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Article

Physico-Chemical Evaluation and Environmental Sustainability of Oil Palm Decanter Cake in Lubok Antu, Sarawak

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Abstract: Oil Palm Decanter Cake (OPDC) is one of the large quantity leftovers in the oil palm mill that has been shown to have nutritional value. As a result of its widespread production, its proper disposal has become a major source of concern especially when it comes to the environmental contamination in Malaysia, with a particular focus on the palm oil mill located in Lubok Antu, Sarawak, as it has been observed that Palm Oil Mill Waste (POMW) is one of the major problems that need to be taken into consideration by the mills, particularly related to OPDC. It is critical that significant efforts to be made to ensure appropriate OPDC waste management in the mill are to be done to address rising environmental concerns, hence the purpose of this project is to evaluate the physical and chemical characteristics of OPDC, besides to analyse the environmental sustainability of the potential applications of OPDC as raw material focusing on organic fertilizer and biomethane gas. In evaluating the physico-chemical analysis of OPDC for the applications, seven analyses have been done including Scanning Electron Microscope (SEM), density, moisture, oil, heavy metals, Nitrogen Phosphorus Potassium (NPK), and Fourier Transmission Infrared Spectroscopy (FTIR) analysis. Besides, the inventory structure for the Carbon Dioxide Equivalent (CO2e) have been designed to analyse the environmental sustainability of OPDC for organic fertilizer and biomethane applications through inventory analysis. As a result, biomethane gas application are selected whereby it emits lower CO2e compared to organic fertilizer application, besides sludge is produced upon biomethane production which can be used as soil conditioner. Biomethane is a chemical alternative to natural gas and can be used in transportation and electricity generation, as it has zero emissions and interchangeable with natural gas as it absorbs methane emissions.

Keywords: Oil Palm Decanter Cake, Physico-chemical analysis, Environmental sustainability

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1. Introduction

Malaysia's oil palm industry is one of the country's most valuable, as the oil palm tree (Elaeis guineensis) is said to have originated in Africa. The British colonialists introduced oil palm to Malaysia from Nigeria in 1917, and it has rapidly become a substantial contributor to the country's GDP, bringing in approximately $7 million each year. According to the most recent statistics, Malaysia produces approximately 89 million tonnes of FFB per year [1]. In 2016, Malaysia was the world's second largest palm oil exporter, trailing only Indonesia, with 2.83 million tonnes (or 17.6%) of total palm oil exports going to India [2]. Palm oil is used for a variety of things, such as deep frying, margarine, and shortening for cakes, snacks, and instant noodles. Cosmetics, soaps, and synthetic detergents all include these. Palm oil has become a popular fuel alternative as crude oil prices have risen throughout the world. Given its various applications, it may be referred to as the "Future Crop." Environmental management in the palm oil sector has become a key concern as a result of this growth in demand. Mills are frequently found in plantations, and the common practise is to collect waste and dispose it in an unethical way, as excess nutrients may be damaging to both developing plants and the environment as a whole. Increased oil content in the mill's effluent is caused by oil losses owing to process instabilities and leaks. It has been claimed that a total oil loss of 10 to 15 kg/t FFB has occurred [3]. Moreover, inefficient equipment, faulty machinery, and leakage which is due to tank failure or overflow are frequently the cause of further oil losses.

POMW generally refers to all wastes from the palm oil sector in Malaysia. The milling process and plantation activities produce a considerable quantity of solid waste, which includes plantation trunks, fronds, and leaves, as well as EFB, POMS, POME, PKC, OPDC, PMF, and shells. Aside from being one of the world's leading producers of palm oil, Malaysia also produces a huge amount of industrial waste which includes POME, EFB, PMF, and OPDC. A typical palm oil mill generates between 0.6 and 0.8 m^3 of POME, 22% to 23% of EFB, 13.5% of PMF, and 4% to 5% of OPDC per tonne of FFB [4].

The palm oil mill contributed significantly to environmental contamination through its waste, such as OPDC, which is a major source of concern in Malaysia. Due to the obvious high amount of OPDC produced, composting will require a large amount of land, posing environmental risks such as soil and water contamination. Furthermore, increased biomass waste production has harmed the palm oil industry's overall OER due to oil losses in the waste [4]. The OER shows how much oil is extracted from FFB as well as the overall efficiency of typical palm oil mills. As a result, methods for converting biomass waste into another kind of energy or even usage should be discovered. OPDC's usefulness as ruminant feed, plant fertiliser, and composting material has only been examined by a few researchers [4,5], besides the demand for biogas is continuously growing [6]. Due to the expected expansion of oil palm acreage in the next years, it is imperative that substantial efforts be made to guarantee appropriate OPDC management in order to address rising environmental issues, whereby the selection on the potential applications of OPDC as raw material via environmental sustainability analysis in the palm oil industry have been evaluated throughout this research study.

The research study project focus on the palm oil mill industry, whereby the major study is related to the OPDC, which is produced as waste product from the production of crude palm oil. Emphasis on OPDC, it has been observed that no proper study been done to evaluate objectively on the potential applications of OPDC which will meet the requirement of sustainability. Hence, this research study aimed to conduct analysis on the proper waste management for the OPDC in the palm oil industry, specifically in Sarawak. Organic fertilizer and biomethane gas applications are proposed to promote a secular economy, minimizing waste and environmental pollution, since abundant of OPDC are discarded in the landfill causing the rise in environmental issues. This research study support four SDG goals: Affordable and Clean Energy (7), Responsible Consumption and Production (12), Climate Action (13), and Life on Land (15). Hence, this project has been achieved by the successfulness of the objectives in evaluating the physical and chemical analysis of OPDC for organic fertilizer and biomethane gas applications, designing the inventory structure for the CO2e for the palm oil industry, organic fertilizer and biomethane applications and analysing the environmental sustainability of OPDC for organic fertilizer and biomethane applications by conducting the inventory analysis.

Fig. 1. The accumulation of OPDC in the palm oil mill industry.

