigerator and allowed to reach room temperature.

4.3.4 Analytical Methods

Parameters measured were pH, total solids (TS), total suspended solids (TSS), total dissolved solids (TDS), chemical oxygen demand (COD), biochemical oxygen demand (BOD_5), total nitrogen, phosphorus, potassium and oil and grease. pH was measured using portable pH-meters XS Series. Total, suspended and dissolved solids were determined using the gravimetric method. Fats and oils were determined using the Soxhlet extraction method. All the remaining parameters were analyzed using Hanna multiparameter photometer (HI83399) and associated reagents. All reagents used were of Analytical Grade. Analyses were carried out according to Standard Analytical Methods prescribed by Standard Methods for Examination of Water and Wastewater (APHA et al., 2017). All analyses were performed in triplicates and the mean value taken.

4.3.5 Statistical Analysis

Statistical analysis was performed using Microsoft Excel. A test for normality was performed using Shapiro-Wilk test with significance level of 95%. The mean and standard deviation were recorded for all the data. An unpaired sample *t*-test ($\alpha=0.05$) was used to test for differences in the parameter between the major and lean seasons. The results were compared to the Ghana Effluent Discharge Standards (GEDS) set by the Ghana Standard Authority (GSA) (GSA, 2019). The GEDS for oil and fat processing industry is presented in Table 1-3.

4.4 Results and Discussions

4.4.1 Characteristics of Palm Oil Mill Wastewater

The mean characteristics of wastewater from small-scale palm oil processing in mills in Ghana's Central Region is summarized in Table 4-1. The wastewater contained solids, oxygen-consuming compounds, nutrients (nitrogen, phosphorus and potassium) and oil and grease. For most of the parameters measured, there were wide disparities in the results as shown by the range of values reported. The results of the pH showed that the wastewater is acidic. Over two-thirds of the solids content were suspended. Around 13-22% of the total solids and 20-23% of suspended solids were in the form of oil and grease. The COD:BOD$_5$ was 2.1-3.1 (mean= 2.5).

Table 4-1. Characteristics of palm oil mill wastewater from small-scale mills and literature

Parameter (unit)	**Mean (SD)**	**Range**	**Department of Environment (1999)**	**Wood et al. (1979)**	**Najafpour et al. (2006)**	**Ghana effluent discharge standard**
	This study					
pH	4.41 (0.29)	3.78-4.74	3.4-5.2		3.8-4.4	6-9
TS (mg/l)	3698 (1372)	2034-5327	11500-79000	29600-55400	-	-
TDS (mg/l)	732 (498)	211-1575		15500-59000	-	1000
TSS (mg/l)	2965 (1418)	1355-5106	5000-54000	14100-26400	16500-19500	50
BOD$_5$ (mg/l)	22840 (4247)	16172-31194	10000-44000*	17000-26700	23000-26000	50
COD (mg/l)	57652 (4558)	50391-65673	16000-100000	42900-88250	42500-55700	250
Total Nitrogen (mg/l)	312 (94)	160-473	180-1400	500-800	500-700	-
Phosphorus (mg/l)	54 (20)	21-90	180	94-131	-	2
Potassium (mg/l)	172 (30)	126-224	2270	1281-1928	-	-
Oil and grease (mg/l)	577 (303)	266-1186	150-1800	4400-8000	4900-5700	10

*BOD$_3$ at 30°C TS-total solids; TDS-total dissolved solids; TSS-total suspended solids

Wastewater with COD:BOD ≥2.5 is characterized as slowly biodegradable organic matter (Henze et al., 2008). The COD:BOD_5 from this study is an indication of the presence of slowly biodegradable organic matter largely attributed to the unrecovered fats and oils in the wastewater as noted by Cisterna-Osorio and Arancibia-Avila (2019). It has been reported that, slowly biodegradable COD constitute 45% of the total COD of raw palm oil mill wastewater with only about 20% being readily biodegradable (Salmiati et al., 2010). The readily biodegradable COD of palm oil mill wastewater is due to the availability of free fatty acids (Salmiati et al., 2010). Low pH of wastewater from palm oil processing is also due to the organic acids formed during fermentation of the palm fruits (Rupani et al., 2010). As observed through in the field, small-scale processing mills store the fresh fruit bunches for 2-6 days for the fruits to undergo fermentation. The storage of fresh palm fruits to allow fermentation at the small-scale mills could increase the readily biodegradable COD fraction of wastewater since fermentation of palm fruits has been attributed to high free fatty acid content (Osei-Amponsah et al., 2012). The acidity of palm oil and by extension, the palm oil mill wastewater have been reported to be affected by the extraction procedure, presence of microorganisms and the genotype of the palm tree (Likeng-Li-Ngue et al., 2017). Suspended solids in the wastewater consists of carbohydrates with oil and other organic and inorganic solids (Wood et al., 1979). Most of these constituents of the solids could serve as nutrient sources for microorganisms.

The wastewater characteristics (pH, total nitrogen, oil and grease, BOD_5 and COD) reported in this study are generally within the range of results of raw palm oil mill effluent reported by the Malaysia Palm Oil Board (Department of Environment, 1999). For the oxygen-demanding substances, the results in this study are consistent with literature (Wood et al., 1979, Najafpour et al., 2006). But, the concentration of solids (total and suspended) recorded in this study are lower as compared to the results from other studies (Iskandar et al., 2018, Ma, 1999, Najafpour et al., 2006). All the literature results of palm oil mill effluent characteristics reported in this paper are for large-scale mills which use more efficient oil extraction techniques. At the large-scale mills fresh fruit bunches are sterilized before stripping to, among others, remove external impurities (Hassan et al., 2004), but the small-scale mills strip and clean the fresh fruits before boiling. Empty fruit bunches is reported to contain high proportion of plant nutrients (Baharuddin et al., 2009, Suhaimi and Ong, 2001) which could be leached into the sterilizer wastewater during boiling. Stripping and cleaning fresh fruits before boiling as practiced by the small-scale mills could have contributed to the low solids and minerals (total nitrogen, phosphorus and potassium) content of the wastewater. Similarly, the mean concentration of oil and grease is lower than those reported in literature (see Table 4-1) but the proportion of oil and grease as a percentage of total solids in this study (13-22%) are higher than those reported by other studies (Iskandar et al., 2018). The results of oil and grease obtained in this study confirm the low oil extraction rate of 12-13% reported for small-scale palm oil processers in Ghana (MASDAR, 2011).

Comparing the results with the Ghana Effluent Discharge Standard (GEDS), 85% (6 out of 7) of the parameters had mean concentrations far higher than the standard. The concentrations of most of the parameters were over 2-order of magnitude higher than the standard. Only the mean concentration of TDS (mean=727 mg/l; SD=498 mg/l) was lower than the GEDS of 1000 mg/l. Even that, one-fourth of the samples had TDS concentration greater than the standard. Using a per capita BOD loading of 54 gBOD/day (Von Sperling, 2007) and average daily wastewater production of 474 litres for small-scale palm oil processing mills in Ghana, the population equivalent (PE) for the small-scale industry is about 200 inhabitants. The PE shows that one small-scale palm oil processing mill in Ghana produces wastewater with BOD_5 equal to the average daily BOD_5 produced by 200 people. The results suggest that the current practice of disposing raw wastewater into the natural environment by small-scale processing mills is negatively affecting the environment. In most of the mills assessed in this study, the areas where wastewater is disposed had lost their vegetation. This confirms observations in Africa by Poku (2002) that the bushes at the small-scale mill wastewater disposal areas die slowly. Moreover, the high oxygen-consuming matter in the wastewater, will deplete the oxygen in a receiving water body (Ahmad et al., 2003, Khalid and Mustafa, 1992). The unrecovered fats and oils in the wastewater would form scum (Bi et al., 2015) on the surface of waterbodies, further depriving the water body of dissolved oxygen.

4.4.2 *Variation of Palm Oil Mill Wastewater Characteristics with Season*

The characteristics of the wastewater sampled during the peak and lean production seasons are presented in Table 4-2. The wastewater characteristics varied with production season. The mean characteristics of wastewater produced during the peak season were generally higher than the lean season except for pH and solids (total and suspended). Irrespective of the production season, the wastewater was characterized by slowly biodegradable organic matter ($COD:BOD_5$ = 2.5-2.6).

Table 4-2. Seasonal characteristics of palm oil mill wastewater

Parameter (unit)	**Mean (SD)**		**Seasonal differences[a] (*p*-value)**
	Peak season	**Lean season**	
pH	4.17 (0.23)	4.65 (0.05)	-0.48 (*0.000*)**
TS (mg/l)	3419 (1381)	3976 (1397)	-557 (*0.436*)
TDS (mg/l)	1107 (431)	358 (158)	749 (*0.001*)**
TSS (mg/l)	2313 (962)	3618 (1551)	-1,305 (*0.066*)
BOD_5 (mg/l)	23803 (3766)	21877 (4728)	1926 (*0.384*)
COD (mg/l)	58948 (5370)	56357 (3441)	2591 (*0.273*)
Total nitrogen (mg/l)	377 (40)	246 (86)	131 (*0.003*)**
Phosphorus (mg/l)	60 (16)	49 (24)	11 (*0.325*)
Potassium (mg/l)	188 (28)	156 (24)	32 (*0.026*)*
Oil and grease (mg/l)	628 (389)	527 (198)	101 (*0.527*)

All values are in mg/l except pH

[a] Peak season minus lean season

*Significant at 5% level

**Significant at 1% level

Interactions with mill operators revealed that during the peak season, more processing cycles (3-5 cycles) are completed in a day as a result of abundance of palm fruits. This reduces the processing time per production cycle and affects the efficiency of oil extraction. However, in the lean season, palm fruits are not readily available. This significantly reduces the number of processing cycles (2-3cycles per week) and gives processers enough time for fruit processing with corresponding higher extraction efficiency. Boiling and clarification time for small-scale processing during the lean season are mostly greater than the peak season. A longer clarification time corresponds to greater oil extraction rate, higher evaporation, lower moisture content and higher solids in the wastewater. This reflects the higher concentration of suspended and total solids in wastewater produced during the lean season as compared to the peak season. Also, the concentrations of pH, TDS and total nitrogen were higher in the lean season than the peak season with the differences been significant at 1% level. On the contrary, potassium concentration in the peak season was significantly higher than the lean season at 5% level. The seasonal differences for TS, TSS, BOD_5, COD, Phosphorus and oil & grease were statistically insignificant. The peak and part of the lean production seasons coincide with the rainy season in Ghana. This implies that the wastewater could be washed by surface runoff into surface water channels and transported away from the point of discharge. Therefore, the impacts associated with discharging raw wastewater in the natural environment could have a wider spatial extent. Again, during the rainy season, the concentrations of most contaminants would reduce due to dilution effect from inflow of rain or runoff. In selecting a treatment technology such as open pond system, the potential volume increase and change in concentration should be borne in mind. It could be deduced from the results that similar organic and solid loading rates may be used for designing treatment system to handle wastewater for both the peak and lean seasons.

4.4.3 Characteristics of Different Wastewater Streams

The characteristics of the wastewater from boiling and clarification sampled during the peak and lean production seasons are presented in Table 4-3. The main sources of wastewater from small-scale palm oil processing are boiling and clarification. For both production seasons, the pH, TDS, BOD_5 and COD of the wastewater from boiling were higher than for clarification. For the remaining parameters (TS, TSS, oil & grease, total nitrogen, phosphorus and potassium) the clarification wastewater was higher than the wastewater from boiling. Apart from BOD_5 and COD, the trend of the results are consistent with the characteristics of individual wastewater streams reported in Malaysia (see Table 4-4).

Table 4-3. Characteristics of wastewater from boiling and clarification for peak and lean production seasons

Parameter (unit)	**Peak season**			**Lean season**		
	Mean (SD)		***p-value***	**Mean (SD)**		***p-value***
	Boiling	**Clarification**		**Boiling**	**Clarification**	
pH	4.36 (0.08)	3.98 (0.13)	*0.054*	4.67 (0.05)	4.62 (0.01)	*0.125*
TS (mg/l)	2130 (82)	4708 (81)	*0.000***	2670 (68)	5282 (40)	*0.000***
TDS (mg/l)	1420 (55)	503 (113)	*0.001***	2168 (84)	214 (4.8)	*0.002***
TSS (mg/l)	710 (27)	4205 (179)	*0.000***	502 (54)	5068 (36)	*0.000***
BOD_5 (mg/l)	26672 (3050)	20935 (1358)	*0.026**	26196 (1211)	17559 (971)	*0.000***

COD (mg/l)	63503 (2867)	54392 (1932)	*0.003****	59141 (1297)	53572 (2295)	*0.008****
Total nitrogen (mg/l)	362 (3.1)	393 (55)	*0.339*	170 (7.1)	321 (44)	*0.006****
Phosphorus (mg/l)	29 (8.1)	69 (12)	*0.003****	46 (2.2)	73 (11)	*0.018***
Potassium (mg/l)	163 (5.4)	214 (7.1)	*0.000****	136 (12)	175 (13)	*0.005****
Oil and grease (mg/l)	276 (19)	980 (147)	*0.003****	358 (35)	695 (119)	*0.006****

All values are in mg/l except pH

*Significant at 5% level

**Significant at 1% level

Table 4-4. Characteristics of individual wastewater streams in Malaysia

Parameter	**Sterilizer condensate**	**Oil clarification wastewater**	**Hydrocyclone wastewater**
pH	5.0	4.5	-
Suspended solids	5000	23000	7000
Dissolved solids	34000	22000	100
BOD_3 at 30°C	23000	29000	5000
COD	47000	64000	15000
Total nitrogen	500	1200	100
Oil and grease	4000	7000	300

All values are in mg/l except pH

Source: (Department of Environment, 1999)

The COD:BOD_5 was 2.3-2.4 for wastewater from boiling and 2.6-3.1 for wastewater from clarification. It has been reported by Henze et al. (2008) that wastewater with high COD:BOD indicates that substantial part of the organic matter will be difficult to degrade biologically. The biodegradability of the wastewater from boiling would be better than the wastewater from clarification. The higher COD:BOD for wastewater from clarification compared to boiling may be attributed to the higher fat and oil content of the wastewater from clarification. Where practicable, treatment systems should target different wastewater streams for optimum recovery of beneficial resources. Alternatively, the different wastewater streams could be mixed in the proportion of their production quantities to ensure some equalization in characteristics.

