Case Studies in Chemical and Environmental Engineering 2 (2020) 100057

Contents lists available at ScienceDirect

Case Studies in Chemical and Environmental Engineering

journal homepage: www.editorialmanager.com/cscee/default.aspx

Solids-liquid separation and solar drying of palm oil mill wastewater sludge: Potential for sludge reuse

Eric Awere [a,c,*], Alessandra Bonoli [a], Peter Appiah Obeng [b]

[a] DICAM, University of Bologna, Via Terracini 28, 40131, Bologna, Italy
[b] Department of Water and Sanitation, University of Cape Coast, Cape Coast, Ghana
[c] Department of Civil Engineering, Cape Coast Technical University, Cape Coast, Ghana

ARTICLE INFO

Keywords:
Calorific value
Empty palm fruit bunch fibre
Solid fuel
Soil conditioner
Solid-liquid separation
Palm oil mill wastewater

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.

1. Introduction

Palm oil is a very essential vegetable oil for both domestic and industrial uses. In the last decade, global consumption has outpaced soybean oil [1]. Palm oil is extracted from fresh fruit bunches (FFB) through a 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). POME 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) contents of POME are 17,000–26,700 mg/L and 42,900–88,250 mg/L respectively [2]. However, the wastewater also contains solids and essential plant nutrients that could be harnessed for beneficial use. Department of Environment [3] 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 [3]. The total solids and essential nutrients content of POME indicate the need for cost-effective methods for recovery and utilization of the solids.

Hassan et al. [4] 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 [5] or sand beds. But other waste materials from the palm oil industry have been used in POME treatment. For instance, Hassan et al. [6] 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 [7,8] and biodegradable [9,10] properties 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) [11]. 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 [12]. It has therefore been recommended for small-scale drying [13] and sludge recovery in low-income countries [11]. Such simple and low-cost technologies have been successfully applied in Sub-Saharan Africa for drying of faecal

*Corresponding author. DICAM, University of Bologna, Via Terracini 28, 40131, Bologna, Italy.
E-mail address: eric.awere2@unibo.it (E. Awere).

https://doi.org/10.1016/j.cscee.2020.100057
Received 29 September 2020; Received in revised form 8 November 2020; Accepted 10 November 2020

sludge [12,14–16].

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.

2. Materials and methods

2.1. 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. 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 within a production cycle.

2.2. Description of solid-liquid separator

The solid-liquid separator was made up of rectangular wooden mould (dimensions 30 cm × 40 cm) with wire mess (aperture 1.2 × 1.2 cm) at one end (see Fig. 1). Solids-liquid separation of the raw wastewater was performed using empty palm fruit bunch fibre.

In selecting the material for the solids-liquid separation, emphasis was placed on using combustible and decomposable waste from the palm oil extraction industry. Mesocarp fibre was not chosen as the filter material because it mostly contains high proportion of unrecovered oils which could limit their potential use as soil conditioner. The empty fruit bunches were washed with distilled water to remove any dirt on them.

It was then crushed twice with a 700 g rod to maximize retting process as used by Ruan et al. [17]. The crushed EFBs were soaked in distilled water for 7 days at room temperature to loosen the fibres (a process called water retting) [18]). Subsequently, the fibres were separated manually, and sun dried for 3 days to ensure the fibres were well dried. The dried fibres were manually fitted and 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.

2.3. Experimental setup

Composite wastewater sample of volume, 9.5 L 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 30 mins. A filtrate of volume 6.5 L was collected from each of the moulds into a container for use in a granular filter column experiment. The volume of wet solids retained on the fibre was 31.6% of the total volume. 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 [14]. The mass of each mould together with the contents was measured every evening at sunset. After the 14 days, the dried sludge was analyzed for moisture content, nutrients content (total nitrogen, phosphorus and potassium) and calorific value.

2.4. Determination of wastewater characteristics

Laboratory analysis was performed on the wastewater before and after the solids-liquid separation. 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 other 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 [19]. All analyses were performed in triplicates and the mean values taken.

2.5. 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 min;
- 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. [20]. One gram of the sample was fetched into the crucible in the bomb calorimeter. After about 10 min 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.

2.6. Determination of nutrient content of dried sludge

The nutrients measured were total nitrogen, phosphorus, and

Fig. 1. Components of the solids-liquid separation setup (a) EFB fibre (b) separator box.

potassium. Prior to the determination of the nutrients content, the samples were dried at 60 °C for 3 h to further reduce its moisture content. The samples were then milled to increase the 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 process and nutrients analysis followed the procedure outlined in Stewart et al. [21]. Each analysis was performed in triplicates and the mean value taken.