2. Materials and Methods

The research project is categorized in two main parts, in which the first part covers the characterization of OPDC whereby the physical and chemical properties of OPDC are to be determined based on experimental approach. The secondary validation on the characterization of OPDC are to be done in order to determine the effectiveness of OPDC in the potential applications of biomass. On the other hand, the second part of the project covers the impact of OPDC towards environmental are to be determined through inventory structure and analysis methodology in which to select the best potential applications of OPDC as raw materials which will be determined throughout the research project period.

2.1 Material collection

The OPDC samples for the research project have been taken from one of the palm oils mills in Lubok Antu district in Sarawak. The samples which will be analysed are divided into several categories as shown in Table 1.

Table 1. Analysis on the OPDC samples by category.

OPDC Samples	Category	Lifespan
	Fresh OPDC	24 Hours
	Aged OPDC	3 Days
	OPDC containing oil	24 Hours

Physical and chemical analysis of OPDC

The analyzation on the physical characteristics of OPDC are listed as follows:

SEM

To capture the pictures of the fresh OPDC sample surfaces by scanning them with a high-energy electron beam in a raster scan pattern based on three different samples taken within two weeks alternate period at 300X, 500X and 1000X magnification by using TM400 Plus Series.

Density

The density of OPDC is defined as the mass of OPDC per unit volume, which is to be calculated based on equation 1.

$$\rho_{OPDC} = \frac{m}{V} \quad (1)$$

Whereby the unit of density of OPDC is declared to be g/cm^3.

Moisture content

The moisture content of OPDC is defined as the proportion of water to the overall weight of OPDC, which is to be calculated based on equation 2 and equation 3.

$$W_{\text{Moisture}} = (W_{\text{OPDC}} + \text{Beaker}) - (W_{\text{Dry OPDC}} + \text{Beaker}) \quad (2)$$

$$\text{Moisture content in OPDC (\%)} = W_{\text{Moisture}} \div W_{\text{OPDC}} \quad (3)$$

The analyzation on the chemical properties of OPDC are listed as follows:

Oil content

The oil content in OPDC is to be determined by using the Soxhlet Extraction Set whereby the oil content can be calculated based on equation 4.

$$\text{Oil content}_{\text{OPDC}} = \frac{W_{\text{extracted oil}}}{W_{\text{dry OPDC}}} \times 100\% \quad (4)$$

Heavy metal content analysis

The existence of heavy metals in OPDC are to be analysed to determine the effect of OPDC towards the soil content for organic fertilizer applications. The heavy metal adsorption which are to be analysed including Cd, Pb, Cu, Ni, and Zn by using TM400 Plus Series after SEM analysis.

NPK content

The NPK content in OPDC are to be analysed in order to meet the requirement of the NPK content in fertilizers, which is categorized as a type of biomass. The NPK content in OPDC is important as it shows the suitability of OPDC towards soil content.

FT-IR analysis

The FT-IR analysis is conducted to determine the functional groups in raw and chemically processed OPDC. The sample disc was made by combining OPDC with KBr and compressing it, with a transmission wavelength range of 4000 cm^{-1} to 400 cm^{-1} by using IRAFFINITY-1.

2.3 Inventory structure and analysis of OPDC and its potential applications

The inventory structure involves four main processes, which are the oil palm plantation, crude palm oil processing, fertilizer production and biomethane production as the potential applications of OPDC as raw material. In these four processes, the carbon transfer involving carbon emission, carbon fixation and carbon reduction are to be analysed for only two types of Kyoto Gases, which is the carbon dioxide and methane gas as shown in Table 2.

Table 2. The elements in Kyoto Gases

GHG	GWP
CO_2	1
CH_4	25

Meanwhile, for the inventory analysis, the International Organization for Standardization (ISO14040) has described the framework of LCA in several steps, which include the goal and scope definition, impact assessment, and interpretation.

2.4 Environmental Sustainability on the Potential Applications of OPDC as Raw Material

The selection on the most environmental-friendly and most sustainable application are to be done based on the designed proposed for the inventory structure and the evaluation on the inventory analysis. In determining the most environmental sustainability application, the following elements are to be considered:

i) The tallies of the physical and chemical characteristics of OPDC obtained with the references and limitations obtained based on past research from literature reviews.
ii) The amount of carbon emission and carbon reduction involved throughout the process with only carbon dioxide and methane gas to be evaluated.
iii) The benefit of the selected application towards environment.

iv) The by-products formed upon processing and its benefits towards the environment.

2.5 Safety Precautions

Safety precautions are to be applied while collecting the OPDC samples by using full protective PPE, and current SOP with the guidelines of the COVID-19 pandemic are to be followed while conducting the analysis in the mill. On the other hand, safety precautions are also to be implemented when conducting experimental works in the laboratory to avoid accidents to happen while conducting the experiment. Besides, chemical and waste disposal are to be done in a proper way, whereby chemical and waste should not be mixed together in the disposal bin, and disposal in the laboratory sinks are not allowed throughout the ongoing of experimental works. Please provide concise but complete information about the materials and the analytical and statistical procedures used. This part should be as clear as possible to enable other scientists to repeat the research presented. Brand names and company locations should be supplied for all mentioned equipment, instruments, chemicals etc. All the ethical permission associated in the research work must be specified. Indicate the statistical methods used and identify statistical significance using superscripts (* and **) following the data (*$P<0.05$, **$P<0.01$).