The duration (up to 2 hours) and method of boiling by submerging fruits in water practiced by the small-scale mills may have contributed to the higher BOD_5 and COD concentrations of the wastewater from boiling compared to clarification. In large-scale mills, as used in Asia, sterilization is accomplished by subjecting the fresh fruit bunches to steam of about 140^oC for 75-90 minutes (Rupani et al., 2010). Moreover, the boiling practice and duration could also have led to the dissolution of minerals and leaching of oil from the palm fruits. The concentration of oil and grease in wastewater from boiling is small compared to clarification, it accounts for about 13% of the total solids and 39-71% of the suspended solids content of the wastewater. The high solids content of the clarification wastewater compared to the wastewater from boiling could have originated from the insoluble organic substances present in the mesocarp which were released during digestion of the boiled fruits. With the exception of pH, the differences in the mean concentrations of parameters between boiling and clarification were statistically significant, mostly at 1% level. As reported earlier in Chapter 3, an average of 64% of wastewater produced by the small-scale processing mills in this study originated from boiling where the levels of the pollutants are even higher. This suggests that large quantities of highly polluted wastewater is disposed into the environment, threatening the health of the immediate environment.

4.4.4 Implications of Findings on Selecting Appropriate Management Solutions

The characteristics of the different wastewater streams from the small-scale mills in Ghana suggests the need to find appropriate solutions for their management. Unlike domestic wastewater, the high COD:BOD, oil and grease and low pH of palm oil mill wastewater makes their treatment challenging. Many technologies have been tested and applied to successfully treat palm oil mill wastewater mostly in Asia. These treatment technologies include anaerobic digestion (Yacob et al., 2005, Ohimain and Izah, 2017), aerobic systems (Vijayaraghavan et al., 2007), co-composting (Hasanudin et al., 2015), adsorption (Alkhatib et al., 2015), advanced oxidation (Ng and Cheng, 2016, Bashir et al., 2017), and membrane filtration (Wang et al., 2015). Detailed description of the different treatment methods can be found in works such as Liew et al. (2015), Iskandar et al. (2018) and Ohimain and Izah (2017). However, most of the technologies are expensive and may not be adaptable to resource-constrained environments such as the small towns and villages where the small-scale mills are located. In addition, downscaling some of the technologies to be applicable to informal small-scale processing mills could increase the unit cost of treatment and affect their acceptance.

The choice of management solutions should therefore be 'appropriate' and must, among other factors, be environmentally friendly, sustainable, affordable, easy to operate and maintain by the local community. Furthermore, potential solutions must utilize local materials and resources, and consider gender issues as suggested by Murphy et al. (2009). Additionally, emphasis should be placed on technologies that could be scaled for different hydraulic and organic loading rates. Based on the characteristics of the palm oil mill wastewater obtained, anaerobic digesters, co-composting and sludge extraction and drying may be considered for adopted. The high BOD and appreciable concentration of nutrients (total nitrogen, phosphorus and potassium) and solids suggest the presence of considerable amount of organics which could serve as nutrients for the microbial community in anaerobic digesters.

Quah and Gillies (1983) reported that anaerobic digestion of 1m^3 of POME could generate 28m^3 of biogas with 65% methane content. Based on the wastewater generation rates reported in Chapter 3, 0.57-1.89 litres of wastewater is produced for a litre of crude palm oil extracted. Thus, about 16 – 53 litres of biogas with 10.4 – 34.4 litres of methane content may be produced for every litre of crude palm oil extracted. Implementation of technologies to generate green energy would reduce the dependence on smoke-producing fuel wood which affects the health of the mill workers. Moreover, tapping the biogas for beneficial use will reduce the release of greenhouse gases into the environment. The functionality of the anaerobic digesters will largely depend on the provision and sustenance of the right operating conditions. For instance, an optimum pH of 6.5-7.6 is required by the microorganisms for biogas production (Nayono, 2010). Since the palm oil mill wastewater was found to be acidic, as reported in other studies (Najafpour et al., 2006), pH adjustment will be required in order to use the wastewater as substrate for anaerobic digestion. Bicarbonates of sodium, potassium and calcium, quicklime and sodium nitrate have been recommended for pH adjustment (Ohimain and Izah, 2017). Other locally available materials such as ash from boilers or agriculture residues could be explored for their potential for pH adjustment. Ash has been successfully applied in raising the pH of agricultural soils (Demeyer et al., 2001).

Biological treatment systems are affected by the presence of inhibitory substances such as fats and oils. The wastewater from palm oil processing contains appreciable quantities of unrecovered fats and oils. Fats, oils and grease have very low biodegradability (Xu and Zhu, 2004, Cammarota and Freire, 2006). They could also solidify under low temperatures to form very thick scum that would affect oxygen transfer in aerobic treatment systems (Becker et al., 1999). Therefore, the removal of excess oils from palm oil milling wastewater is very crucial for their use as substrate for biodigesters. Excess oils could be removed together with the suspended solids using empty palm fruit bunches, sawdust from local sawmills or other locally available decomposable and combustible waste materials as biofilter. Through field measurement at twenty-five (25) small-scale palm oil processing mills in Ghana, the average wastewater production per litre of oil extracted was determined to be 1.26 litres. Based on a suspended solids content of 1355 – 5106 mg/l, the potential quantity of solids that could be generated per litre of oil extracted is about 1.7 – 6.4 grams. The residue which would contain solids and oils could be dried and used as either solid fuel in the palm oil processing operations. The presence of unrecovered oil in pressed palm fibre is reported to enhance their combustibility and use in starting fires at the palm oil processing mills (Heuzé et al., 2015).

Empty fruit bunches have been shredded and used as mulch on palm plantations. Palm oil mill wastewater has also been applied directly on plantations. In Indonesia, palm oil mill wastewater has been co-composted with empty fruit bunches to produce compost and biogas (Hasanudin et al., 2015). Their composting plant was capable of producing an average of 77.2m^3 of biogas for a tonne of empty fruit bunches. The pH of the compost could be adjusted using boiler ash. The favourable climatic conditions of Ghana could enhance the compost production and biogas yield. The filtrate from the composting station could also be assessed for their potential as liquid fertilizer.

Simple granular filters have been successfully applied in treating municipal wastewater. Some of the filter media applied are sand, activated carbon, biochar, anthracite, glass beads, and blast-furnace slag (Chaudhary et al., 2003). Palm kernel shells which is currently a waste product could be tested as mono granular media or in combination with biochar and promoted for treating the filtrate from biofilters or effluent from biodigesters.

4.5 Conclusions

This study characterized different palm oil mill wastewater from different sources and seasons from small-scale processing mills in the Central Region of Ghana to inform the selection of appropriate management solutions for small-scale industries. The characteristics of the palm oil mill wastewater shows variation in wastewater characteristics with source and season. The wastewater was characterized by low pH, high oxygen consuming compounds (BOD_5 and COD), low solids content, fairly high nutrients (total nitrogen, phosphorus and potassium) and unrecovered fat & oil content. The general characteristics of the wastewater were pH (3.7-4.7), total solids (2034-5327 mg/l), TSS (1355-5106 mg/l), TDS (211-1575 mg/l), BOD_5 (16172-31194 mg/l), COD (50391-65673 mg/l), total nitrogen (160-473 mg/l), phosphorus (21-90 mg/l), potassium (126-224 mg/l) and oil & grease (266-1186 mg/l). The mean characteristics of wastewater produced during the peak season were generally higher than the lean season except for pH and solids (total and suspended). Irrespective of the production season, the wastewater was characterized by slowly biodegradable organic matter ($COD:BOD_5 = 2.5\text{-}2.6$). Wastewater from clarification had higher solids and nutrients content but lower oxygen-consuming compounds compared with wastewater from boiling. Discharging the wastewater without treatment will have dire consequences on the natural environment. On the contrary, useful resources in the wastewater could be tapped to produce beneficial energy and materials. The current practice of disposing raw wastewater into the natural environment by the small-scale processing mills is negatively affecting the environment. Based on the characteristics of the wastewater and the tropical climatic conditions in Ghana, the most appropriate technologies that could be tested for the small-scale mills are anaerobic digesters for biogas production, co-composting with shredded empty fruit bunches, dewatering and drying of sludge for use as solid fuel or soil conditioner. Locally available materials such as ash from boilers or agriculture residues could be explored for adjusting the pH of palm oil mill wastewater. Attention should be paid to the small-scale processing mills which dominate the palm oil production industry in Ghana. Enforcement of environmental regulations should be extended to the small-scale (cottage) industries to ensure adoption of appropriate wastewater management technologies.

5 CHAPTER FIVE

SOLIDS-LIQUID SEPARATION AND SOLAR DRYING OF PALM OIL MILL WASTEWATER SLUDGE: POTENTIAL FOR SLUDGE REUSE

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5.1 Abstract

In this study, empty palm fruit bunch fibre was used for solids-liquid separation of palm oil mill wastewater and the sludge was sun-dried for potential uses as soil conditioner or solid fuel. The fibre was manually compressed into a wooden mould to obtain a fibre bulk density of 70 kg/m^3. A composite wastewater sample was poured evenly over the surface of the fibre. The wet solids were sun-dried for 14 days to achieve a moisture content of <10%. The mass of each mould was determined daily after sunset throughout the drying period. The nutrients content and calorific value of the dried sludge were determined using standard methods. The solids-liquid separation process was able to achieve >99% solids and up to 65% COD removal. Analysis of the dried sludge showed nutrients content (% of dry weight) of 0.84 for total nitrogen, 0.15 for phosphorus and 0.49 for potassium. The mean calorific value of the dried sludge was 17.1 MJ/kg. The results show the potential of sun-dried palm oil mill wastewater sludge for use as sustainable soil conditioner or solid fuel. The effluent from the solids-liquid separation must be given additional treatment as it may still contain harmful constituents.

Keywords: calorific value, empty palm fruit bunch fibre, fuel, soil conditioner, solid-liquid separation, palm oil mill wastewater

5.2 Introduction

Palm oil is a very essential vegetable oil for both domestic and industrial use. In the last decade, global consumption has outpaced soybean oil (Shahbandeh, 2020b). Palm oil is extracted from fresh fruit bunches (FFB) through sequence of unit processes. The processing activities generate various waste streams such as empty fruit bunches (EFB), palm kernel shells (PKS), mesocarp fibre and palm oil mill effluent (POME). Preparation, conditioning, and beneficial uses have been found for EFB, PKS and mesocarp fibre. In Malaysia for example, palm oil processing industries utilizes PKS and mesocarp fibre as boiler fuel (Vijaya et al., 2008). POME which originate from sterilization, clarification and hydrocyclone in industrial mills (Nasution et al., 2018a, Prasertsan and Prasertsan, 1996, Department of Environment, 1999) and from boiling and clarification in small-scale mills, presents a greater challenge due to its high environmental polluting properties. Reviewed literature shows that the biochemical oxygen demand (BOD) and chemical oxygen demand (COD) content of POME are 17000-26700 mg/L and 42900-88250 mg/L respectively (Najafpour et al., 2006). However, the wastewater also contains solids and essential plant nutrients that could be harnessed for beneficial use. Department of Environment (1999) reported that POME is rich in total nitrogen (80-1400 mg/L), phosphorus (180 mg/L), potassium (2270 mg/L), magnesium (615 mg/L) and calcium (440 mg/L). Similarly, the concentration of total solids in POME is reported as 11.5-79 g/L from industrial mills in Malaysia (Department of Environment, 1999) and 2.0-5.3 g/L from small-scale mills in Ghana (see Chapter 4). The total solids and essential nutrients content of POME indicate the need for cost-effective methods for recovery and utilization of the solids.

Many technologies have been applied to successfully treat palm oil mill wastewater mostly in Southeast Asia. These treatment technologies include anaerobic digestion (Yacob et al., 2005, Ohimain and Izah, 2017), aerobic systems (Vijayaraghavan et al., 2007), co-composting (Hasanudin et al., 2015), adsorption (Alkhatib et al., 2015), advanced oxidation (Ng and Cheng, 2016, Bashir et al., 2017), and membrane filtration system (Wang et al., 2015). Detailed description of the different treatment methods can be found in the works of Liew et al. (2015), Iskandar et al. (2018) and Ohimain and Izah (2017). Resource recovery options from processing palm oil wastewater include biogas from anaerobic digestion, soil conditioner from co-composting and liquid effluent. Hassan et al. (2004) suggested that the sludge from dewatered POME could be dried and used as a soil conditioner. Solids-liquid separation of wastewater is normally accomplished in ponds, sedimentation tanks (Fytili and Zabaniotou, 2008) or sand beds. But other waste materials from the palm oil industry have been used in POME treatment. For instance, Hassan et al. (2013) produced briquettes using different ratios of POME sludge and palm fronds mixture and tested their suitability as biomass fuel. They concluded that the combined properties of POME sludge and palm fronds resulted in high caloric value of fuel briquette. The combustible (Batcha et al., 2020, Ninduangdee and Kuprianov, 2016) and biodegradable (Nahrul Hayawin et al., 2012, Baharuddin et al., 2009) property enhance the potential use of EFB fibre as solid fuel or soil conditioner and consequently its use for dewatering POME. But to date, EFB fibre has not been utilized to dewater raw POME sludge for use as fuel. This may be due to the bulky nature of EFBs or the alternative use of EFB as boiler fuel or mulch.

For use as industrial fuel, sludge must be dried to achieve 90% total solids (10% moisture content) (Tchobanoglous et al., 2003). Cost-effective sludge drying methods must be explored particularly for low-income countries. The use of solar energy for drying is known to have low capital and operational cost as well as low operational requirements (Seck et al., 2015). It has therefore been recommended for small-scale drying (Tiwari, 2016) and sludge recovery in low-income countries (Tchobanoglous et al., 2003). Such simple and low-cost technologies have been successfully applied in Sub-Saharan Africa for drying of faecal sludge (Muspratt et al., 2014, Seck et al., 2015, Gold et al., 2017, Cofie et al., 2006).

The current study was aimed at using empty palm fruit bunch fibre for solids-liquid separation of POME and assessing the potential of the sun-dried sludge for use as soil conditioner or solid fuel. To the best of our knowledge, this is the first study to determine the nutrients content and calorific value of sun-dried palm oil mill wastewater sludge.

5.3 Materials and Methods

5.3.1 Source of Wastewater and Empty Fruit Bunches

Palm oil mill wastewater and empty fruit bunches were obtained from a small-scale processing mill located in the Abura Aseibu Kwamankese District of Ghana on Longitude 1°12'19"W and Latitude 5°15'59"N. The small-scale mill was part of the four (4) mills from where wastewater was collected for characterization as reported in Chapter 4 of this thesis. To obtain a composite sample, wastewater from boiling and clarification tanks were mixed in the ratio of 5:1 (5-part boiler wastewater and 1-part clarification wastewater). The mixing ratio was based on the mean production quantities by each of the unit operations during a production cycle as reported in Chapter 3. The storage, transportation and preservations practices are also specified in Chapter 4.

5.3.2 Description of Solid-Liquid separator

The solid-liquid separator was made up of rectangular wooden mould (dimensions 30cm x 40cm) with wire mess (aperture 1.2 x 1.2cm) at one end (see Figure 5-1). Solids-liquid separation of the raw wastewater was performed using empty palm fruit bunch (EFB) fibre. In selecting the material for the solids-liquid separation, was placed on using combustible and decomposable waste from the palm oil extraction industry. The empty fruit bunches were washed with distilled water to remove any dirt on them.