2.7. Statistical analysis

Data analysis was done using Microsoft Excel. All data sets 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 ($\alpha = 0.05$) was used to test for statistically significant differences.

3. Results and discussions

3.1. Efficiency of solids-liquid separation

Table 1 shows the efficiency of the EFB fibre in separation of solids and removal of 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. Fig. 2 shows the wastewater before and after the solids-liquid separation.

The removal efficiency was 99.5% for total solids and 99.7% for suspended solids. The removal efficiencies were 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 [16]. The removal efficiency achieved could be attributed to the bulk density (70 kg/m^3) of the fibre in the mould. 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.

The removal efficiency was 64.5% for COD. The fairly high reduction of COD may be associated with the higher solids removal rate achieved. On the other hand, the remaining COD of about 35% could be present in a dissolved form considering 99.7% removal of suspended solids. A much higher COD removal (85–90%) was achieved during solid-liquid separation of faecal sludge in Ghana [16]. 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.

3.2. Drying conditions of palm oil mill wastewater sludge

The characteristics of the EFB fibre and palm oil mill sludge composite is summarized in Table 2. The mean mass of the composite biomass reduced from 2979 g on the 1st day to 274 g 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 Fig. 3. The mass of the dried samples were 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 [22].

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 Fig. 4. The temperatures fluctuated between the 1st day (July 21, 2020) and 7th day (July 27, 2020) and again between 10th day (July 30, 2020) and 14th day (August 3, 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 g) and 5th day (502 g) 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 [23]. The cumulative rate of mass loss over the 14-day period is also presented in Fig. 2.

From Fig. 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 Fig. 5.

A higher rate of mass loss and lower drying time could be achieved in the dry season. The months (July–August) within which the experiment was conducted is considered part of the year with relatively lower average temperatures [24]. Drying time is reported to be shorter under sunny conditions [13]. 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. [25] 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 [14].

3.3. 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 3.

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. These values do not include the nutrients content of the EFB fibre. In terms of dry weight, empty palm fruit bunches is reported to contain 0.86% nitrogen, 0.18% phosphorus and 2.4% potassium [26]. The nutrients content of the composite biomass could therefore be significantly higher should the EFB fibre be included. Physico-chemical analysis of 37 commercial compost from France,

Table 1
Removal efficiency of empty fruit bunch fibre.

	TS	SS	COD	Total nitrogen	Phosphorus	Potassium
Raw Wastewater	3976 (1397)	3618 (1551)	56,357 (3441)	246 (86)	49 (24)	156 (24)
Filtrate	20.3 (2.1)	9.7 (1.3)	19,947 (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.

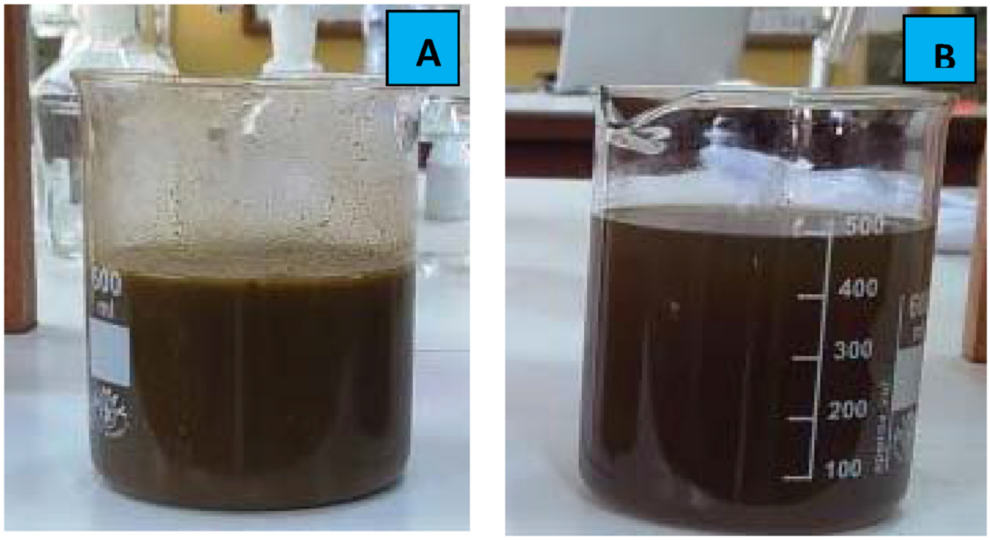

Fig. 2. Palm oil mill wastewater (A) before and (B) after solids-liquid separation.