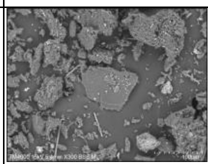
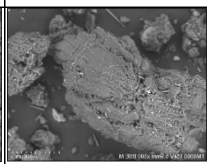
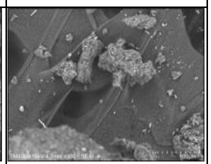
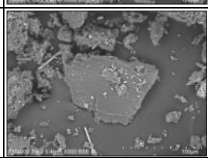
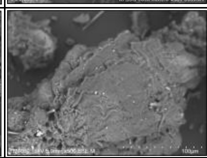
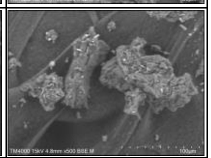
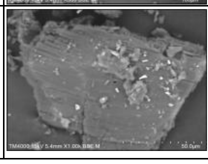
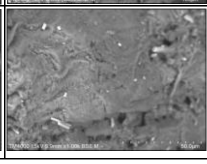
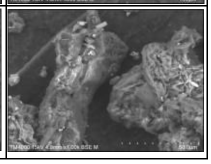
3. Results

In the first section, the physical analysis of OPDC is evaluated to analyse the physical characteristics of OPDC through SEM, density and moisture content analysis. Moving on to the second section, the chemical analysis of OPDC is also evaluated to analyse the chemical characteristics of OPDC by conducting the oil content, heavy metal adsorption, NPK content, and FT-IR analysis. As the physical and chemical analysis of OPDC have been done, the evaluation on the environmental sustainability of the proposed potential applications of OPDC as raw material is to be analysed by constructing the inventory structure of CO2e in the third section which results in the inventory analysis of CO2e in the fourth section. To conclude on the best potential applications of OPDC as raw material, the environmental sustainability analysis is to be done in the fifth section which results in the comparison and selection of the most environmentally friendly and sustainable application of OPDC as raw material in the last section.

3.1. SEM Analysis

The SEM captures pictures of the fresh OPDC sample surfaces by scanning them with a high-energy electron beam in a raster scan pattern based on three different samples taken within two weeks alternate period at 300X, 500X and 1000X magnification which are shown as tabulated in Table 3.

Table 3. The SEM analysis of OPDC

Magnification	Sample 1	Sample 2	Sample 3
300X			
500X			
1000X			

Based on the SEM analysis of the three different samples taken within two weeks alternate period at 300X, 500X and 1000X magnification shown as tabulated in Table 3, small pores and particles exists in OPDC. The small particles exist in OPDC might due to the presence of heavy metals which will be further discussed via analysis through EDX method.

3.2. Density analysis

Density is defined as the mass per unit volume of OPDC as shown in equation (1) represented in section 2.2. Throughout the analysis for the density of OPDC, only fresh OPDC is being taken for sampling which are calculated as follows:

$$\text{Average density fresh OPDC} = \frac{1.2516\ \mathrm{g/cm^3} + 1.2262\ \mathrm{g/cm^3} + 1.2020\ \mathrm{g/cm^3}}{3}$$
$$= 1.2266\ \mathrm{g/cm^3}$$

Based on the density analysis of fresh OPDC, the calculated density of fresh OPDC of the three samples are taken to be in the average of 1.2266 g/cm^3. Organic matter weights substantially less than mineral solids of the same volume and has a particle density between the range of 1.2 g/cm^3 to 1.4 g/cm^3[7]. Looking into the perspective of the organic fertilizer and bio-methane gas applications, organic fertilizer has an average density of 1.21039±0.07307 g/cm^3 [8], while bio-methane gas has a density between the range of 1.15 g/cm^3 to 1.25 g/cm^3 due to the presence of carbon dioxide gas present throughout the process [9]. Hence, based on the density analysis conducted for the fresh OPDC samples, it can be concluded that OPDC is potential towards the organic fertilizer and bio-methane gas applications as it falls in the density range for the respective applications.

3.3. Density analysis of OPDC

Moisture content refers to the water content that is present in OPDC. Moisture content is determined upon weight reduction after drying, which is known to be one of the common indicators. Throughout the analyzation of the moisture content of OPDC, three different categories have been analysed to determine the range of the moisture contents, involving fresh OPDC, aged OPDC and oil content OPDC with three alternates sampling for each category, as constructed in Figure 2.

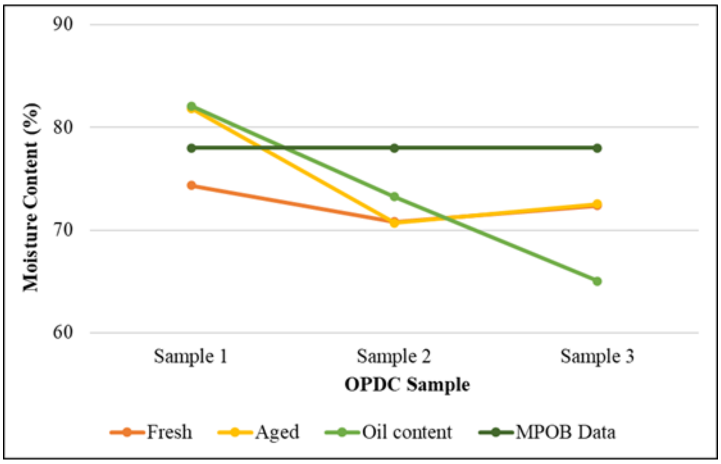


Fig.2. The moisture content analysis via wet basis of OPDC with MPOB data benchmarking

The benchmark for the OPDC moisture content provided by the MPOB via wet basis is 78% [10]. Based on the graph of moisture content analysis via wet basis of OPDC with MPOB data benchmarking shown in Figure 2, the moisture content for sample 1 for both aged and oil-content OPDC are calculated to be higher that the MPOB Data, which is 81.85% and 82.10% respectively, while the moisture content for fresh OPDC of sample 1 is lower than the MPOB data benchmarking with 74.35% of moisture content. Meanwhile for sample 2, all of the moisture content for fresh, aged and oil-content of OPDC are calculated to be lower than the MPOB benchmarking data with aged OPDC detected to deviate the most with 70.70%. Lastly, for sample 3, all of the moisture content for the three OPDC samples are calculated to be below the MPOB data, but oil-content sample detected to deviate the most with 65.03%. Looking at OPDC from a different perspective, OPDC is potential to be proposed as organic fertilizer based on the moisture content analysis shown in Figure 2. The soil moisture content for crops to grow fertile occurred in the range of 63.7% to 86%. Since all of the three categories of the three samples of OPDC are within the range of soil moisture content for crops to grow fertile, hence it can be concluded that OPDC is potential towards organic fertilizer application.