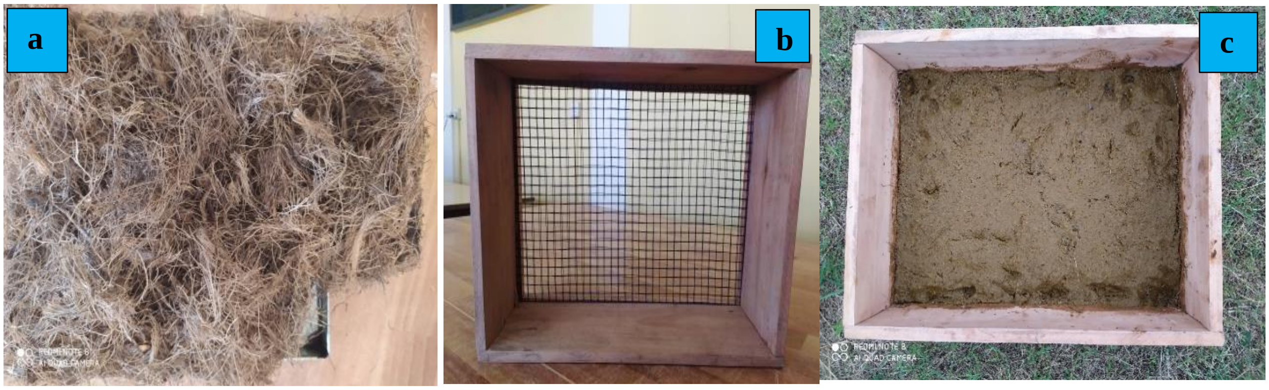

Figure 5-1. Components of the solids-liquid separation setup (a) EFB fibre (b) separator box (c) fresh sludge separated on EFB fibre

They were then crushed twice with a 700 gram rod to maximize retting performance as used by Ruan et al. (2015). The crushed EFBs were soaked in distilled water for 7 days at room temperature to loosen the fibres (a process called water retting) (Jankauskienė et al., 2015). Subsequently, the fibres were separated manually, and sun dried for 3 days to ensure that the fibres were well dried. The dried fibres were fitted and manually compressed into the wooden mould. The bulk density of the fibres (ratio of mass of the fibre to the total volume of the mould) was 70 kg/m^3. The experiment was setup in triplicates.

5.3.3 Experimental Setup

Composite wastewater sample of volume 9.5 litres was poured evenly over the surface of the fibre in each mould to separate the liquid from the solids. The setup was allowed to drain for 30mins. A filtrate of volume 6.5 litres was collected from each of the moulds into a container for the granular column filter experiment in Chapter 6. The volume of the wet solids retained on the fibre was 31.6%. The initial mass of the mould together with the wet solids and fibre was measured. They were then sun-dried for 14 days. The same duration of sun drying but under transparent plastic roof was used to achieve sufficient drying of faecal sludge in Ghana (Muspratt et al., 2014). The mass of each box together with the contents was measured every evening at sunset. After the 14 days, the dried sludge was analysed for moisture content, nutrients (total nitrogen, phosphorus and potassium) and calorific value.

5.3.4 Determination of wastewater characteristics

Laboratory analysis was performed on the influent and effluent wastewater of each solids-liquid separator. Parameters measured were total solids, suspended solids, chemical oxygen demand (COD), total nitrogen, phosphorus, and potassium. The solids content was determined using the gravimetric method. The remaining parameters were analyzed using Hanna multiparameter photometer (HI83399) and associated reagents. Analysis was carried out according to Standard Methods for Examination of Water and Wastewater (APHA et al., 2017). All analyses were performed in triplicates and the mean values taken.

5.3.5 Determination of Calorific Value

An oxygen bomb calorimeter (Sundy, Model: SDC 311, China) was used to determine the calorific value of the dried sludge. The calorimeter conforms to ASTM D5865 (2007) and ISO 1928. The specifications of the oxygen bomb calorimeter are:

- Analysis time: <11 minutes;
- Precision: RSD < 0.1%;
- Heat capacity stability: 0.20% within three months;
- Heat capacity precision: 0.1%
- Temperature resolution: 0.0001 K
- Gas requirement: 99.5% purity of oxygen.
- Water requirement – distilled water

The oxygen bomb calorimeter testing station and the test method was as used by Obeng et al. (2020). One gram of the sample was fetched into the crucible in the bomb calorimeter. After about 10 minutes when the test was completed, the sample was completely combusted. The calorific value was computed and displayed on the windows-based desktop computer. The experiment was conducted in triplicate and the average calorific value computed.

5.3.6 Determination of Nutrient Content of dried sludge

The nutrients measured were total nitrogen, phosphorus, and potassium. Prior to the determination of the nutrients content, the samples were dried at 60^{o}C for 3 hours to reduce its moisture content. The samples were then milled to increase surface area for reaction in order to favour the extraction process. A sulphuric acid-hydrogen peroxide digestion mixture (350 mL hydrogen peroxide, 0.42 g of selenium powder, 14 g Lithium Sulphate and 420 mL sulphuric acid) was prepared. The digestion procedure and nutrients analysis followed the procedure outlined in Stewart et al. (1974). Each analysis was performed in triplicates and the mean values taken.

5.3.7 Statistical Analysis

Data analysis was done using Microsoft Excel. All data set were tested for normality with Shapiro-Wilk test at 95% significance level. The daily mass loss was determined by finding the difference between the daily masses. A paired sample *t*-test (α=0.05) was used to test for statistically significant differences.

5.4 Results and Discussions

5.4.1 Efficiency of Solids-Liquid Separation

Table 5-1 shows the efficiency of the EFB fibre in reducing/increasing of solids, COD, total nitrogen, phosphorus and potassium concentrations in the influent wastewater. The EFB fibre was able to achieve a remarkable removal efficiency for total and suspended solids. Figure 5-2 shows the wastewater before and after the solids-liquid separation.

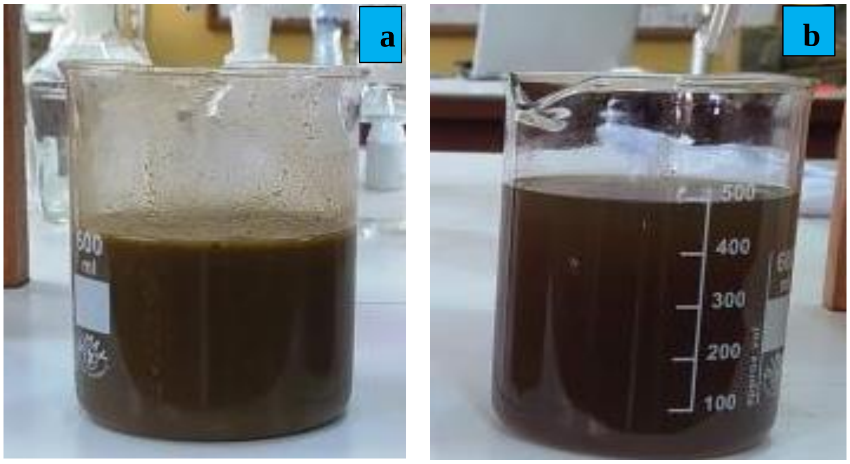

Figure 5-2. Palm oil mill wastewater (a) before and (b) after solids-liquid separation

The removal efficiency was 99.5% for total solids and 99.7% for suspended solids. The removal efficiencies are higher than the removal efficiency of 80-81% for total solids and 96-98% for suspended solids obtained using gravel-sand filter material for faecal sludge dewatering and drying in Ghana (Cofie et al., 2006). The removal efficiency achieved could be attributed to the bulk density (70 kg/m^3) of the fibre in the solids-liquid separator. The high suspended solids separation shows that empty palm fruit bunch fibre is a potential material for solids-liquid separation of palm oil mill wastewater sludge.

Table 5-1. Removal efficiency of empty fruit bunch fibre

	TS	**TSS**	**COD**	**Total nitrogen**	**Phosphorus**	**Potassium**
Raw Wastewater	3976 (1397)	3618 (1551)	56357 (3441)	246 (86)	49 (24)	156 (24)
Filtrate	20.3 (2.1)	9.7 (1.3)	19947 (626)	200 (28.4)	60 (7.2)	193 (18.0)
% Removal	99.5	99.7	64.6	18.7	-22.4	-23.7

All parameters are in mg/L

The removal efficiency was 64.5% for COD. The fairly high reduction of COD is associated with the higher solids removal rate achieved. On the other hand, the remaining COD of about 35% occurs in the dissolved form considering the 99.7% removal of suspended solids. A much higher COD removal (85-90%) was achieved during solid-liquid separation of faecal sludge in Ghana (Cofie et al., 2006). A low total nitrogen reduction of 18.7% was achieved. On the contrary, higher concentrations of phosphorus and potassium were recorded in the filtrate. The fibre increased the phosphorus and potassium concentrations by 22.4% and 23.7% respectively. The fibre may have leached phosphorus and potassium into the filtrate.

5.4.2 Drying Conditions of Palm Oil Mill Wastewater Sludge

The characteristics of the EFB fibre and palm oil mill sludge composite is summarized in

Table 5-2. The mean mass of the composite biomass reduced from 2979 grams on the 1st day to 274 grams on the 14th day. The difference in the mean mass loss was statistically significant at 1% level. The cumulative mass lost by the 14th day was about 91%. The mean daily mass loss varied over the 14 days of drying as shown in Figure 5-3. The mass of the dried samples was fairly constant from the 11th to the 14th day signalling completion of the drying process. But the duration of drying could be longer during the rainy season. In the rainy season, daily temperatures are generally low with corresponding higher relative humidity. Increased relative humidity reduces the rate of evaporation (Farhat, 2018).

The variabilities in the daily mass loss could be attributed to variation in the mean daily temperatures within the experimental period. The average daily temperatures for Cape Coast, Ghana during the experimental period is shown in Figure 5-4. The temperatures fluctuated between the 1st day (21 July 2020) and 7th day (27 July 2020) and again between 10th day (30 July 2020) and 14th day (3 August 2020). These fluctuations reflected in the daily mass loss. The average daily temperatures ranged between 27°C and 31°C. A higher daily mass loss (in grams) was recorded on the 3rd day (497 grams) and 5th day (502 grams) when the average daily temperatures were higher. Even though the temperature was 30°C on the 13th day, the mass lost was only about 4% because over 90% of the mass had been lost by the 13th day. Increasing ambient temperature has corresponding increase in drying rate. However, too high temperatures result in case-hardening

(Yaciuk, 1981). The cumulative rate of mass loss over the 14-day period is also presented in Figure 5-3.

Table 5-2. Mean characteristics of empty palm fruit bunch fibre and palm oil mill wastewater sludge composite

	Mean (SD)		Difference
	Day 1	**Day 14**	**(*p-value*)**
Mass of fibre and solids composite (g)	2979 (89)	274 (22)	2705 (*0.000*)*
Daily mass loss (g)	297 (68)	12.5 (0.5)	
Cumulative mass loss (%)	9.9 (2.0)	90.8 (1.0)	

SD – Standard deviation *significant at 1% level

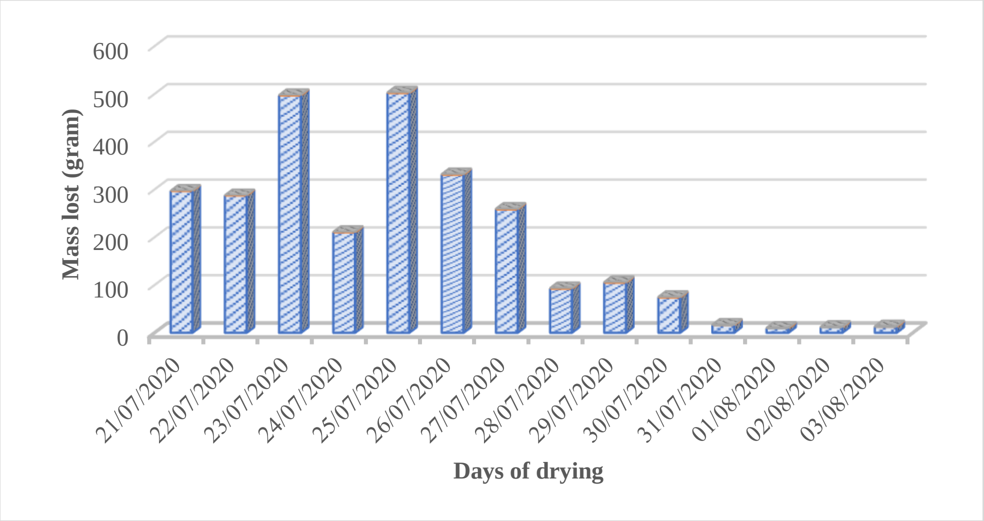

Figure 5-3. Mean daily mass loss during the 14 days of drying

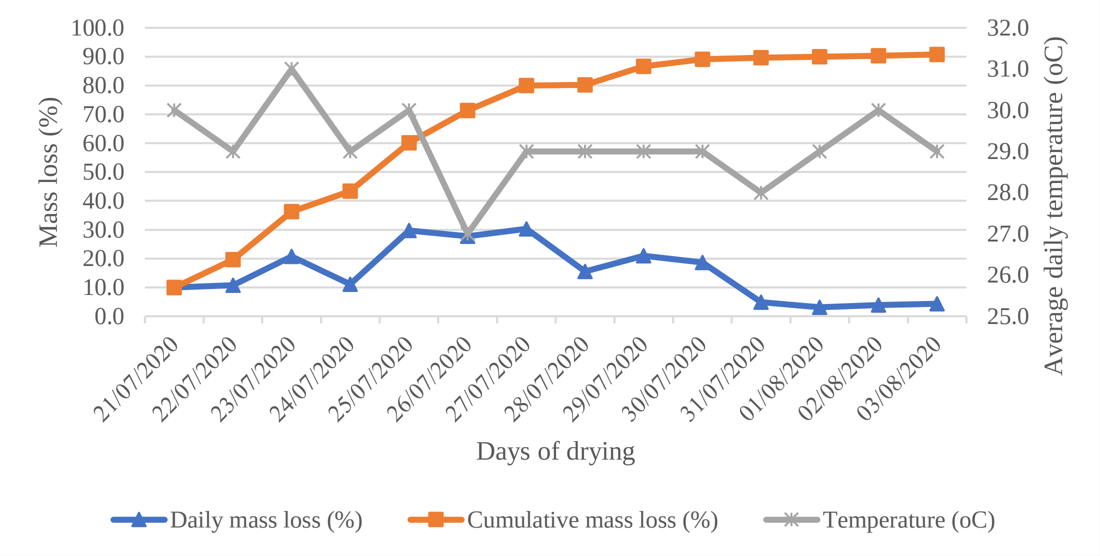

Figure 5-4. Percentage daily mass loss during the 14 days of drying

From Figure 5-4, over 50% of the mass of the composite biomass was lost within the first 5 days even though the daily rate of mass loss was variable. Within 10 days of solar drying, about 89% of the overall mass had been lost. These results seem promising for managing the large volume of palm oil mill wastewater sludge particularly for resource-constrained environments such as those that occur at small-scale palm oil processing mills in Africa. A picture of the sun-dried palm oil mill wastewater sludge and fibre composite is shown in Figure 5-5.