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

	Mean (SD)		Difference (*p-value*)
	Day 1	Day 14	
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.

Greece and the Netherlands showed typical total nitrogen content of 0.67%–3.8% of dry weight [27]. 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 were within the range of total nitrogen content (0.64–1.54%) of vegetable waste compost reported by Kokkora et al. [28].

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 [10]. The essential nutrient content in the dried sludge from this study were lower than the concentrations reported by Baharuddin et al. [10]. This could be attributed to the characteristics of the wastewater used which is influenced by the processing technique and season [29,30]. 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.

3.4. *Energy value of palm oil mill wastewater sludge*

The moisture content and calorific value of the dried POME sludge and other solid fuels from literature are presented in Table 4.

3.4.1. *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 [33]. The recommended moisture content for firewood is 10–20% of the total weight [34,35]. The maximum moisture content required for reuse of dried faecal sludge as biofuel is 20% [36]. Using convective and infrared drying rigs at variable drying temperatures and residence time, the moisture content of faecal sludge waste was

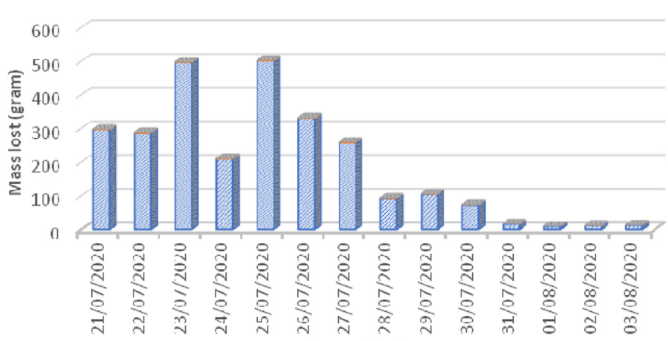

Fig. 3. Mean daily mass loss during the 14 days of drying.

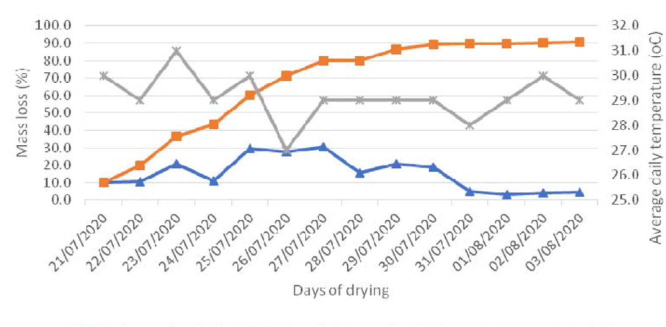

Fig. 4. Percentage daily mass loss during the 14 days of drying.

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

obtained as 5–74% (wet basis) [32]. 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 [36].

3.4.2. Calorific value

The calorific value of the sun-dried sludge was 15.3–18.5 MJ/kg. In a study, Nyakuma et al. [31] 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 used as fuel briquette had a calorific value of 18–26 MJ/kg based on the proportions of POME sludge and palm frond waste [6]. Similar to palm oil mill wastewater sludge, Gold et al. [15] demonstrated through a pilot study that dried faecal sludge could 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 temperature (40–80 °C) and residence time (4–25 min) was reported by Septien et al. [32] 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.

4. 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 suggest 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.

Table 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.

Table 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. [31]
Faecal sludge	Convective drying rig	5–10	13.3–13.7	Septien et al. [32]
Palm oil mill sludge and palm fronds briquette	Oven drying	10.3 (POME sludge) 3.73 (palm fronds)	18–26	Hassan et al. [6]
Separator Sludge from clarification tank[a]	Oven drying	–	16.13 ± 3.73	Loh [33]