3.4 Oil content analysis of OPDC

Oil content refers to the oil content that is present in OPDC, in which also known as oil losses. Upon determination, oil content is determined by Soxhlet Extraction method upon weight reduction after drying, which is the most common procedures for extracting analytes from solid materials. Throughout the analyzation of the oil content of OPDC, three different categories have been analysed to determine the range of the oil contents, involving fresh OPDC, aged OPDC and oil content OPDC with three alternates sampling for each category, as constructed in Figure 3.

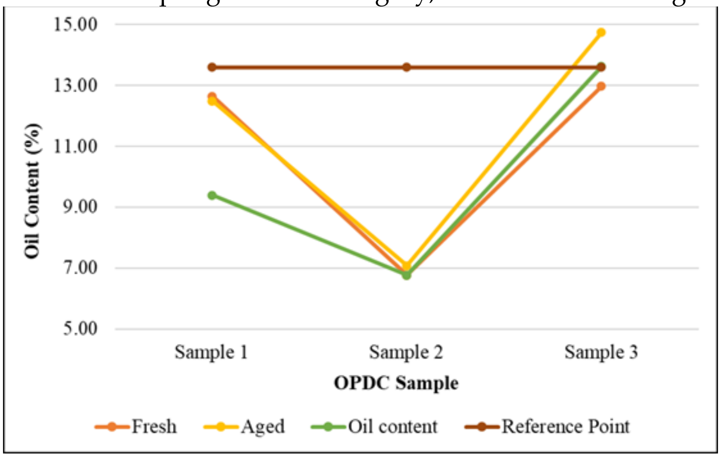


Fig.3. fresh OPDC, aged OPDC and oil content OPDC with three alternates sampling

The reference point for the OPDC oil content via dry basis is 13.60% [4]. Based on the graph of oil content analysis via dry basis of OPDC shown in Figure 3, the oil content for sample 1 and sample 2 for fresh, aged and oil-content OPDC are calculated to be lower that referencing data [4], while the oil content for aged and oil-content OPDC of sample 3 is higher than referencing data reference with 14.74% and 13.62% of oil content respectively [4]. Looking at OPDC from a different perspective, OPDC is potential to be proposed as bio-methane gas application based on the oil content analysis shown in Figure 3. In selecting the suitable state for OPDC as raw material for biomethane gas application, dry basis state is more suitable to be taken as the raw material as dry basis have higher oil content compared to wet basis after undergoing heating and extraction via Soxhlet Extraction method. Hence it can be concluded that OPDC is potential towards biomethane gas application.

3.5. Heavy metals content analysis of OPDC

The most common method for heavy metal analysis is by conduction adsorption process. Adsorption processes are widely used for the removal of heavy metals from waste streams, in which OPDC samples are being analysed for organic fertilizer and bio-methane gas applications. Throughout the analyzation of the heavy metal adsorption analysis of OPDC, only fresh OPDC are taken to be send for heavy metal analysation of Cd, Cu, Pb, Ni and Zn with three alternates sampling by using EDX, which is an alternative for the adsorption process as mentioned after evaluating the SEM analysis, in which the heavy metals content in OPDC are being analysed as constructed in Figure 4.

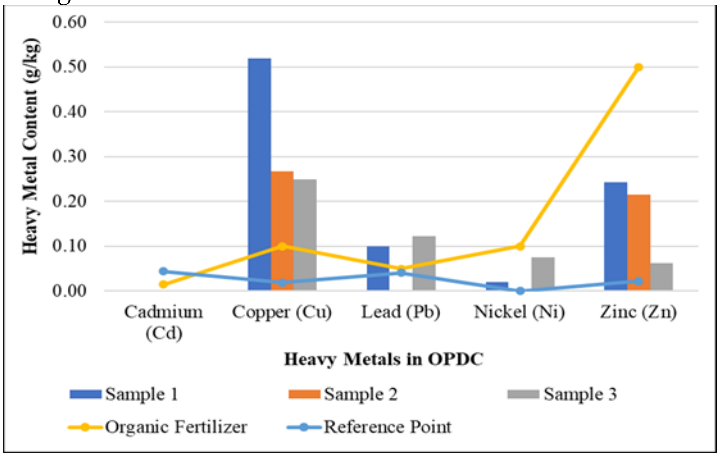


Fig.4. The limitation on the heavy metal adsorption analysis of OPDC with the reference point and organic fertilizer limitation [11,12]

Looking at the limitation for heavy metal adsorption analysis of OPDC shown in Figure 4, the reference point for Cadmium, Copper, Lead, Nickel and Zinc are 0.0440g/kg, 0.0186g/kg, 0.0408g/kg, 0.0000g/kg and 0.0223g/kg respectively [11]. Meanwhile, for the organic fertilizer limitation, the five heavy metals are 0.0150g/kg, 0.1000g/kg, 0.0500g/kg, 0.1000g/kg and 0.5000g/kg respectively [12]. Therefore, comparing with the heavy metal adsorption analysis, the OPDC are considerable to be taken as the raw materials for organic fertilizers as the experimental data obtained throughout this study for cadmium is lower compared to the reference point limitations while cadmium, nickel and zinc is lower compared to the organic fertilizer limitations. The experimental data obtained for copper and lead for OPDC is higher than the data obtained for both reference point and organic fertilizer limitations. In this matter, heavy metals content in OPDC can be removed through adsorption process as heavy metals, both necessary and non-essential, have similar toxic effects on plants, including poor biomass accumulation, chlorosis, suppression of growth and photosynthesis, altered water balance and nutrient absorption, and senescence, all of which led to plant death [13]. Hence, it can be concluded that OPDC is potential towards organic fertilizer application as the content of heavy metals in OPDC is in considerable safe condition which will give very less impact to the agricultural industries and the environment.