Figure 5-5. Sun-dried palm oil mill wastewater sludge

A higher rate of mass loss lower drying time could be achieved in the dry season. The months (July-August) within which the experiment was conducted is considered as part of the year with relatively lower average temperatures (Weatherspark, 2020). Drying time is reported to be shorter under sunny conditions (Tiwari, 2016). But, to control the drying rate and avoid surface hardening, solar air-drying bed with transparent roof covering may be adopted in place of open-air solar drying especially during seasons with higher temperatures. Moreover, adopting a covered drying bed would prevent rainfall from falling directly on the drying beds during field application. In Turkey, Salihoglu et al. (2007) compared the performance of covered and open solar drying beds for municipal wastewater sludge and reported that covered solar drying system was more efficient in terms of drying and faecal coliform reduction. Transparent roofing has also been suggested as a simple design technique to speed drying and consequently reduce land area requirement (Muspratt et al., 2014).

5.4.3 Nutrient Content of Dried Palm Oil Mill Wastewater Sludge

Raw palm oil mill wastewater sludge and empty fruit bunches have been reported to contain essential plant nutrients (nitrogen, phosphorus, potassium) with the potential for use as soil conditioner. The mean nutrients content of the dried sludge is given in Table 5-3.

Table 5-3. Mean total nitrogen, phosphorus and potassium content of sun-dried palm oil mill wastewater sludge

Parameter	**Mean (SD)**	**Minimum**	**Maximum**
Moisture Content	7.31 (0.415)	6.47	7.70
Total nitrogen	0.84 (0.017)	0.814	0.874
Phosphorus	0.15 (0.006)	0.141	0.159
Potassium	0.49 (0.044)	0.416	0.536

All units are % of dry weight

The essential nutrients content (in % of dry weight) of the dried sludge for total nitrogen, phosphorus and potassium were 0.84, 0.15 and 0.49 respectively. Physico-chemical analysis of 37 commercial compost from France, Greece and the Netherlands showed typical total nitrogen content of 0.67% - 3.8% of dry weight (Zmora-Nahum et al., 2007). Compost produced from oilcake had a mean total nitrogen content of 3.03% (SD=0.84) of dry weight. Whiles the total nitrogen content of the dried sludge (in this study) is lower than compost from oilcake, the results are within the range of total nitrogen content of vegetable waste compost reported by Kokkora et al. (2010).

Compost produced from co-composting of shredded empty fruit bunches and partially digested palm oil mill wastewater had total nitrogen, phosphorus and potassium contents (in % of dry weight) of 2.2 (SD=0.3), 1.3 (SD=0.2) and 2.8 (SD=0.3) respectively (Baharuddin et al., 2009). The essential nutrient content in the dried sludge from this study were lower than the concentrations reported by Baharuddin et al. (2009). This could be attributed to the characteristics of the wastewater used which is influenced by the processing technique and season (Wu et al., 2010, Yusof and Ariffin, 1996). In this study, wastewater was obtained from small-scale palm oil processing mills which use inefficient processing techniques. Moreover, the empty fruit bunches may have contributed to the high nutrients content of the compost. At the industrial mills, palm fruit bunches (empty fruit bunches and fresh fruits) are sterilized together. This could lead to leaching of minerals from the EFBs into the wastewater. However, at small-scale mills only palm fruits are boiled. The differences in the sterilization methods may have contributed to the higher nutrients content of compost reported in studies conducted in the major palm oil producing countries. The nutrient content of the dried sludge shows their potential for use as soil conditioner.

5.4.4 Energy value of palm oil mill wastewater sludge

The moisture content and calorific value of palm oil mill wastewater sludge and some fuels are presented in Table 5-4.

Table 5-4. Moisture content and calorific value of various dried sludge and biomass for use as fuels

Biomass	**Drying method**	**Moisture content (% dry weight)**	**Calorific value (MJ/kg)**	**Reference**
POME sludge and EFB fibre	Sun-drying	6.5-7.7	15.5-18.3	This present study
EFB fibre	Open air drying	8.43	17.97	Nyakuma et al. (2014)
Faecal sludge	Convective drying rig	5-10	13.3-13.7	Septien et al. (2020)
Palm oil mill sludge and palm fronds briquette	Oven drying	10.3 (POME sludge) 3.73 (palm fronds)	18-26	Hassan et al. (2013)
Separator Sludge from clarification tank[a]	Oven drying	-	16.13±3.73	Loh (2017)

[a] moisture free sludge

5.4.4.1 Moisture Content

The mean moisture content of 6.5 – 7.7% shows that the samples are well dried. Combustibility of solid fuel is inversely related to the moisture content since wet fuels require extra energy for evaporating moisture before combustion (Loh, 2017). The recommended moisture content for firewood is 10-20% of the total weight (Nord-Larsen et al., 2011, Brock, 2004). The maximum moisture content required for reuse of dried faecal sludge as biofuel is 20% (Stasta et al., 2006). Using convective and infrared drying rigs at variable drying temperatures and residence time, the moisture content of faecal sludge waste was obtained as 5-74% (wet basis) (Septien et al., 2020). The moisture content of the dried palm oil mill wastewater sludge was up to 2.5 folds lower than that of firewood and biofuel from faecal sludge. The level of moisture content in the sun-dried sludge (in this study) was lower than moisture content of 8% achieve in industrial practice (Stasta et al., 2006).

5.4.4.2 Calorific Value

The calorific value of the sun-dried palm oil mill effluent sludge was 15.3 – 18.5 MJ/kg. In a study, Nyakuma et al. (2014) found the heating value of empty fruit bunch fibre at 8.43% moisture content to be 17.97 MJ/kg. Palm oil mill sludge and palm fronds was used as fuel briquette with a calorific value of 18-26 MJ/kg based on the proportion of palm oil mill effluent sludge and oil palm frond waste (Hassan et al., 2013). Similar to palm oil mill wastewater sludge, Gold et al. (2017) demonstrated through a pilot study that dried faecal sludge can be used as industrial fuel with a mean calorific value of 10.9-13.4 MJ/kg. The calorific value of faecal sludge obtained by drying with convective and infrared driers at variable drying temperatures (40-80^{o}C) and residence time (4-25 minutes) was reported by Septien et al. (2020) to range between 13.3 and 21.8 MJ/kg dry solid. The calorific value of the sun-dried palm oil mill wastewater sludge (in this study) compared to literature suggests that dried POME sludge possesses suitable calorific value to be used as solid fuel.

5.5 Conclusions

In this study, solids-liquid separation of palm oil mill wastewater was carried out using empty palm fruit fibre. The fibre was able to achieve >99% solids and about 65% COD removal. The solids were sun-dried to obtain a moisture content of <10% (dry weight) over 14 days. The percentage mass lost increased from about 10% on the first day to 91% on the 14th day. The essential nutrients content (% of dry weight) of the dried sludge were 0.84 for total nitrogen, 0.15 for phosphorus and 0.49 for potassium. The nutrient content of the dried sludge shows its potential for use as soil conditioner. Further study is required to determine the impact of the dried sludge as soil conditioner on the physical, chemical or biological characteristics of soils. On the other hand, the mean calorific value of the dried sludge was 17.1 MJ/kg. The moisture content and calorific value suggests that sun-dried palm oil mill wastewater sludge possesses suitable calorific value to be used as solid fuel especially for palm oil processing. To better understand the valorisation potential of the dried sludge and EFBs, future research could focus on examining the EFBs and sludge using Thermal Gravimetric Analysis (TGA), Scanning Electron Microscope (SEM), Energy Dispersive X-ray (EDX) Analysis and X-ray Fluorescence (XRF). Open-air sun drying of palm oil mill sludge into biofuel and soil conditioner shows great potential as a renewable resource. Therefore, further research should focus on optimization of the drying techniques and enhancing the calorific value of the sludge. For use in both dry and rainy seasons, transparent roofed drying beds could be considered. Other low energy and shorter drying duration techniques may be explored.

6 CHAPTER SIX

PALM KERNEL SHELL AND CHARCOAL AS GRANULAR FILTER MEDIA FOR TREATMENT OF PRE-FILTERED PALM OIL MILL WASTEWATER

6.1 Abstract

In this study, the potential of using palm kernel shell and charcoal as granular filter media for treating pre-filtered palm oil mill wastewater was evaluated. Palm oil mill wastewater was collected from small-scale palm oil mills in the Abura Aseibu Kwamankese District of Ghana. Solid-liquid separation was performed using empty palm fruit bunch fibre. The effluent from the solid-liquid separation of palm oil mill wastewater was used in the filtration experiment. Granular filter media (palm kernel shell and charcoal) of particle size 1.18mm were packed into acrylic cylinders. The characteristics of influent wastewater, filter media and the filters were determined prior to the experiment. Each filter was run as a batch system with a static bed under anaerobic conditions. Experimental setups were run at six (6) different hydraulic retention times (0, 24, 48, 72, 96, and 120 hours). Effluent was drawn from the bottom of each filter at the end of each retention time for analysis. Parameters measured were colour, COD, total nitrogen, phosphorus and potassium using standard analytical methods. The removal efficiency for PKS filter was in the order COD (77%) > potassium (71%) > colour (69%) > total nitrogen (64%) > phosphorus (60%). Similarly, the performance of charcoal filter for removal of test parameters were in the order COD (80%) > colour (70%) > total nitrogen (66%) > potassium (63%) > phosphorus (20%). The performance of charcoal filter was comparable to PKS filter except for phosphorus. All the filters failed to treat the influent wastewater to acceptable limit for effluent discharge in Ghana.

Keywords: Charcoal, filter media, palm kernel shells, palm oil mill wastewater, physico-chemical parameters

6.2 Introduction

Palm oil is a very essential ingredient in traditional West African cuisine and the most important vegetable oil globally (OECD/FAO, 2020). As the 3rd highest producer in Africa (FAOSTAT, 2019), Ghana's palm oil production industry is dominated by the small-scale mills that produces up to 80% of the national production quantities (Angelucci, 2013). Ghana is seeking to expand palm oil production to meet domestic demand and for export. This is exhibited in the numerous interventions implemented by successive governments (MOFA, 2011, Angelucci, 2013). Increasing production will lead to corresponding increase in palm oil mill wastewater quantities. But the small-scale palm oil processing mills discharge their wastewater into the natural environment without any treatment as was observed (see Chapter 3.4.6) and also reported by other researchers (MASDAR, 2011, Poku, 2002, Osei-Amponsah et al., 2012).

Assessment of the characteristics of palm oil mill wastewater from small-scale mills in Ghana as presented in Chapter 4 has shown that the wastewater has high oxygen-demanding compounds (16,172-31,194 mg/L BOD_5 and 50,391-65,673 mg/L COD) necessitating the need for treatment to meet effluent discharge requirement before final disposal. Many technologies have been tested at both laboratory and full scales for their potential to treat wastewater. One of the low-cost technologies which has shown great promises (for tropical, resource-constrained countries like Ghana) is the recovery, sun drying and use of the solids as fuel or soil conditioner. But, the effluent from the solid-liquid separation process still may not meet the requirement for direct discharge into the environment.

Filter systems for on-site treatment of wastewater is very common in Ghana. Globally, the commonest filter media for treating water and wastewater is sand (Dalahmeh et al., 2014) but recently, activated carbon has also attracted attention. However, the relatively high cost and challenges associated with the acquisition and maintenance of sand and activated carbon filters have incited the search for alternative low-cost filter media (Bari et al., 2014, Dalahmeh et al., 2012). Materials with high porosity, high carbon content and the possibility for sustainable reuse or recycle such as charcoal and sawdust have gained much attention. Researchers around the globe continue to identify and assess the potential of new low-cost materials for treatment of wastewater in particular. Palm kernel shell (PKS), a solid by-product from palm oil processing and waste material at most small-scale mills, could be potential candidate. PKS and charcoal have high carbon content and appreciable porosity making them potentially suitable materials to be used as adsorbents. In most studies involving the utilization of PKS, they have been prepared into activated carbon for use as adsorbent for wastewater treatment (Mohammad Razi et al., 2018), dye removal (García et al., 2018), carbon dioxide capture (Rashidi and Yusup, 2019, Hidayu and Muda, 2016), nitrogen dioxide and ammonia removal (Guo and Lua, 2003). Studies on the use of PKS as granular filter media for wastewater treatment are very limited.

The objective of this study was to investigate the potential of using PKS and charcoal as granular filter media for the treatment of pre-filtered palm oil mill wastewater at laboratory scale.

6.3 Materials and Methods

6.3.1 Wastewater Sample Source and Preservation

Raw palm oil mill wastewater was collected from a small-scale palm oil processing mill located in the Abura Aseibu Kwamankese District of Ghana on Longitude 1°12'19''W and Latitude 5°15'59''N. Solids-liquid separation of the raw wastewater was performed using empty palm fruit bunch fibre. The detailed description of the solids-liquid separation setup and process is reported in Awere et al. (2020) and in Chapter 5 of this thesis. Effluent from solid-liquid separation was used for the filtration experiment. Figure 6-1 shows the wastewater before and after the solids-liquid separation.

Figure 6-1. Palm oil mill wastewater before and after solids-liquid separation

After the solids-liquid separation, the effluent was stored under 4°C in a refrigerator to inhibit microbial activities (Choo et al., 2015, Lauber et al., 2010) before use in the experiment. Prior to using the samples in the experiment, they were kept out of the refrigerator and allowed to reach room temperature.

6.3.2 Filter Materials

Three (3) filter materials were studied for their potential in treating pre-filtered palm oil mill wastewater. The materials were PKS, charcoal and sand, which was included as a reference media because of its extensive use in treating water and wastewater (Dalahmeh et al., 2012, Kaetzl et al., 2018). In selecting the filter media, emphasis was placed on locally available materials particularly waste from the palm oil extraction industry. PKS was obtained from the same processing mill where wastewater samples were collected. The biochar which was locally produced was purchased from a local market at Abura in Cape Coast, Ghana.