[a] Moisture free sludge.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] M. Shahbandeh, Vegetable oil: global consumption by oil type 2013/14 to 2019/20, statista. https://www.statista.com/statistics/613471/palm-oil-production-volume-worldwide/, 2020. (Accessed 19 September 2020).
[2] G. Najafpour, A. Zinatizadeh, A. Mohamed, M.H. Isa, H. Nasrollahzadeh, High-rate anaerobic digestion of palm oil mill effluent in an upflow anaerobic sludge-fixed film bioreactor, Process Biochem. 41 (2006) 370–379, https://doi.org/10.1016/j.procbio.2005.06.031.
[3] Department of Environment, Industrial Processes and the Environment (Handbook No. 3): Crude Palm Oil Industry, Department of Environment, Malaysia, 1999.
[4] M.A. Hassan, S. Yacob, Y. Shirai, Y.-T. Hung, Treatment of palm oil wastewaters, in: L.K. Wang, Y.-T. Hung, H.H. Lo, C. Yapijakis (Eds.), Handbook of Industrial and Hazardous Wastes Treatment, Marcel Dekker, New York, 2004, pp. 776–796.
[5] D. Fytili, A. Zabaniotou, Utilization of sewage sludge in EU application of old and new methods—a review, Renew. Sustain. Energy Rev. 12 (2008) 116–140, https://doi.org/10.1016/j.rser.2006.05.014.
[6] S. Hassan, L. Kee, H.H. Al-Kayiem, Experimental study of palm oil mill effluent and oil palm frond waste mixture as an alternative biomass fuel, J. Eng. Sci. Technol. 8 (2013) 703–712.
[7] M.F.M. Batcha, M.F. Othaman, S. Sabudin, A.N. Mohammed, M.K. Abdullah, M.F.M. Ali, Combustion and emission of pelletized empty fruit bunch and oil palm shell in a swirling fluidized bed combustor, Biomass Convers. Biorefin. 10 (2020) 755–763, https://doi.org/10.1007/s13399-020-00903-x.
[8] P. Ninduangdee, V.I. Kuprianov, A study on combustion of oil palm empty fruit bunch in a fluidized bed using alternative bed materials: performance, emissions, and time-domain changes in the bed condition, Appl. Energy 176 (2016) 34–48, https://doi.org/10.1016/j.apenergy.2016.05.063.