3.6. NPK content analysis of OPDC

The nitrogen, phosphorus, and potassium or also known as the NPK content in OPDC are to be analysed as the "Big 3" major nutrients in commercial fertilisers. Each of these essential elements has a specific function in plant nutrition. Throughout the analyzation of the NPK content of OPDC, only fresh OPDC are taken to be send for analysation with three alternates sampling by undergoing three different analysis which includes Kjeldahl Digestion for Nitrogen, Colorimetric Analysis for Phosphorus, and ICP-OES for Potassium, as constructed in Figure 5.

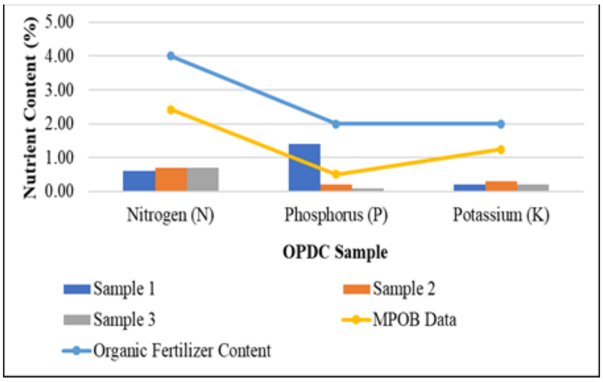


Fig.5. The NPK content analysis of OPDC with MPOB data benchmarking

The benchmark for the OPDC NPK content provided by the MPOB is 2.42%, 0.51% and 1.24% respectively [10]. Based on the graph of NPK content analysis with MPOB data benchmarking shown in Figure 5, the Nitrogen and Potassium content for all of the three samples are lower than the MPOB benchmarking data, meanwhile the Phosphorus content of sample 1 is higher than the MPOB benchmarking data but sample 2 and sample 3 are detected to be lower than the benchmarking data. Looking at OPDC from a different perspective, OPDC is potential to be proposed as organic fertilizer based on the NPK content analysis shown in Figure 5. The accepted NPK content of fertilizers are 4% of Nitrogen and 2% for both Phosphorus and Potassium [14]. Hence, to produce a good quality of organic fertilizer from OPDC for agricultural purposes, OPDC can be mixed with other organic materials either from botanical or animal waste to achieve the targeted NPK content for organic fertilizers since the NPK content for OPDC is analysed to be in a lower range. In addition to this, it can be concluded that OPDC is potential towards organic fertilizer application.

3.7. FT-IR analysis

Based on the three FT-IR analysis for the three alternate OPDC samples shown in Figure 6(a), (b) and (c), the functional groups exist in OPDC within the wavelength range of 400cm^(-1) to 4000cm^(-1)have been analysed by looking at the highest peak at every 1000cm^(-1) range.

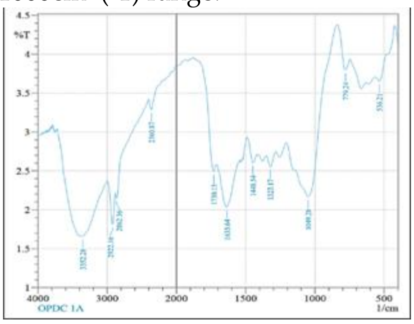


Fig. 6(a). Sample 1

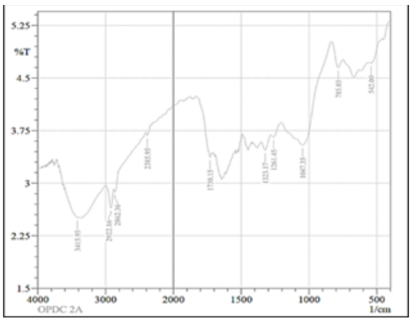


Fig. 6(b). Sample 2

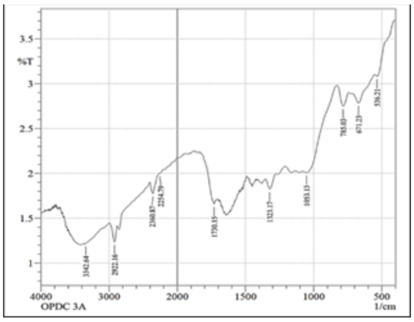


Fig.6(c). Sample 3

According to the analyzation of functional groups exist in OPDC by FT-IR analysis obtained from the FT-IR spectra shown in Figure 6 (a), (b) and (c) with reference to the Infrared Spectroscopy Absorption Table. Halo compounds consist of C-I and C-Br stretching, and 1,3-disubstituted compound with C-H stretching exists between the range of 400 to 1000cm^(-1). Meanwhile, the presence of anhydride (CO-O-CO), aromatic amine (C-N), and sulfone (S=O) stretching were indicated by the broad absorbance peak between 1001 to 2000cm^(-1) range. The functional groups of aldehyde and alkane with the stretching of C=O and C-H respectively have been seen within the range of 2001 to 3000cm^(-1) absorbance peaks. Lastly, alcohol compound was seen within the absorbance peak range of 3001 to 4000cm^(-1) with the stretching of O-H. Hence, it can be concluded that the FT-IR analysis with KBr obtained strongly supports that the OPDC contains more halo compounds compared to the other existed compounds discussed. Halo compounds or also known as halocarbon consists of any chemical compound of the element carbon and one or more of the halogens including bromine, chlorine, fluorine, iodine. Since halo compounds have no effect towards the environment especially on greenhouse gases and thickening of ozone layer, it can be concluded that OPDC is potential towards organic fertilizer and biomethane gas applications.