6.3.3 Preparation and Characterization of Filter Materials

The PKS was crushed using a mechanical crusher located at the Mechanical Workshop of the Department of Mechanical Engineering, Cape Coast Technical University, Ghana. The biochar was crushed into granular form. Physical properties of the filter materials were determined following standard procedure for soil analysis (Dane and Topp, 2002). The properties were chosen based on studies reported in literature (Dalahmeh et al., 2012, Kaetzl et al., 2018). The physical properties of the filter materials were particle size and density. In determining the particle size, the media were sieved through sieve sizes 0.6, 1.18, 2 mm stack of sieves placed on a mechanical sieve shaker (Octagon Digital, Endecotts Limited, England) to obtain similar grain fractions. The mechanical sieve shaker was run at a vibration speed of 3000 rpm, and amplitude of 3.0 mm for five minutes. The materials with particle size 1.18mm which conformed to ASTM classification of medium sand was chosen.

The particle density was determined by dividing a 20 g sample by the total volume, excluding pore space. The effective volume of particles was determined by adding deionized water and gently boiling the mixture to eliminate air-filled pores. The submerged particles were left to saturate for 24 hours (Dalahmeh et al., 2012). The particle density was determined using Equation 1 from Dalahmeh et al. (2012).

$$\rho_p = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \qquad (1)$$

Where ρ_p is the particle density, M_1 is the mass of pycnometer, M_2 is the mass of pycnometer and sand, M_3 is the mass of pycnometer, sand and water and M_4 is the mass of pycnometer and water.

6.3.4 Filtration Column Design

The experimental setup was designed as a batch system with a static bed. The setup consisted of 12 acrylic plastic filter columns with internal diameter of 6.3cm and height of 42cm (Figure 6-2). A small outlet of diameter 0.5cm was made at the bottom to serve as a sampling point.

Figure 6-2. The filter column design

The filter materials were washed with tap water to remove fine particles and air dried for 48 hours before placing in the columns. The air-dried filter materials were manually packed into the filter columns and levelled after every 10 cm by manual shaking. Each column contained filter material of depth 32 cm (working volume of about 1000 mL).

6.3.5 Characterization of Filtration Columns

After packing the filter columns, the bulk density and total porosity were determined for each of the filter columns. The analytical methods followed were based on those used by other researchers (Dalahmeh et al., 2012, Kaetzl et al., 2018, Perez-Mercado et al., 2018). Bulk density was determined by dividing dry weight of the filter media by the volume occupied by the media (6 cm diameter by 55 cm high). The Porosity of the filter column was determined using Equation 2 from Perez-Mercado et al. (2018).

$$p = \left(1 - \frac{\rho_B}{\rho_p}\right) x\ 100 \tag{2}$$

Where p is the porosity in percent of the total volume, ρ_B is the bulk density and ρ_p the particle density.

6.3.6 Experimental Setup

At the start of the experiment, the outlet valves were closed, and the filters were fed with distilled water for 24 hours after which the outlet valves were opened and drained for 48 hours. Distilled water, serving as a blank sample, was filtered through each of the filters and analysed to understand the contribution of the media to the characteristics of the final treatment. Influent wastewater was then fed from the top of each filter with the outlet valve closed. A constant head of wastewater was maintained over each media surface to ensure steady state and continuous anaerobic conditions within the filter column. Experimental setups were run at six (6) hydraulic retention time (HRT) of 0, 24, 48, 72, 96, and 120 hours. Effluents were drawn from the bottom of each filter at the end of each HRT for analysis. Three replicate filter columns were used for each filter media. The experiments were conducted under room temperature around 25°C.

6.3.7 Laboratory Analysis

Laboratory analyses were performed on the influent wastewater and effluent from each of the filter columns at the start of the experiment and at 24-hour interval as previously mentioned. Parameters measured were colour, chemical oxygen demand (COD), total nitrogen, phosphorus and potassium. The equipment, reagents and test methods for the various parameters are as described in Chapter 5 of this thesis. Each analysis was performed in triplicates and the mean value taken. The efficiency of the filter media was based on reduction for the various parameters analysed and calculated using Equation 3 from Dalahmeh et al. (2014).

$$E = \left(\frac{C_{in} - C_{out}}{C_{in}}\right) x100 \qquad (3)$$

Where E is the efficiency (percent), C_{in} the influent concentration (mg/l) and C_{out} the effluent concentration (mg/l).

6.3.8 Kinetics models

The pollutants removal kinetics was determined from the uptake-time data obtained from the experimental results. Pollutant degradation was considered as an irreversible reaction. The four kinetic models used by Yin et al. (2017) were adopted. The linear equations for the four kinetic models are as presented in Equation 4 to Equation 7.

$$Zero-order: [C] = -kt \tag{4}$$

$$1st-order: ln[C] = -kt + ln[C_0] \tag{5}$$

$$2nd-order: {}^{1}/_{[C]} = kt + {}^{1}/_{[C_0]} \tag{6}$$

$$3rd-order: {}^{1}/_{[C]^2} = kt + {}^{1}/_{[C_0]^2} \tag{7}$$

The kinetics models corresponding to zero-order (c – t), 1st-order (-lnc – t), 2nd-order (1/c – t) and 3rd-order ($1/c^2$ – t) were plotted. The best-fitting linear model for c – t, -lnc – t, 1/c – t and $1/c^2$ – t relationship for all pollutants were determined to description the pollutant removal mechanism. All the correlation coefficient, R^2 values among the four kinetic models for each pollutant and media column were compared. The highest R^2 values was taken to be the best model for the overall reaction order.

6.3.9 Statistical Analysis

Statistical analysis was performed using SPSS statistical software (version 16). A test for normality was performed using Shapiro-Wilk test at 95% confidence interval. The mean and standard deviations were recorded for all the data set. Depending on the number of parameters tested, a *t*-test or one-way ANOVA test (α=0.05) was used to test for the statistical significance of differences among means. When a statistically significant difference was found, a Bonferroni multiple comparison of means at 95% confidence interval was performed.

6.4 Results and Discussions

6.4.1 Properties of Filter Media

The properties of filter media (PKS, charcoal, sand) are also presented in Table 6-1.

Table 6-1. Properties of PKS, charcoal and sand

Parameter	PKS	Charcoal	Sand
Particle size (mm)	1.18	1.18	1.18
Particle density (kg/m^3)	1330	1040	2220
Bulk density (kg/m^3)	676	570	1560
Total Porosity (%)	49	45	30

6.4.2 Characteristics of Influent Wastewater and Filtered Blank Samples

The characteristics of the influent wastewater and distilled water from the filters are presented in Table 6-2. The mean influent wastewater COD concentration was 19947±626 mg/L. The COD concentration in this study is higher than the COD of secondary palm oil mill effluent from final discharge pond reported by Darajeh et al. (2016). The COD is also higher than that of greywater (23-8071 mg/L) (Shaikh and Ahammed, 2020). Phosphorus concentration (52-67 mg/L) was the least followed by potassium (173-208 mg/L) and total nitrogen (175-231mg/L). As reported in Awere et al. (2020) and in Chapter 5, the empty fruit bunch fibre increased the phosphorus and potassium concentrations by 22.4% and 23.7% respectively. That notwithstanding, the concentration of nutrients (total nitrogen, phosphorus and potassium) were still lower than those reported by Darajeh et al. (2016).

Table 6-2. Characteristics of influent wastewater and filtered blank samples

Parameter	Influent wastewater			Blank Samples[1]		
	Mean (SD)	Min.	Max.	PKS	Charcoal	Sand
Colour (PtCo)	8067 (823)	7117	8544	883 (63.2)	240 (13.1)	190 (13.9)
COD (mg/L)	19947 (626)	19384	20621	488 (30.4)	590 (34.1)	0
Total nitrogen (mg/L)	200 (28.4)	175	231	0	0	0
Phosphorus (mg/L)	60 (7.2)	52	67	0	12 (1.1)	0
Potassium (mg/L)	193 (18.0)	173	208	247 (13.7)	650 (45.6)	0

[1] Values are mean (SD) SD – standard deviation

The properties of the distilled water after a 24-hour contact time for the sand were lower than PKS and charcoal. Sand only impacted on the colour of the water increasing the colour by 190 mg/L. There was no contribution to COD and nutrients from the sand. Charcoal was the highest contributor to both COD and potassium, with mean concentrations of 590 mg/L and 650 mg/L respectively. Similarly, even though very low, charcoal was the only media to contribute phosphorus (12 mg/L) to the distilled water. PKS rather impacted highly on the colour of distilled water (883 mg/L) compared to charcoal and sand. The COD and potassium concentrations for the PKS filter were lower than those of the charcoal filter. None of the three media contributed total nitrogen to the distilled water. The results presuppose that the filter media used are potential contributor to some of the parameters measured and could lead to spikes in the initial concentrations of the parameters.

6.4.3 Mean Characteristics of Final Effluent from Different Filters

The mean characteristics of the influent wastewater and effluent from the different filters after 120-hour contact time are presented in Table 6-3. There were differences in the performance of different media type in removing contaminants in the wastewater.

Table 6-3. Mean characteristics of influent and effluent wastewater after 120 hours retention time

Parameter	**Mean (p-value[1])**				**F-statistic (p-value[2])**	**GEDS**
	Influent	**PKS**	**Charcoal**	**Sand**		
Colour (PtCo)	8067	2480 *(0.000)***	2420 *(0.000)***	3040 *(0.000)***	10.070 *(0.087)*	300
COD (mg/L)	19947	4560 *(0.000)***	3940 *(0.000)***	4090 *(0.000)***	0.572 *(0.492)*	250
Total nitrogen (mg/L)	200	72 *(0.000)***	68 *(0.000)***	55 *(0.000)***	1.128 *(0.348)*	-
Phosphorus (mg/L)	60	24 *(0.000)***	48 *(0.000)***	5 *(0.000)***	81.221 *(0.000)***	2

Potassium (mg/L)	193	57 (0.000)**	72 (0.000)**	31 (0.000)**	18.488 (0.012)*	-

GEDS – Ghana Effluent Discharge Standard

[1] Statistical significance between influent and effluent
[2] Statistical significance among effluent from PKS, charcoal and sand filter columns
[**] Significant at 1% level
[*] Significant at 5% level

All the filters were able to reduce the concentrations of all parameters in the influent wastewater. There were differences in the characteristics of the final effluent among the three filter media types. The concentration of total nitrogen, phosphorus and potassium were lower for the effluent from the sand filters than for PKS and charcoal filters. More so, the concentration of phosphorus and potassium were lower for PKS filter (phosphorus-24 mg/L and potassium-57 mg/L) than charcoal filter (phosphorus-48mg/L and potassium-72mg/L). Similarly, the wastewater from the charcoal filter had lower colour and COD compared with PKS and sand filters. For all the media types, a paired-sample *t*-test showed statistically significant difference in the mean characteristics of all parameters between the influent and effluent wastewater at 1% level as shown in Table 6-3. The results presented in Table 6-3 suggests that all the different filters were able to treat the wastewater. But the final effluents failed to meet the minimum threshold for discharge into the environment in Ghana. The concentration of the final effluents after 120-hour contact time were higher than the GEDS by 8-18 times for PKS filter, 8-24 times for charcoal filters and 2.5-16 times for sand filters.

6.4.4 Removal Efficiency for Different Parameters

All the filters showed great potential in reducing the concentration of different parameters over the 120-hour contact time. The trend of reduction efficiency for the analysed parameters for each of the filters are shown in Figure 6-3 to Figure 6-7.

6.4.4.1 Colour Reduction

Figure 6-3 shows the colour removal efficiency by the PKS, charcoal and sand filters. The effluent from all the media types immediately after addition of influent wastewater showed a spike in colour.

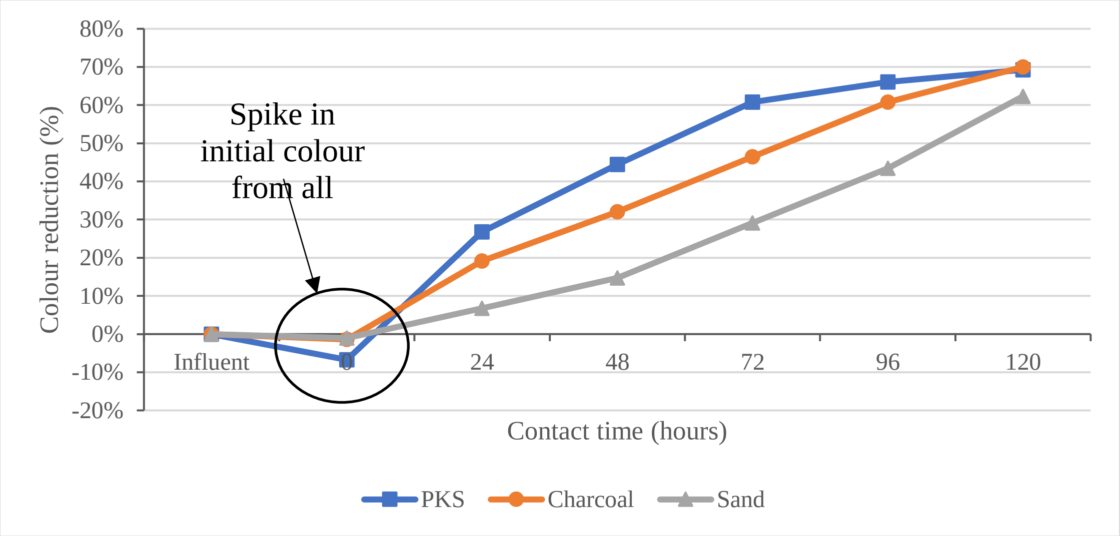

Figure 6-3. Colour removal in palm oil mill wastewater with different filter media

The percentage increases were 7% for PKS and 1% each for charcoal and sand. The spike in the colour may have been contributed by the media themselves as shown in Table 6-2. But after 24 hours, there were reductions in the colour for all the media with a highest of 27% recorded by the PKS. The sand filters exhibited low reduction of 7% within 24-hour contact time. However, the efficiency of the media types in reducing colour at the end of 120 hours were in the order charcoal (70%) > PKS (69%) > sand (62%). The comparatively better efficiency of charcoal filter for colour removal may be attributed to the higher adsorption capacity of charcoal. In adsorption studies using charcoal, Bari et al. (2014) recorded 74-100% colour removal with 10 mg/L methylene blue solution. Similarly, Rashida and Nawas (2015) used granular charcoal (particle sizes ≤2mm) to achieve 85-99% colour removal from a dye solution. Activated carbon from PKS was used to remove over 90% of the equilibrium adsorptions for colour (methylene blue) after 4-hour contact time (García et al., 2018). The differences in the mean colour concentration at the end of 120-hour contact time among the media types were not statistically significant ($p>0.05$) (see Table 6-3).

6.4.4.2 COD Reduction

The trend of COD reduction for the PKS, charcoal and sand are shown in Figure 6-4. The sand filters were characterised by high initial reduction of COD exhibiting a percentage reduction of 34%. A lower initial COD reduction was recorded for PKS (18%) and charcoal (13%) filters.

Subsequently, each of the filters recorded increased performance in COD reduction but at varying rates.