[9] Z. Nahrul Hayawin, A.A. Astimar, M. Anis, M.H. Ibrahim, H.P.S.A. Khalil, Z. Ibrahim, Vermicomposting of empty fruit bunch with addition of solid palm oil mill effluent, J. Oil Palm Res. 24 (2012) 1542–1549.
[10] A.S. Baharuddin, M. Wakisaka, Y. Shirai, S. Abd-Aziz, R. Abdul, M. Hassan, Co-composting of empty fruit bunches and partially treated palm oil mill effluents in pilot scale, Int. J. Agric. Res. 4 (2009) 69–78, https://doi.org/10.3923/ijar.2009.69.78.
[11] G. Tchobanoglous, F.L. Burton, H.D. Stensel, Metcalf & Eddy Inc, F. Burton, Wastewater Engineering: Treatment and Reuse, McGraw-Hill Education, Boston, 2003.
[12] A. Seck, M. Gold, S. Niang, M. Mbéguéré, C. Diop, L. Strande, Faecal sludge drying beds: increasing drying rates for fuel resource recovery in Sub-Saharan Africa, J. Water, Sanit. Hyg. Dev. 5 (2015) 72–80, https://doi.org/10.2166/washdev.2014.213.
[13] A. Tiwari, A review on solar drying of agricultural produce, J. Food Process. Technol. Society 7 (2016) 623, https://doi.org/10.4172/2157-7110.1000623.
[14] A.M. Muspratt, T. Nakato, C. Niwagaba, H. Dione, J. Kang, L. Stupin, J. Regulinski, M. Mbéguéré, L. Strande, Fuel potential of faecal sludge: calorific value results from Uganda, Ghana and Senegal, J. Water, Sanit. Hyg. Dev. 4 (2014) 223–230, https://doi.org/10.4172/2157-7110.1000623.
[15] M. Gold, D.I.W. Ddiba, A. Seck, P. Sekigongo, A. Diene, S. Diaw, S. Niang, C. Niwagaba, L. Strande, Faecal sludge as a solid industrial fuel: a pilot-scale study, J. Water, Sanit. Hyg. Dev. 7 (2017) 243–251, https://doi.org/10.2166/washdev.2017.089.
[16] O.O. Cofie, S. Agbottah, M. Strauss, H. Esseku, A. Montangero, E. Awuah, D. Kone, Solid–liquid separation of faecal sludge using drying beds in Ghana: implications for nutrient recycling in urban agriculture, Water Res. 40 (2006) 75–82, https://doi.org/10.1016/j.watres.2005.10.023.
[17] P. Ruan, V. Raghavan, Y. Gariepy, J. Du, Characterization of flax water retting of different durations in laboratory condition and evaluation of its fiber properties, Bioresources 10 (2015) 3553–3563.
[18] Z. Jankauskienė, B. Butkutė, E. Gruzdevienė, J. Cesevičienė, A.L. Fernando, Chemical composition and physical properties of dew-and water-retted hemp fibers, Ind. Crop. Prod. 75 (2015) 206–211, https://doi.org/10.1016/j.indcrop.2015.06.044.
[19] APHA, AWWA, WEF, Standard Methods for the Examination of Water and Wastewater, 23rd ed., American Public Health Association, Washington, DC, 2017.
[20] G.Y. Obeng, D.Y. Amoah, R. Opoku, C.K. Sekyere, E.A. Adjei, E. Mensah, Coconut wastes as bioresource for sustainable energy: quantifying wastes, calorific values and emissions in Ghana, Energies 13 (2020) 2178, https://doi.org/10.3390/en13092178.
[21] E.A. Stewart, H.M. Grimshaw, J.A. Parkinson, C. Quarmby, Chemical Analysis of Ecological Material, Black-Well Scientific Publication, Oxford, 1974.
[22] N. Farhat, Effect of relative humidity on evaporation rates in Nabatieh Region, Leban. Sci. J. 19 (2018) 59–66, https://doi.org/10.22453/LSJ-019.1.059-066.
[23] G. Yaciuk, 24 - solar crop drying, in: A.F. Janzen, R.K. Swartman (Eds.), Solar Energy Conversion II, Pergamon, 1981, pp. 377–396, https://doi.org/10.1016/B978-0-08-025388-6.50049-0.
[24] Weatherspark, Average weather in Cape Coast, Ghana. https://weatherspark.com/y/40140/Average-Weather-in-Cape-Coast-Ghana-Year-Round#Sections-Precipitation, 2020. (Accessed 16 August 2020).
[25] N.K. Salihoglu, V. Pinarli, G. Salihoglu, Solar drying in sludge management in Turkey, Renew. Energy 32 (2007) 1661–1675, https://doi.org/10.1016/j.renene.2006.08.001.
[26] A. Yahya, C.P. Sye, T.A. Ishola, H. Suryanto, Effect of adding palm oil mill decanter cake slurry with regular turning operation on the composting process and quality of compost from oil palm empty fruit bunches, Bioresour. Technol. 101 (2010) 8736–8741, https://doi.org/10.1016/j.biortech.2010.05.073.
[27] S. Zmora-Nahum, Y. Hadar, Y. Chen, Physico-chemical properties of commercial composts varying in their source materials and country of origin, Soil Biol. Biochem. 39 (2007) 1263–1276, https://doi.org/10.1016/j.soilbio.2006.12.017.
[28] M.I. Kokkora, D.L. Antille, S.F. Tyrrel, Considerations for recycling of compost and biosolids in agricultural soil, in: A.P. Dedousis, T. Bartzanas (Eds.), Soil Engineering, Springer Berlin Heidelberg, Berlin, Heidelberg, 2010, pp. 195–215, https://doi.org/10.1007/978-3-642-03681-1_13.
[29] T.Y. Wu, A.W. Mohammad, J.M. Jahim, N. Anuar, Pollution control technologies for the treatment of palm oil mill effluent (POME) through end-of-pipe processes, J. Environ. Manag. 91 (2010) 1467–1490, https://doi.org/10.1016/j.jenvman.2010.02.008.
[30] B. Yusof, D. Ariffin, The oil palm industry-from pollution to zero waste, Planter 72 (1996) 141–165.
[31] B.B. Nyakuma, A. Johari, A. Ahmad, T.A.T. Abdullah, Comparative analysis of the calorific fuel properties of empty fruit bunch fiber and briquette, Energy Procedia 52 (2014) 466–473, https://doi.org/10.1016/j.egypro.2014.07.099.
[32] S. Septien, S.W. Mirara, B.S.N. Makununika, A. Singh, J. Pocock, K. Velkushanova, C.A. Buckley, Effect of drying on the physical and chemical properties of faecal sludge for its reuse, J. Environ. Chem. Eng. 8 (2020), https://doi.org/10.1016/j.jece.2019.103652, 103652-103652.
[33] S.K. Loh, The potential of the Malaysian oil palm biomass as a renewable energy source, Energy Convers. Manag. 141 (2017) 285–298, https://doi.org/10.1016/j.enconman.2016.08.081.
[34] T. Nord-Larsen, A. Bergstedt, O. Farver, N. Heding, Drying of firewood – the effect of harvesting time, tree species and shelter of stacked wood, Biomass Bioenergy 35 (2011) 2993–2998, https://doi.org/10.1016/j.biombioe.2011.03.039.
[35] G. Brock, Properties of firewood, in: Agriculture Notes, Department of Primary Industries, State of Victoria, 2004.
[36] P. Stasta, J. Boran, L. Bebar, P. Stehlik, J. Oral, Thermal processing of sewage sludge, Appl. Therm. Eng. 26 (2006) 1420–1426, https://doi.org/10.1016/j.applthermaleng.2005.05.030.