3.8. The inventory structure of CO2e

Based on the analyzation of carbon transfer involved in the palm oil industry and the proposed potential applications of OPDC, the oil palm plantation only involved the carbon emissions with the element of diesel for soil preparation and transportation, and NPK fertilizer. Meanwhile throughout the process of crude palm oil production, all of the three-carbon transfer exists involving electricity, diesel for generator set and transportation in carbon emissions, CPO, PK and OPDC for carbon fixation as both are the products formed from the production, and by-products of EFB, shell and fibre and POME involves in the carbon reduction for the CPO production processing. Since OPDC is discarded by dumping into the landfill as observed in the selected mill in Lubok Antu, Sarawak, two potential applications have been proposed in which for fertilizer production, only carbon emission and carbon fixation involved with phosphoric acid, electricity, diesel for transportation, boiler fuel, and methane as the carbon emissions elements while organic fertilizer as the carbon fixation component. Meanwhile for biomethane production, carbon fixation unidentified whereby electricity, diesel for transportation, boiler fuel, and methane as the carbon emissions elements and biomethane gas and sludge as the carbon reduction elements. Hence, based on the tabulated carbon transfer, the inventory structure of the carbon transfer involved in the palm oil industry and the proposed potential applications of OPDC are constructed as shown in Figure 7.

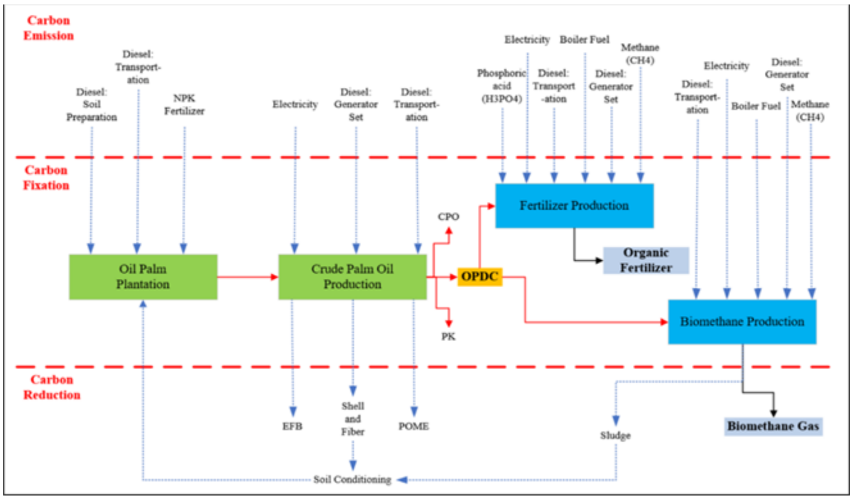


Fig.7. The Inventory Structure of CO2e for the OPDC Processing and Potential Applications

Hence, based on the constructed inventory structure of CO2e for OPDC processing and potential applications shown in Figure 7, it can be concluded that OPDC is potential towards biomethane gas applications as the application involves lesser carbon transfer as compared to the organic fertilizer application. However, to prove this statement, the inventory analysis of the CO2e for the OPDC processing and potential applications are calculated based on the provided and reviewed mass balances composition.

3.9. CO2e in Palm Oil Industry

Rely on the emissions in carbon dioxide equivalents for each composition involved throughout the processes in palm oil industry as constructed in Figure 7 based on 1kg of CO2e per ton and mass balance and basic mass composition, the tabulation of data based on carbon emission, carbon fixation and carbon reduction for both 1kg of CO2e per ton and mass balance and basic mass composition are represented as shown in Table 4 (a) and (b), and Figure 8 (a) and (b).

Table 4 (a). The CO2e in Palm Oil Industry for 1kg/ton

Carbon Transfer (kg CO2e/ton)	Oil Palm Plantation	Crude Palm Oil Production	Fertilizer Production	Biomethane Production
Carbon Emission	72.8000	5.6000	31.3000	36.9000
Carbon Fixation	0.0000	184.0000	3.6700	0.0000
Carbon Reduction	0.0000	18.8000	0.0000	12.2510
Net Carbon Emission			**109.7000**	**103.0490**

Table 4 (b). The CO2e in Palm Oil Industry based on mass balance and basic mass composition

Carbon Transfer (kg CO2e/ton)	Oil Palm Plantation	Crude Palm Oil Production	Fertilizer Production	Biomethane Production
Carbon Emission	9318.4000	716.8000	910.8480	119.6237
Carbon Fixation	0.0000	4265.8272	56.3712	0.0000
Carbon Reduction	0.0000	503.8202	0.0000	162.6642
Net Carbon Emission			**10946.0480**	**9992.1594**

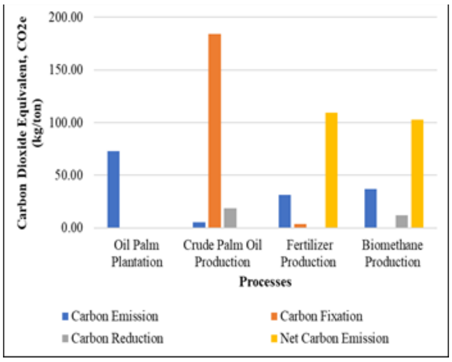


Fig. 8(a). The comparison based on 1kg/ton basis

Hence, based on the constructed graph on the processes comparison of the CO2e for carbon emission, carbon fixation, carbon reduction and net carbon emission in Palm Oil Industry based on 1kg/ton basis and based on mass balance and basic mass composition shown in Figure 10 (a) and (b), the highest carbon emission for both comparison is in the oil palm plantation as this is due to the usage of diesel for soil preparation and transportation, and NPK fertilizer which releases the most carbon dioxide and methane gases with 72.80kg/ton and 9318.40kg/ton respectively. In the oil palm plantation process, it can be seen that both carbon fixation and carbon reduction does not exist in which product does not form at this stage. Meanwhile in the process of crude palm oil production, carbon emission, carbon fixation and carbon reduction exist with carbon fixation to be the containing the highest CO2e value with 184.00kg/ton and 4265.8272kg/ton respectively. Carbon fixation exist as the highest CO2e value in this process due to the fix product of CPO, PK and OPDC formed in which will be used for further processing in producing beneficial products such as cooking oils from CPO, palm kernel oil from PK, and organic fertilizer and biomethane gas from OPDC as proposed in the potential applications of OPDC. Solid waste and effluent such as EFB, shell and fibre, and POME produced from the production of crude palm oil involved in carbon reduction with 18.80kg/ton and 503.8202kg/ton respectively as it can be further processed for soil conditioning for both EFB and shell and fibre, and also biomethane gas for POME, in which helps to reduce the emissions to the environment.