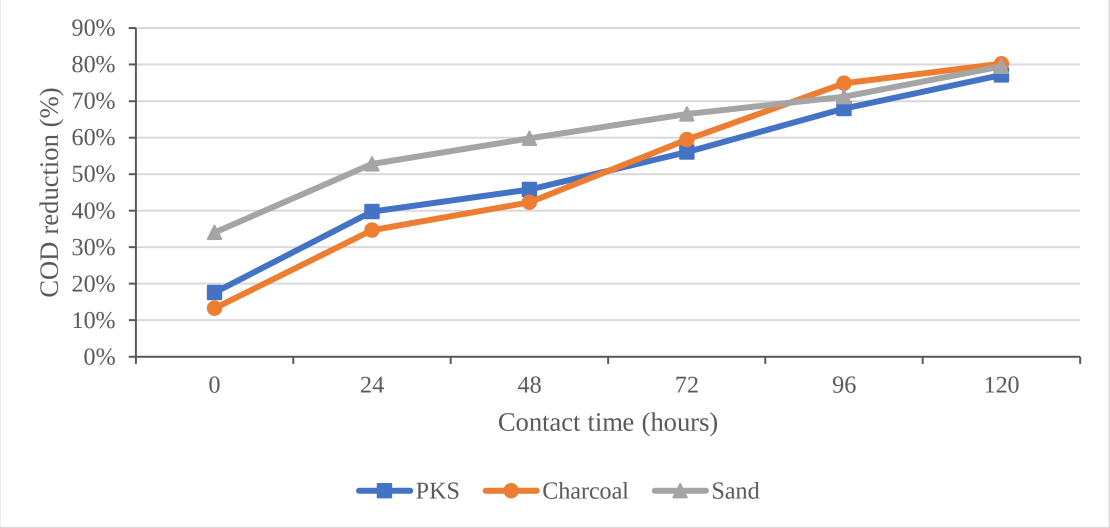

Figure 6-4. COD removal in palm oil mill wastewater with different filter media

The charcoal filters which showed the lowest initial reductions, however, achieved the highest reduction of 80% at the end of the 120-hour contact time. The COD reductions for the sand and PKS at the end of the experiment were 79% and 77% respectively. Dalahmeh et al. (2012) observed a similar trend in greywater COD reduction of 94% for charcoal and 72% for sand but at a much longer contact time of 113 days. A mean COD reduction of 85-88% using biochar for treating municipal wastewater have been previously reported (Ahsan et al., 2001, Kaetzl et al., 2018). Similarly, Kätzl et al. (2014) found biochar to be better than sand in achieving COD removal of 73% with biochar and 58% with sand. Other studies have reported 83-90% COD removal rate for different hydraulic loading rates in anaerobic sand filters (Tonon et al., 2015). The COD reduction rates by biochar observed in this study falls within the results reported in other studies. However, the reduction of COD of 79% by sand filters was higher in this study than the 58% reported by Kätzl et al. (2014). The absolute percentage reductions depict that the performance of the filters was in the order charcoal (80%) > sand (79%) > PKS (77%). But, the differences in the mean COD concentrations among the different media types at the end of the 120-hour contact time was not statistically significant (p>0.05) (see Table 6-3).

6.4.4.3 Total Nitrogen Reduction

The sand filter was the best in reducing the concentration of total nitrogen from an influent concentration of 200 mg/L to 68 mg/L in 120 hours. The trend of total nitrogen reduction in the PKS, charcoal and sand filters are presented in Figure 6-5. The initial reduction was 22% and increased to 73% at the end of the 120-hour contact time. The performance of PKS and charcoal filters respectively increased from 2% and 8% at the start to 64% ($p<0.01$) and 66% ($p<0.01$) (Table 6-3) by the end of the experiment.

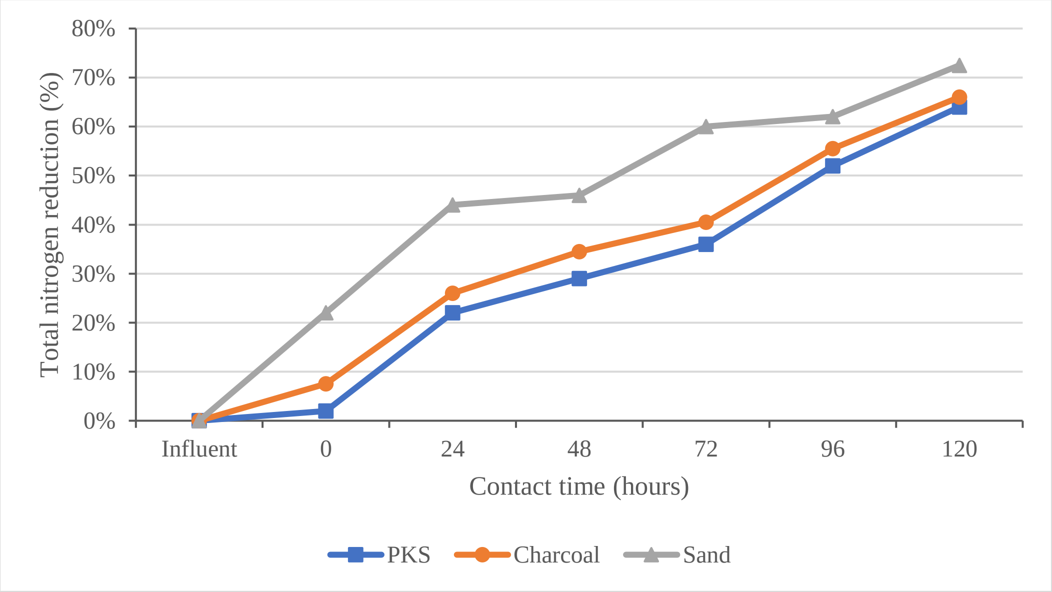

Figure 6-5. Total nitrogen removal in palm oil mill wastewater with different filter media

A very low removal efficiency of 14% for biochar and 12% for gravel for treating municipal wastewater have been reported (Kaetzl et al., 2018). But Dalahmeh et al. (2012) recorded total nitrogen reduction of 98% for charcoal but very low reduction of 5% for sand filters. As confirmed by other researchers (Gill et al., 2009, Dalahmeh et al., 2012) the relatively high total nitrogen reduction could be associated with denitrification in the filter columns as a result of the anaerobic conditions. The significantly low total nitrogen reduction (12%) by the gravels obtained by Kaetzl et al. (2018) could be attributed to the size of the media used. In our study, the size of the media was 1.18mm as against 11-16mm used by Kaetzl et al. (2018). Moreover, the low reduction of total nitrogen (5%) reported by Dalahmeh et al. (2012) was not attributed to denitrification due to the absence of anaerobic conditions in the sand filters. The large surface area of sand particles could have increased the adhesion area for nitrifying microorganisms.

In terms of absolute values, the total nitrogen reduction was in the order sand > charcoal > PKS filters. But a one-way ANOVA test at 95% confidence level reveal statistically insignificant differences in the means of total nitrogen concentrations among the different filter media (see Table 6-3). This implies that the performance of PKS, charcoal and sand filters in removing total nitrogen in the wastewater was not statistically different.

6.4.4.4 Phosphorus Reduction

The reduction rate for phosphorus was high in the sand (92%) and PKS (60%) filters but low in the charcoal filters (20%) (see Figure 6-6). The low rate of reduction in the charcoal filter could be attributed to the high phosphorus concentration in the charcoal as exhibited by the characteristics of the filtered distilled water from that filter in Table 6-2. Unlike the PKS and sand filters, there was a surge in the initial phosphorus content from the charcoal filters increasing the phosphorus concentration in the influent wastewater from 60 mg/L to 79 mg/L. The concentration of phosphorus in the charcoal filters started reducing after 24 hours resulting in a final phosphorus reduction of 20% as shown in Figure 6-6.

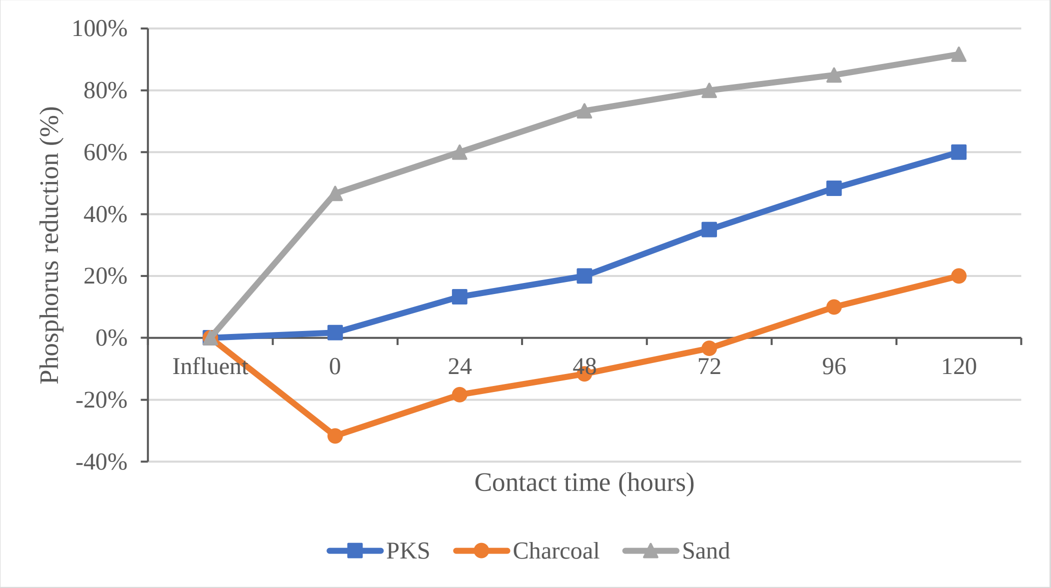

Figure 6-6. Phosphorus removal in palm oil mill wastewater with different filter media

The phosphorus reduction rate in the charcoal filters obtained in this study was far lower than the 98% reduction obtained by Dalahmeh et al. (2012) and marginally higher than the 11-17% in coconut charcoal used by Ahsan et al. (2001). The charcoal used in this study and the study by Ahsan et al. (2001) were not activated as compared to the activated charcoal used by Dalahmeh et al. (2012) and this could have accounted for the wide differences in their removal efficiencies. For sand filters, phosphorus removal rate of 40-60% have been reported (Nielsen et al., 1993). In another study, Kaetzl et al. (2018) recorded 13% phosphorus reductions in biochar filters and 15±8.5% in gravel filters. The relatively lower surface area of the gravel filters as against the sand filters used in this study could be the reason for the higher performance achieved by the sand filters in this study. Analysis of variance in the mean phosphorus concentration among the different media types showed that differences were statistically significant at 1% level ($p<0.01$). A post-hoc test further revealed statistically significant differences at 1% level between combinations of all the media types. This is also exhibited by the wide variations in the absolute values of phosphorus reduction rates recorded for the filters. The sand filter was the best medium followed by PKS in terms of phosphorus removal.

6.4.4.5 Potassium Reduction

The initial concentration of potassium increased after coming into contact with the charcoal leading to 11% increase in the influent potassium concentration (Figure 6-7). The filter medium contributed to the initial poor performance of the charcoal filters as exhibited by the characteristics of distilled water (see Table 6-2).

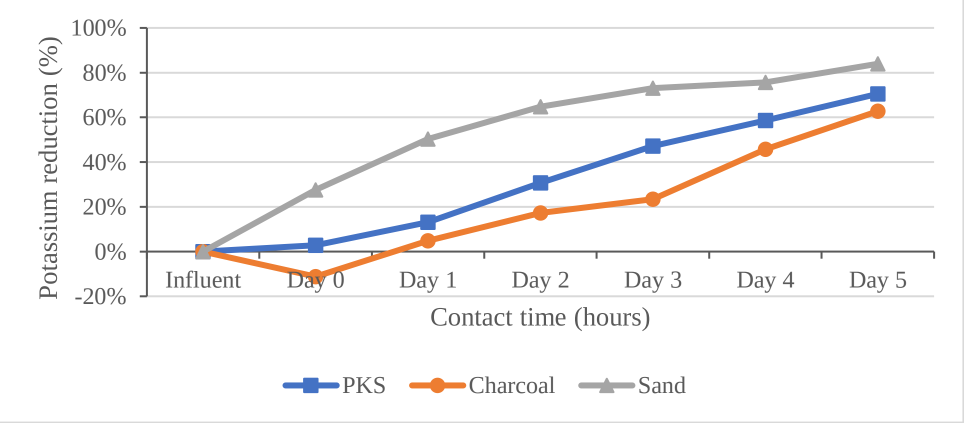

Figure 6-7. Potassium removal in palm oil mill wastewater with different filter media

Subsequently, the performance of the charcoal filter increased over the 120-hour contact time reaching 63% reduction in the potassium concentration at the end of the experiment. However, even though the PKS showed the potential to increase the initial potassium concentration (Table 6-2), this was not observed as an initial potassium reduction of 3% was recorded. This could be due to the low concentration of potassium (247 mg/L) contributed by PKS to the distilled water. It is possibility that much of the potassium concentration from the PKS filter have been removed after the 24-hour contact with the distilled water. After the initially low reductions, the performance of PKS filter increased, leading to 71% reduction. The sand filters reduced the initial potassium concentration by 28% and increased the daily reductions, leading to an overall reduction of 84% at the end of 120 hours. The performance of the different filters was in the order: sand (84%) > PKS (71%) > charcoal (63%).

The differences among the potassium removal efficiencies of the three filter was found to be statistically significant at 1% confidence level. A post-hoc test further revealed statistically significant differences at 1% level between charcoal and sand filters as well as PKS and sand filters but insignificant difference between PKS and charcoal filters ($p>0.05$).

6.4.5 Kinetics models for pollutants removal

From the experimental data, the fitting curve for COD removal studied under PKS column is presented in Figure 6-8 as an example. The kinetic equations for the zero-, 1st-, 2nd- and 3rd-order parameter removal obtained from the fitting curves are presented for PKS column (Table 6-4), sand column (Table 6-5) and charcoal column (Table 6-6). A summary of the selected kinetics models for test parameters (COD, colour, nitrogen, phosphorus and potassium) under PKS, sand and charcoal filter columns are presented in Table 6-7.

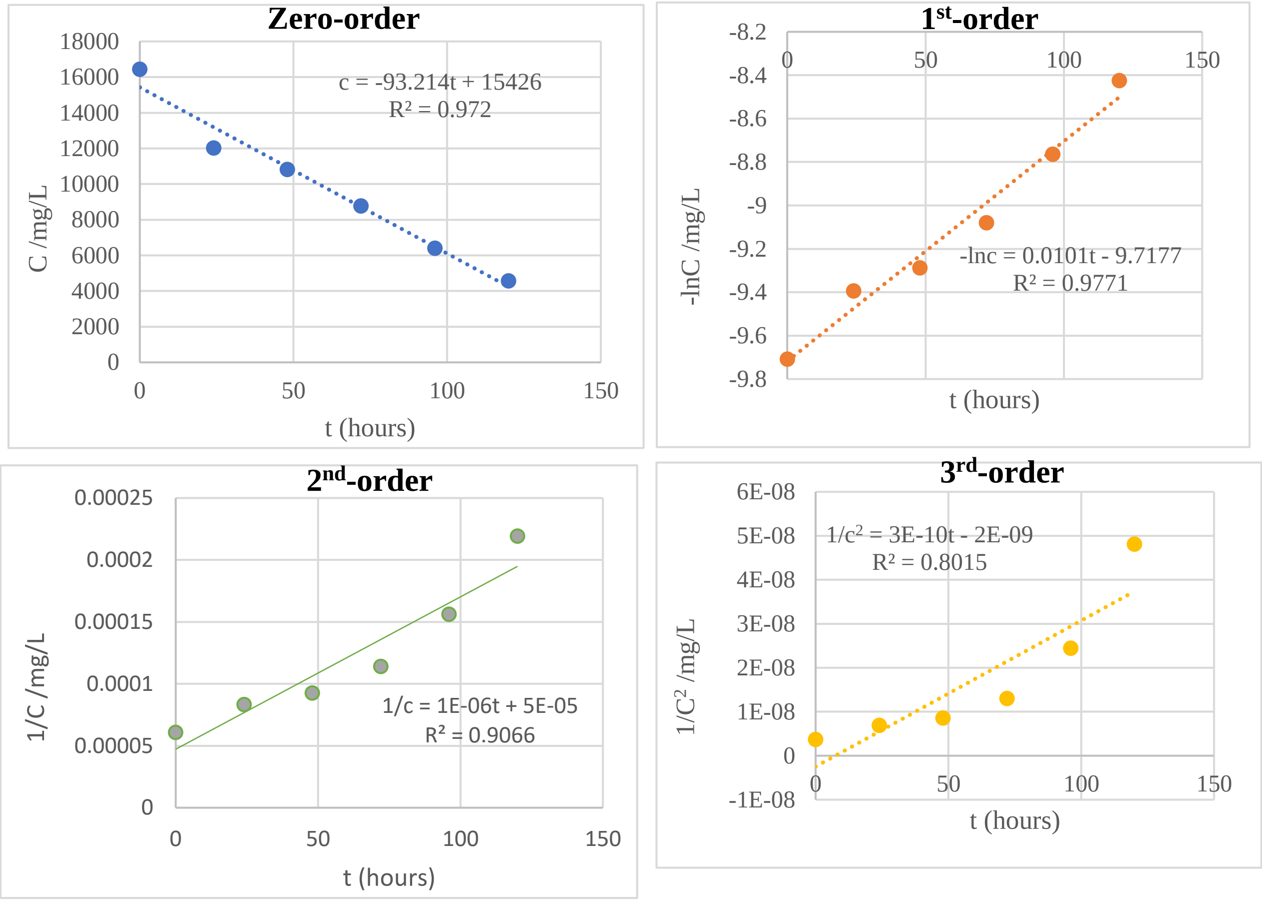

Figure 6-8. Fitting curves for COD removal by PKS column

For the PKS filter column, the nutrients (NPK) removal reactions were consistent with zero-order kinetics model while the COD and colour removal followed the first-order and second-order kinetics model respectively (see Table 6-4). When considering the sand filter columns, the NPK and COD removal followed the first-order kinetics model, but the colour removal followed a zero-order kinetics model (see Table 6-5).

Table 6-4. Linear regression equations for PKS columns

Parameter	**Zero-order**		**1st-order**		**2nd-order**		**3rd-order**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
COD	$c= -93.214t + 15426$	0.972	$-\ln c=0.0101t – 9.7177$	**0.9771**	$1/c=1x10^{-6}t + 5x10^{-5}$	0.9066	$1/c^2=3x10^{-10}t – 3x10^{-9}$	0.8015
Colour	$c= -49.381t + 7526.2$	0.8832	$-\ln c=0.0106t – 8.9579$	0.9585	$1/c=3x10^{-6}t + 0.0001$	**0.9866**	$1/c^2=1x10^{-9}t + 2x10^{-9}$	0.976
Nitrogen	$c= -0.969t + 189.81$	**0.9775**	$-\ln c=0.0087t – 5.2986$	0.9595	$1/c=7x10^{-5}t + 0.0044$	0.8976	$1/c^2=1x10^{-6}t + 5x10^{-6}$	0.8143
Phosphorus	$c= -0.294t + 59.81$	**0.9917**	$-\ln c=0.0074t – 4.1428$	0.9653	$1/c=0.0002t + 0.0141$	0.9125	$1/c^2=1x10^{-5}t + 8x10^{-5}$	0.8425
Potassium	$c= -1.132t + 189.43$	**0.9936**	$-\ln c=0.0101t – 5.3227$	0.9816	$1/c=1x10^{-4}t + 0.0038$	0.9171	$1/c^2=2x10^{-6}t – 2x10^{-5}$	0.8185

The R^2 values in bold indicate the selected kinetics models

Table 6-5. Linear regression equations for sand columns

Parameter	**Zero-order**		**1st-order**		**2nd-order**		**3rd-order**	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
COD	$c= -68.679t + 11972$	0.9397	$-\ln c=0.0089t – 9.4369$	**0.9801**	$1/c=1x10^{-6}t + 7x10^{-5}$	0.9397	$1/c^2=4x10^{-10}t + 3x10^{-10}$	0.844
Colour	$c= -42.369t + 8520.5$	**0.9719**	$-\ln c=0.0079t – 9.1166$	0.9131	$1/c=2x10^{-6}t + 9x10^{-5}$	0.8258	$1/c^2=7x10^{-10}t – 3x10^{-10}$	0.7295
Nitrogen	$c= -0.7631t + 143.62$	0.9292	$-\ln c=0.0079t – 5.0053$	**0.9593**	$1/c=9x10^{-5}t + 0.0061$	0.9304	$1/c^2=2x10^{-6}t + 2x10^{-5}$	0.8566
Phosphorus	$c= -0.219t + 29.476$	0.9571	$-\ln c=0.0149t – 3.5117$	**0.9859**	$1/c=0.0013t + 0.0117$	0.8602	$1/c^2=0.0003t – 0.0054$	0.6895
Potassium	$c= -0.8429t + 122.9$	0.904	$-\ln c=0.0118t – 4.8708$	**0.9788**	$1/c=0.0002t + 0.0059$	0.9444	$1/c^2=7x10^{-6}t – 6x10^{-5}$	0.8266

The R^2 values in bold indicate the selected kinetics models

Table 6-6. Linear regression equations for charcoal column

Parameter	Zero-order		1st-order		2nd-order		3rd-order	
	Equation	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**	**Equation**	**R^2**
COD	$c= -112.26t + 16549$	**0.9781**	$-\ln c=0.0126t - 9.822$	0.9755	$1/c=2\times10^{-6}t + 3\times10^{-5}$	0.9121	$1/c^2=5\times10^{-10}t - 7\times10^{-9}$	0.8268
Colour	$c= -47.667t + 7873.3$	0.989	$-\ln c=0.0101t - 9.0441$	**0.9915**	$1/c=2\times10^{-6}t + 9\times10^{-5}$	0.9375	$1/c^2=1\times10^{-9}t - 7\times10^{-9}$	0.8514
Nitrogen	$c= -0.9214t + 178.62$	**0.9804**	$-\ln c=0.0079t - 5.2366$	0.9686	$1/c=7\times10^{-5}t + 0.0047$	0.9121	$1/c^2=1\times10^{-6}t + 6\times10^{-6}$	0.8318
Phosphorus	$c= -0.2512t + 78.571$	**0.9914**	$-\ln c=0.004t - 4.3795$	0.9826	$1/c=7\times10^{-5}t + 0.0122$	0.9631	$1/c^2=2\times10^{-6}t + 0.0001$	0.935
Potassium	$c= -1.1476t + 216.19$	**0.9797**	$-\ln c=0.0086t - 5.4479$	0.929	$1/c=7\times10^{-5}t + 0.0035$	0.8413	$1/c^2=1\times10^{-6}t - 5\times10^{-6}$	0.7428

The R^2 values in bold indicate the selected kinetics models

Table 6-7. Summary of selected kinetics models of test parameters for PKS, sand and charcoal filter columns

Parameter	PKS		Sand		Charcoal	
	Kinetic equation	**Rate constant**	**Kinetic equation**	**Rate constant**	**Kinetic equation**	**Rate constant**
COD	$-\ln c = 0.0101t - 9.7177$ ($R^2 = 0.9771$)	$k = 0.0101$	$-\ln c = 0.0089t - 9.4369$ ($R^2 = 0.9801$)	$k = 0.0089$	$c = -112.26t + 16549$ ($R^2 = 0.9781$)	$k = -112.26$
Colour	$1/c = 3\times10^{-6}t + 0.0001$ ($R^2 = 0.9866$)	$k = 3 \times 10^{-6}$	$c = -42.369t + 8520.5$ ($R^2 = 0.9719$)	$k = -42.369$	$-\ln c = 0.0101t - 9.0441$ ($R^2 = 0.9915$)	$k = 0.0101$
Nitrogen	$c = -0.969t + 189.81$ ($R^2 = 0.9775$)	$k = -0.969$	$-\ln c = 0.0079t - 5.0053$ ($R^2 = 0.9593$)	$k = 0.0079$	$c = -0.9214t + 178.62$ ($R^2 = 0.9804$)	$k = -0.9214$
Phosphorus	$c = -0.294t + 59.81$ ($R^2 = 0.9917$)	$k = -0.294$	$-\ln c = 0.0149t - 3.5117$ ($R^2 = 0.9859$)	$k = 0.0149$	$c = -0.2512t + 78.571$ ($R^2 = 0.9914$)	$k = -0.2512$
Potassium	$c = -1.132t + 189.43$ ($R^2 = 0.9936$)	$k = -1.132$	$-\ln c = 0.0118t - 4.8708$ ($R^2 = 0.9788$)	$k = 0.0118$	$c = -1.1476t + 216.19$ ($R^2 = 0.9797$)	$k = -1.1476$

Similarly, the specific pollutant removal followed zero-order kinetics model for nitrogen, phosphorus, potassium and COD. However, the colour removal followed a first-order kinetics model (see Table 6-6). The R^2 for the kinetic models selected for COD, colour, nitrogen, phosphorus and potassium removal for all media columns ranged between 0.9593 to 0.9936 (see Table 6-7). The results show that experimental data agreed well with zero-, first- or second-order kinetics model for specific pollutant and media. The margin of deviation of R^2 values from unity indicates the level of irreconcilability of each kinetic model (Amosa et al., 2016). The relatively low reaction rate constant values (k= -0.969 – 0.0149) of the selected kinetics models could have triggered the slow contaminant removal rate as noted also by Yin et al. (2017). On the other hand, the high concentration of influent pollutants could possibly have led to the lower rate constant as compared to other literature results as observed by Shen et al. (2009). The rate of adsorption may be limited by external and internal/intra-particle diffusion and bulk solution transport (Çeçen and Aktaş, 2012). The smaller particle size of the media (1.18mm) used in this study might have contributed to the non-fitting of the kinetics models (Amosa et al., 2016). Large particle sizes have been identified to possess large internal surface area enhancing sorbate diffusion into the internal sites of the adsorbent (Amosa et al., 2014). The effectiveness of the model obtained to describe and approximate the removal kinetics could be affected by the presence of high affinity contaminants present in the effluent (Amosa et al., 2016). These notwithstanding, the removal of specific pollutants using the selected kinetics models agree well with the experimental data (see Table 6-7) with very slight difference due to the small deviation of R^2 (0.0064 – 0.0407) from unity.

6.5 Conclusions

This study assessed the potential of using PKS and charcoal as granular filter media for treating pre-filtered palm oil mill wastewater. PKS filter performance was comparable to charcoal filter for the removal of colour, COD, total nitrogen and potassium but with a better performance for removal of phosphorus. The removal efficiency for PKS filter was in the order COD (77%) > potassium (71%) > colour (69%) > total nitrogen (64%) > phosphorus (60%). Similarly, the performance of charcoal filter for removal of test parameters were in the order COD (80%) > colour (70%) > total nitrogen (66%) > potassium (63%) > phosphorus (20%). In comparing with the reference media (sand) the performances of PKS and charcoal filters were relatively lower.

Removal of specific pollutants using PKS, charcoal and sand columns can be described and approximated using differently selected kinetics models (R^2=0.9593 – 0.9936). The removal of specific pollutants using the selected kinetics models agree well with the experimental data with very slight differences due to the small deviation of R^2 (0.0064 – 0.0407) from unity. However, none of the filters was able to reduce the influent concentration below the acceptable limit for discharge into the environment. At low pollutant loading rates, PKS filter could have a great potential for treating wastewater to achieve a reusable limit of pollutants. Further laboratory-scale studies on pre-filtered palm oil mill wastewater may be conducted using the PKS as granular media but at a longer contact time.

7 CHAPTER SEVEN

CONCLUSIONS, IMPLICATIONS AND CONTRIBUTION TO KNOWLEDGE

7.1 Introduction

In Ghana, palm oil processing is dominated by the small-scale mills which employs less efficient processing techniques. They are also reported to be non-compliant with environmental regulations. Notwithstanding, irrespective of the efficiency of the processing methods employed, palm oil extraction is a water-consuming and wastewater producing activity. Knowing the wastewater sources, generation rates and characteristics will enable the selection of appropriate and sustainable management solutions for the small-scale industry. In this study, the sources and quantity of water used, the rate of generation and quality of wastewater produced from small-scale palm oil processing mills in Ghana were assessed. In addition, palm empty fruit bunch fibre was used for solids-liquid separation of the wastewater and the sludge was sun-dried to assess its potential uses as a soil conditioner or solid fuel. Subsequently, the potential of using palm kernel shell and charcoal as granular media for treating the effluent from the solids-liquid separation was evaluated in a column filtration.

7.2 Conclusions on Research Objectives

7.2.1 Water consumption, wastewater production and disposal practices

This aspect of the study was aimed at assessing the water usage, wastewater return factors and wastewater disposal practices by small-scale palm oil processing mills in the Central Region of Ghana. The unit processes which consumed fresh water and generated wastewater were boiling of fresh fruits, extraction of oil (optional), and cleaning of working tools. Water for processing was sourced from protected hand dug wells, piped water from public standpipes, boreholes with handpumps, unprotected hand-dug wells and rivers/streams. The proportion of water from each source used by the mills reflect the types of water sources available to the inhabitants of the study communities. The distance to the water source influenced the consumption rate, with higher water consumption being associated with processing mills with on-plot water sources. The price of water paid by the processing mills was the same as the price paid by householders who fetched water for domestic use. The price of water did not influence the consumption. For a litre of crude palm oil extracted, 0.76-2.39 litres of water was used with a wastewater return factor of 68-82%. Boiling of fresh fruits is the major consumer of water and producer of wastewater. Wastewater produced by the processing activities are discharged on the bare land without treatment. The findings of this study affirm previous concerns raised about the apparent disregard for environmental regulations and wastewater discharge standards. It, therefore, calls for a scientific determination of the characteristics of the wastewater that is discharged into the environment without any form of treatment.