Since OPDC contributes to 12.00kg/ton and 184.32kg/ton of carbon fixation respectively, the OPDC are proposed to be further processed for organic fertilizer and biomethane gas application in order to reduce the emission to the environment. Looking into the first potential applications of OPDC as raw material, OPDC can be further processed for fertilizer production, in which involved both carbon emission and carbon fixation throughout the process. For this application, 31.30kg/ton and 910.8480kg/ton of carbon emits to the environment which is due to the composition elements of phosphoric acid, electricity, diesel for both transportation and generator set, boiler fuel and methane. Although the carbon emission for the fertilizer production is higher, the product formed from the process, which is the organic fertilizer contain 3.67kg/ton and 56.3712kg/ton of carbon fixation respectively. Hence, comparing with the initial NPK fertilizer used at the oil palm plantation with the organic fertilizer produced from OPDC, it can be seen that the NPK fertilizer emits higher CO2e content with 69.40kg/ton and 8883.20kg/ton respectively, as compared to the organic fertilizer produced containing 3.67kg/ton and 56.3712kg/ton of CO2e respectively.

Proceeding with the second proposed potential applications of OPDC as raw material, biomethane gas is produced based on the processing of OPDC, in which carbon emission and carbon reduction involved throughout this process. 36.90kg/ton and 119.6237kg/ton of CO2e emits to the environment respectively, while 12.2510kg/ton and 162.6642kg/ton of CO2e reduces as biomethane gas and sludge are formed at the end of the process. Looking into both carbon emission and carbon reduction, more CO2e is being reduced in biomethane production as biomethane gas can be further utilised in gas-powered vehicles as a renewable power source and by heating systems with very efficient fuel values while, from the process of biomethane production, sludge can be utilized for soil conditioning applications increase aeration, water holding capacity, and nutrients to aid in improving soil structure.

Although organic fertilizer application is better in terms of mass production, but looking into the CO2e in terms of carbon emission, carbon fixation and carbon reduction, it can be concluded that biomethane gas application is better than organic fertilizer application as biomethane gas is more towards environmental-friendly processing and product formed which is more sustainable for daily usage.

3.10. Environmental Sustainability on the Potential Applications of OPDC

Environmental sustainability is a concept in conservation that refers to satisfying the needs of the current and future generations in terms of resources and services without compromising the wellbeing of the ecosystems that produce those resources and services [15,16]. Based on the outcome on the CO2e for the proposed potential applications of OPDC as raw material obtained for 1kg/ton basis and mass balance and basic mass composition, the CO2e for fertilizer production for organic fertilizer product and biomethane production for biomethane gas and sludge formation are calculated and extracted as represented in Table 5 (a) and (b), and Figure 9 (a) and (b).

Table 5(a). The CO2e of the potential applications of OPDC as raw material for 1kg/ton

Carbon Transfer (kg CO2e/ton)	Organic Fertilizer	Biomethane Gas	Sludge
Carbon Emission	109.7000	115.3000	0.0000
Carbon Reduction	0.0000	0.2510	12.0000
Total Carbon Emission	109.7000	115.3000	0.0000
Total Carbon Reduction	0.0000	0.2510	12.0000
Net Carbon Emission	**109.7000**	**115.0490**	**-12.0000**

Table 5(b). The CO2e of the potential applications of OPDC as raw material based on mass balance and basic mass composition

Carbon Transfer (kg CO2e/ton)	Organic Fertilizer	Biomethane Gas	Sludge
Carbon Emission	10946.0480	10154.8237	0.0000
Carbon Reduction	0.0000	0.4626	162.2016
Total Carbon Emission	10946.0480	10154.8237	0.0000
Total Carbon Reduction	0.0000	0.4626	162.2016
Net Carbon Emission	**10946.0480**	**10154.8237**	**-162.2016**

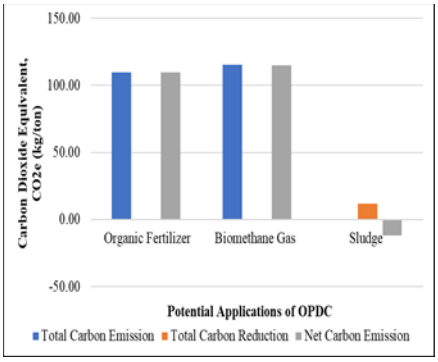


Fig.9(a). The comparison based on 1kg/ton basis

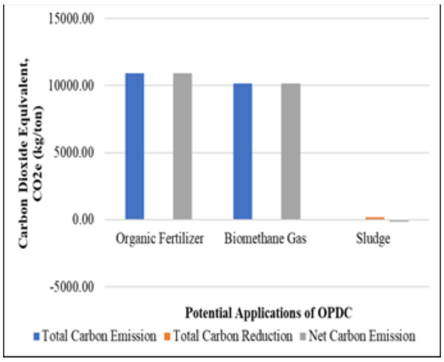


Fig. 9(b). The comparison based on mass balance and basic mass composition

Hence, based on the constructed graph on the comparison of CO2e for total carbon emission, total carbon reduction and net carbon emission for the potential applications of OPDC as raw material based on 1kg/ton basis and based on mass balance and basic mass composition shown in Figure 9 (a) and (b), biomethane gas application is seen to contribute lesser towards total carbon emission, total carbon reduction and net carbon emission from the biomethane gas and sludge product formed based on mass balance and basic mass composition with 10154.8237kg/ton of total carbon emission, 0.4626kg/ton of total carbon reduction, resulting in 10154.8237kg/ton of net carbon emission for 12% of OPDC is processed for biomethane gas with the by-product of 0kg/ton total carbon emission, 162.2016kg/ton of total carbon reduction, resulting in 162.2016kg/ton net carbon emission for 88% of OPDC converted into sludge at the end of the biomethane production overall as compared to organic fertilizer application shown as in Figure 9(b). Looking into the CO2e of the potential applications of OPDC as raw material based on 1kg/ton basis shown as in Figure 9(a), organic fertilizer generally seen to contribute lesser towards total carbon emission, total carbon reduction and net carbon emission from the organic fertilizer product formed with 109.70kg/ton of total carbon emission, 0kg/ton of total carbon reduction, which results in 109.70kg/ton of net carbon emission upon 100% of OPDC converted into organic fertilizer. Therefore, from the results obtained, although the application of organic fertilizer is superior in terms of mass production as said in previous sections, when considering the CO2e in terms of total carbon emission, total carbon reduction and net carbon emission, it can be said that the application of biomethane gas is superior to that of organic fertiliser based on mass balance and basic mass composition as it tends to produce products of biomethane gas and sludge that are more environmentally friendly and sustainable for daily use.