7.2.2 Seasonal and source characterization of POME

This study characterized palm oil mill wastewater from different streams and seasons sampled from small-scale processing mills in the Central Region of Ghana. The characteristics of the palm oil mill wastewater shows variation in wastewater characteristics with source and season. The wastewater was generally characterized by low pH, high oxygen consuming compounds (BOD_5 and COD), low solids content, high nutrients (total nitrogen, phosphorus and potassium) and appreciable quantity of unrecovered fats and oils contents. The mean characteristics of wastewater produced during the peak season were generally higher than the lean season except for pH and solids (total and suspended). Irrespective of the production season, the wastewater was characterized by slowly biodegradable organic matter. Wastewater from clarification had higher solids and nutrients content but lower oxygen-consuming compounds compared with wastewater from boiling. Comparing the results with the Ghana Effluent Discharge Standard (GEDS), 85% (6 out of 7) of the parameters had mean concentrations far higher than the standard. The concentrations of most of the parameters were over 2-order of magnitude higher than the standard. The characteristics of the palm oil mill effluent brings to the fore, the need to explore environmentally friendly and appropriate technologies for wastewater treatment and reuse at the small-scale palm oil industry. The current practice of disposing raw wastewater into the natural environment by the small-scale processing mills is negatively affecting the environment. Hence, there is the need to explore opportunities for recovering useful resources from the wastewater in order to minimise its impact on the environment and to introduce the practice of circular economy into the operation of the small-scale palm oil extraction industry in Ghana.

7.2.3 Solids-liquid separation and solar drying of palm oil mill effluent sludge to assess sludge reuse potential

In this study, solids-liquid separation of palm oil mill wastewater was carried out using empty palm fruit bunch fibre, which is a by-product of the palm oil extraction process. The EFB fibre was able to achieve a remarkable removal efficiency for suspended solids. An average daily temperature of 27°C and 31°C for 14 days was able to dry the solids to less than ten percent moisture content. The nutrient content of the dried sludge shows its potential for use as a soil conditioner. In addition, the moisture content and calorific value suggest that sun-dried palm oil mill wastewater sludge possesses suitable calorific value to be used as solid fuel especially for palm oil processing. Open-air sun drying of palm oil mill sludge into biofuel and soil conditioner shows great potential as renewable resource. The successful application of the EFB for removal of solids and the potential of the sun-dried palm oil mill wastewater sludge as a solid fuel are encouraging examples of the promising practice of circular economy in the small-scale palm oil extraction industry. This provided inspiration for examining the potential reuse of other palm oil extraction by-products such as palm kernel shells (PKS) as an input for the sustainable management of other waste by-products to minimise environmental pollution.

7.2.4 Potential use of palm kernel shell and charcoal as granular filter media for treating pre-filtered POME

This study assessed the potential of using PKS and charcoal as granular filter media for treating pre-filtered palm oil mill wastewater. PKS filter performance was comparable to charcoal filter for the removal of colour, COD, total nitrogen and potassium but with a better performance for removal of phosphorus. The removal efficiency for PKS filter was in the order COD (77%) > potassium (71%) > colour (69%) > total nitrogen (64%) > phosphorus (60%). Similarly, the removal efficiency for charcoal filter was in the order COD (80%) > colour (70%) > total nitrogen (66%) > potassium (63%) > phosphorus (20%). In comparing with the reference media (sand) the performance of PKS and charcoal filters were relatively lower. Removal of specific pollutants using PKS, charcoal and sand columns can be described and approximated using differently selected kinetics models (R^2=0.9593 – 0.9936). The removal of specific pollutants using the selected kinetics models agree well with the experimental data with very slight differences due to the small deviation of R^2 (0.0064 – 0.0407) from unity. However, none of the filters was able to reduce the influent concentration below acceptable limit for discharge into the environment. At low organic loading rates, PKS filter could have great potential for treating wastewater to achieve reusable standards.

7.3 Implications of the Study

7.3.1 Implications for policy and practice

While the Government of Ghana is seeking to increase palm oil production to meet domestic needs and for export, greater quantities of water will be required and consequently higher quantities of wastewater will be generated. There is the need for a policy intervention to encourage water-use efficiency among the small-scale palm oil mills. On paper, the Ghana Small Towns Operation and Maintenance Guidelines (CWSA, 2010b) provides that the unit rate of tariff for small-scale commercial entities shall be 140-150% of the normal tariff for standpipe (domestic) customers. However, this study found no distinction between the price of water for domestic or industrial uses since they all obtain from public standpoints. The price of water paid by the small-scale mills may not encourage water-use efficiency. For commercial and industrial use, the price of water should be relatively higher than for domestic use in order to reduce competition and encourage water-use efficiency and recycling by commercial and industrial entities. In this direction, the Community Water and Sanitation Agency (CWSA) should device an implementation arrangement for its policy of commercial and industrial water consumers paying a higher tariff than domestic consumers.

In terms of the percentage contribution, about 70% of the total water consumption is used for boiling. A shift from the current method of boiling where fruits are submerged in water to steam sterilization could significantly reduce the amount of water used for boiling. This could further reduce the total quantity of water used and consequently the wastewater generation rate.

Wastewater is currently disposed on the bare ground without any form of treatment. Considering the characteristics and wastewater disposal practices, particular attention should be paid to the small-scale processing mills which dominate the palm oil production sector. The Ghana Environmental Protection Agency, which is responsible for ensuring environmental compliance in Ghana, should extend enforcement of the Ghana Environmental Protection Requirements for Effluent Discharge to the small-scale (cottage) industries to ensure compliance. The government of Ghana, acting through the relevant agencies and the Artisanal Palm Oil Millers and Outgrowers Association, should provide technical support on sustainable waste management to the small-scale processing mills.

7.3.2 Implications for further research

This study focused on the Central Region of Ghana. Additional studies are needed in other palm oil production regions of Ghana to confirm the findings on the sources and quantities of water for processing a unit quantity of palm oil. Moreover, the quantity and quality of the wastewater produced in these regions need to be determined to generate national-level data. A comprehensive data on the sources of water and quantities for small-scale processing of palm oil would provide useful inputs into future designs of small towns water supply projects in palm-oil-producing communities in Ghana. Findings from the studies on wastewater quantities and characteristics will guide the development of a compendium of wastewater treatment technologies applicable to small-scale processing mills in Ghana.

Moreover, research must be directed towards finding appropriate wastewater treatment technologies adaptable in resource-constrained environments such as pertains in small towns and villages where small-scale mills are located. The choice of management solutions should therefore be ‘appropriate’ and must, among other factors, be environmentally friendly, sustainable, affordable, easy to operate and maintain by the local community, utilizes local materials and resources, and considers gender issues. Additionally, emphasis should be placed on technologies that could be scaled for different hydraulic and organic loading rates.

Palm oil mill wastewater sludge was sun dried for 14 days. Further research may focus on optimization of the drying techniques and enhancing the calorific value of the sludge. To better understand the valorisation potential of the dried sludge and EFBs, future research could focus on examining the EFBs and sludge using Thermal Gravimetric Analysis (TGA), Scanning Electron Microscope (SEM), Energy Dispersive X-ray (EDX) Analysis and X-ray Fluorescence (XRF). Further studies are also required to determine the impact of the dried sludge as soil conditioner on the physical, chemical or biological characteristics of soils. Furthermore, palm oil mill wastewater sludge was sun dried in this study at an experimental level. The solids-liquid separation and sun drying processes can be adopted and implemented on a pilot scale at one of the processing mills. The data derived from the pilot study would aid the understanding and optimization of the operational parameters for upscaling. Open-air solar drying of sludge during the rainy seasons could be problematic due to the potential intermittent wetting and drying. For use of drying beds in both dry and rainy seasons, the pilot study could consider the use of transparent roofed drying beds. Other low-energy and short-duration drying techniques may be explored.

7.4 Contribution to Knowledge

The Ghanaian palm oil production industry is dominated by small scale mills, which account for about 80% of the national production output. However, until this one, there had been virtually no scientific studies to generate locally-specific data on the water consumption, wastewater generation and characteristics to guide the development of sustainable local solutions for mitigating the environmental impact of the industry within the framework of circular economy.

In particular, the contribution of this study to the body of knowledge on the subject matter include the following:

- Determination of water usage per unit volume of palm oil produced to support the planning of water demand in the rural communities where small-scale palm oil production mills are mostly located: this will help to avoid underestimation of water demand and competition between domestic water needs and that of the palm oil production industry due to the absence of scientific data on the industry’s water consumption rate.
- Establishment of the generation rate and characteristics of palm oil mill effluent (POME) in Ghana, which provides insight into the potential impact of the discharge of untreated POME into the environment: this affords a scientific basis for identifying the kind of technological solutions that may be required to treat the effluent before disposal and derive beneficial materials and energy from the waste by-products of the industry.
- Demonstration of the potential of using EFB fibre to dewater POME and solar drying of the sludge for use as a soil conditioner or solid fuel: to the best of this author’s knowledge, this is the first study to determine the nutrients content and calorific value of sun-dried palm oil mill wastewater sludge.

- Evaluation of the suitability of palm kernel shell (PKS) as a granular medium for filtration: prior to this study, PKS had been prepared into activated carbon for use as adsorbent for wastewater treatment (Mohammad Razi et al., 2018), dye removal (García et al., 2018), carbon dioxide capture (Rashidi and Yusup, 2019, Hidayu and Muda, 2016), nitrogen dioxide and ammonia removal (Guo and Lua, 2003) but not as granular filter media for POME treatment. This study has assessed the potential of using PKS as granular filter media for POME treatment, albeit, at low organic loading rates. The findings of this study could stimulate studies on the use of PKS as granular media for filtration.

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APPENDICES

Appendix A – Data Collection Instrument

A. General Information

1. District: …………………………………………………………………….…….................

2. Name of Processing Facility: ………………………………………….………..................

3. Location of production premises (Town/Community): …………………………....................

4. GPS Coordinates: Longitude: ………….…........... Latitude: ……………………

5. Contact Person (optional): ……………………..... 6. Tel number (optional):…………....

7. Sex: A. Male B. Female 8. Age: ……………………….……..

9. Educational background A. No education B. Basic (did not complete JHS) C. Basic (Completed JHS) D. Secondary/Technical/Vocation E. Tertiary or above

10. Quantity of FFB processed per cycle (Kg / tons): ……………………..……………….......

11. Quantity of Palm oil Produced (Lit/Gal): ……….……………………………………….....

B. Water Usage

12. Main source of water for production A. Groundwater (hand-dug well/borehole)

B. Rain water C. Untreated surface water (river/stream/pond etc.) D Treated piped water

E. Others (specify: ………………………………………………………………………

13. Distance of water source from point of water storage A. Less than 100m B. 100—200m

C. 200—500m D. 500m—1km E. More than 1km

14. Water storage capacity (lits): ………………………………………………………………

15. Type of water charge A. Free of charge B. Flat rate per month C. Per quantity fetched

16. Cost of water A. Free of charge B. GH¢……………………......................................

17. Mode of payment for water A. Pay as you fetch B. Pay at end of month C. Others (Specify): ………………………………………..

18. How does the producer perceive the availability of water A. Easy to get water

B. Difficult to get water C. Normal

19. Does the producer adopt any measures to control or manage the quantity of water used?

A. Yes B. No

20. If Yes (question 18), what measures does he/she adopt to manage/control water usage?

…………………………………………………………………………………………............

Production Process, Water usage and Wastewater generation

Process	Process	Technology used	Duration	Water usage		Wastewater production	
			(hours or days)	Source	Vol (lits.)	Vol (lits.)	Disposal method
Receipt and weighing of FFB							
Quartering of FFB							
Storage of quartered FFB							
Threshing/ Stripping of fruits							
Cleaning of stripped fruits							
Boiling/sterilization of fresh fruits							
Digestion / pounding							
Oil Extraction / Pressing of digested fruits							
Clarification of Crude Palm oil							
Cleaning of working tools and equipment							

FFB – Fresh Fruit Bunches

Appendix B – Daily Quantities of Water Usage and Wastewater Production by Small-scale palm oil processing mills in Central Region, Ghana

Processing mills	Quantity of palm oil produced per day (Litres)	No. of people involved per day	Water usage			Wastewater production		
			Quantity per Litre of oil (Litres)	Daily quantities (Litres)	Potential no. of domestic users to be served[a]	Quantities Per litre of oil (Litres)	Daily quantities (Litres)	Potential no. of domestic producers[b]
PM 1	375	15	1.55	580.00	29	1.13	424.70	27
PM 2	500	12	1.28	640.00	32	1.00	500.80	31
PM 3	300	15	1.80	540.00	27	1.42	426.15	27
PM 4	720	12	1.06	765.00	38	0.76	549.00	34
PM 5	348	18	1.98	690.00	35	1.46	507.30	32
PM 6	375	15	1.57	590.00	30	1.24	463.80	29
PM 7	280	12	1.69	472.00	24	1.25	350.72	22
PM 8	325	15	1.85	600.00	30	1.43	463.75	29
PM 9	288	12	2.04	588.00	29	1.59	457.68	29
PM 10	170	10	2.06	350.00	18	1.64	279.50	17
PM 11	288	12	2.31	666.00	33	1.89	543.72	34
PM 12	606	9	1.62	984.00	49	1.26	762.00	48
PM 13	668	12	1.17	780.00	39	0.92	616.40	39
PM 14	425	15	1.74	740.00	37	1.29	546.30	34
PM 15	400	12	1.80	720.00	36	1.37	547.20	34
PM 16	475	15	1.87	890.00	45	1.48	702.30	44

PM 17	630	4	1.08	680.00	34	0.79	499.40	31
PM 18	835	15	1.07	890.00	45	0.80	666.10	42
PM 19	280	15	1.61	450.00	23	1.25	350.50	22
PM 20	150	12	2.32	348.00	17	1.75	262.56	16
PM 21	115	10	2.39	275.00	14	1.81	207.75	13
PM 22	250	15	1.96	490.00	25	1.47	366.40	23
PM 23	300	18	1.56	468.00	23	1.20	360.00	23
PM 24	750	15	1.13	850.00	43	0.77	576.50	36
PM 25	750	8	0.76	570.00	29	0.57	426.30	27
Average	**424**	**13**	**1.65**	**624.64**	**31**	**1.26**	**474.27**	**30**

[a] Based on CWSA design guide of 20 litres/capita/day for standpipes (CWSA 2010)

[b] Based on domestic wastewater return factor of 80% (Mara 2013)