3.11. Selection on the best potential applications of OPDC

Emphasis on OPDC, it was first noted that no appropriate research had been done to objectively assess on the prospective uses of OPDC which would fulfil the need of sustainability. As a result, several laboratory and environmental assessments have been conducted throughout this research study with the goal of suggesting prospective uses of OPDC as raw material that technically aid in effective waste management for the OPDC in the palm oil sector, mainly in Sarawak. Throughout this research study, two potential applications have been proposed which is the organic fertilizer and biomethane gas.

To conclude based on the physical and chemical characteristics and environmental sustainability perspective, biomethane gas applications producing biomethane gas and sludge is more potential for the application of OPDC as raw material for the proposal on the proper handling of OPDC waster in the palm oil industry. It can be stated that the application of biomethane gas is preferable compared to the organic fertiliser applications based on the net carbon emission via mass balance and basic mass composition since it tends to generate products of biomethane gas and sludge that are more environmentally friendly and less harmful especially to the ecosystem.

Biomethane, which contains 98% of methane, is a pure type of biogas. It is comparable to natural gas produced from traditional fossil fuels and is sometimes referred to as green gas. The composition of biogas is around 60% methane, 40% carbon dioxide, and traces of other pollutants. Biomethane is a full chemical alternative for natural gas and can thus be integrated into gas distribution and transport networks. As a sustainable energy source, biomethane is used to generate electrical power and heat homes and industries, besides it can also be utilised as a motor vehicle fuel. Biomethane gas is the best selection as it is towards zero emissions overall in which interchangeability with currently used natural gas. On the other hand, biomethane gas application are able to absorb methane emissions from other activities like landfill and manure production, in which helps to reduce the methane emissions from the environment.

4. Conclusion

To summarize on the overall findings of the research project, conclusions on OPDC have been made as follows:

- OPDC is potential towards organic fertilizer and biomethane gas applications, in which prior to the biomethane gas application as it meets the requirement on the environmental sustainability as mentioned throughout this research project.
- OPDC have been clarified that it is potential towards organic fertilizer application as the results obtained for the density, moisture content, heavy metals content, NPK content and FTIR are within the range of an organic fertilizer properties.
- OPDC is also potential towards biomethane gas application based on the density, oil content, and FT-IR analysis, which have made both of the application to be taken into consideration for proposal.
- OPDC which is proposed to be further processed into organic fertilizer and biomethane gas releases carbon dioxide and methane gas with 1GWP and 25GWP coefficient respectively. The evaluation on the inventory structure and analysis of the potential applications of OPDC as raw material have led to the decision on choosing the most environmental sustainability applications, in which biomethane gas application have been selected throughout this research project.

Hence, based on the outcome of the research, the aim and objectives of this research have been successfully achieved, whereby the study on the proper waste management for the OPDC in the palm oil industry in Sarawak, specifically in Lubok Antu have been successfully done which helps in minimizing the OPDC waste generated from crude palm oil processing for future usage in which organic fertilizer and biomethane gas applications have been proposed and analysed by conducting the physical and chemical analysis of OPDC for organic fertilizer and biomethane gas applications which have successfully been evaluated, the inventory structure of CO2e for the palm oil industry, organic fertilizer and biomethane applications have been designed successfully, and the environmental sustainability of OPDC for organic fertilizer and biomethane applications have been successfully evaluated by conducting the inventory analysis.

Nomenclatures	
%	Percentage
Cd	Cadmium
$\mathbf{CH_4}$	Methane
$\mathbf{cm^{-1}}$	Per centimetre
$\mathbf{CO_2}$	Carbon Dioxide
CO2e	Carbon Dioxide Equivalent
Cu	Copper
$\mathbf{g/cm^3}$	Gram per centimetre cube
g/kg	Gram per kilogram
HFCs	Hydrofluorocarbons
$\mathbf{H_3PO_4}$	Phosphoric acid
K	Potassium
KBr	Potassium bromide
kg/ton	Kilogram per tonne
kWh	Kilowatt-hours
MT	Metric tonne
N	Nitrogen
Ni	Nickel
$\mathbf{(NF_3)^3}$	Nitrogen trifluoride
$\mathbf{N_2O}$	Nitrous oxide
P	Phosphorus
Pb	Lead
PFCs	Perfluorocarbons
$\mathbf{SF_6}$	Sulfur hexafluoride
Zn	Zinc

Abbreviations	
CPO	Crude Palm Oil
EFB	Empty Fruit Bunches
EDX	Energy Dispersive X-ray Spectroscopy
FFB	Fresh Fruit Bunches
FT-IR	Fourier Transmission Infrared Spectroscopy
FYP	Final Year Project
GHG	Green House Gas
GWP	Global Warming Potential
ISO	International Organisation for Standardisation
LCA	Life Cycle Analysis
LCI	Life Cycle Inventory
MPOB	Malaysian Palm Oil Board
OER	Oil Extraction Rate
OPDC	Oil Palm Decanter Cake
PK	Palm Kernel
PKC	Palm Kernel Cake
PKO	Palm Kernel Oil
PMF	Palm Mesocarp Fibre
PO	Palm Oil

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