Anaerobic digestion of fungally pre-treated oil palm empty fruit bunches: energy and carbon emission footprint

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Abstract. Oil palm empty fruit bunches (OPEFB) is one of the abundant lignocellulosic biomass in Indonesia. However, high lignin content in EFOB has becoming one of the obstacles in valorising it as bioenergy resources, as it is hardly broken down by the microorganisms. Therefore, pre-treatment is often needed to enhance the biodegradation process of organic content in OPEFB. The biological pre-treatment is besieged to enhance the utilisation of OPEFB as bioenergy resources. This study was aimed to investigate the impact of fungal pre-treatment on the OPEFB characteristics and its methane potential, and to estimate the energy and carbon emission saving from anaerobic digestion (AD) of OPEFB. In this study, OPEFB was treated using Phanerocheate chrysosporium under the standard condition and incubated for 7 and 14 days. The energy and carbon emission footprint were calculated using AD Assessment Tool (ADAT) software. The results showed that fungal pre-treatment was able to increase organic matter and enhance methane potential. Estimation on energy (i.e. electrical and heat), however, indicated a lower energy balance and carbon emissions saving for fungal pre-treated OPEFB. The higher moisture content (MC) on treated OPEFB may reduce the biogas and methane production. Yet, further research is still required to have an in-depth understanding of improving the efficacy of biogas production from OPEFB by incorporating other green pre-treatment approaches.

1. Introduction

Oil palm industry waste is remained a big challenge needs to be tackled. The global production of oil palm in 2019 was 75.7 million tons [1]. In Indonesia, oil palm production in 2019 was approximately 42.7 million tonnes [2]. In each ton of fresh fruit bunches (FFB) generated about 21-23 (w/w) of oil palm empty fruit bunches (OPEFB) [3]. Thus, it is estimated that the potential of OPEFB is approximately 8.97 million tons, which available to be further valorised. Furthermore, inadequate handling of this large amount of OPEFB may pose a detrimental menace to the environment.

Many studies have reported the utilisation of OPEFB for renewable energy sources, such as biogas [5]; bioethanol [6]; biodiesel [7]; briquette [8]; biohydrogen [9]; bio-oil [10]; biochar [11]; fuels pellet
Despite various alternative fuels utilisation, anaerobic digestion (AD) seems to be one of the best ways to be implemented in many developing countries, such as Indonesia, for attaining their sustainable energy development goals. This is also consistent with the Indonesian Government policy to support biogas generation from biomass resources, including from OPEFB [13]. Furthermore, using AD technology can produce not only biogas as energy sources, but also organic residue (or digestate) as biofertiliser.

However, OPEFB contains high lignin (~28.8%) [14], which poses a negative synergy on biomass biodegradation and inhibit biogas production. Therefore, pre-treatment of OPEFB is necessary to enhance its digestibility and to increase biogas/methane yield. One of the green approaches to be used is biological pre-treatment using white-rot fungi [15]. This fungal pre-treatment can reduce lignin and increase cellulose content, providing more easily degraded organic materials prior to hydrolysis [16]. A study by Kamcharoen et al. [17] reported that biodegradability of OPEFB after fungal pre-treatment was higher than that of without pre-treatment.

Therefore, this study was aimed to investigate the impact of white-rot fungal pre-treatment on the OPEFB characteristics and methane potential, as well as to estimate the energy and carbon emission saving from AD of OPEFB.

2. Materials and Method

2.1. Feedstocks and inoculums

OPEFB was collected from oil palm industry in Blitar City, Indonesia. The samples were then sliced with a size of 1 cm in length. The parameters analysed include moisture content/MC, ash, total solids/TS, and volatile solids/VS.

Digestate taken from a full-scale mesophilic AD of cattle manure at Balai Besar Pelatihan Peternakan in Batu City, Indonesia was used as inoculum for the Biochemical Methane Potential (BMP) test. Prior used in the BMP test, the digestate was sieved through a 1 mm screen to remove larger particles and degased for 48 hours at 37 °C for removing the residual biogas. The inoculum was analysed for pH, MC, ash, TS, and VS. The characteristics of OPEFB used in this research are shown in Table 1.

2.2. Fungal pre-treatment

White-rot fungi of Phanerocheate chrysosporium was used to biologically pre-treated OPEFB, following the procedures in Nurika et al. [18], with the incubation period of 14 days.

2.3. BMP test set-up

Completely Randomized Design (CRD) was employed in the BMP test experiment. Samples used included control blank, control positive, untreated and treated OPEFB, all prepared in triplicate.

A manual BMP test procedure was carried out in accordance with Suhartini et al. [19], using water bath (37 °C) and operated for 30 days in batch condition, and used 250 mL serum bottles with 40-mL working volume. Control blank samples were prepared with 100% inoculum used to measure the indigenous methane production from the inoculums. The positive control was prepared with standard α-cellulose (Sigma Aldrich), used to assess the activity of microorganism consortia in the inoculum. Treated and untreated OPEFB samples were also tested. These samples were prepared in I/S ratio of 6:1. Daily pressure was measured using a Digitron 2026P absolute pressure meter (Electron Technology, UK).

2.4. AD modelling

AD Assessment Tool (ADAT) software (http://www.bioenergy.soton.ac.uk/AD_software_tool.htm), developed by the University of Southampton, was used to model energy balance and carbon emission from AD of treated and untreated OPEFB. Parameters used in the model were based on data from the experimental work combined with data from the literature reviews. The scenario of AD with combined
heat and power (CHP) for electricity and heat generation, was selected. The organic loading rate used was 2, 3, 4 and 5 kg VS/m$^3$/day for treated and untreated OPEFB.

The AD was operated in mesophilic conditions and complex systems, with a digester input of 100,000 tonnes per year. The complex system indicated a complex process with the following units: digester, a separate gas-holder, CHP, digestate pasteuriser, digestate storage, digestate separation (dewatering facilities) and composting. Based on the ADAT software, the construction material for digester was made of steel. CHP unit has conversion efficiency of 35%, load factor of 8300 hrs and biogas loss of 1%. Digestate was pasteurised after digestion at temperature of 70°C for 1 hr and stored in a steel tank with the volume capacity for up to 6 months. Digestate separation unit was by belt press with the separation efficiency for a dry matter of 56%. While for the composting unit was an open system with a mass reduction of 50%.

2.5. Analysis
TS, VS, MC and ash were analysed based on the Standard Method 2540 G [20]. pH was measured using a digital pH meter using a standard method [20]. Biogas production was calculated at standard temperature and pressure (STP) of 273.15 K and 101.325 kPa based on the equation explained in Suhartini et al. [21]; while the specific methane potential (SMP) was calculated using the equation in Strömberg et al. [22]. The SMP data obtained from the BMP test was used for modelling energy and carbon emission footprint from the AD of OPEFB.

3. Results and Discussion
3.1. Physical characteristics of OPEFB
Table 2 shows the physical characteristics of untreated and treated OPEFB. It can be seen that untreated OPEFB has a high organic content as indicated by a high VS of 94.12%TS. However, after fungal pre-treatment with Phanerocheate chrysosporium with 14 days incubation time, a slight increase in the organic content was found, giving the value of 94.45%TS. This is well within the previous study by Ishola et al. [23], who found that fungal pre-treatment on OPEFB enhance the hemicellulose content and reduce the hydrogen bond in the cellulose. Furthermore, the finding in this study may indicate that treated OPEFB can be a potential candidate as feedstock for the AD process.

| Parameters  | Untreated OPEFB | Treated OPEFB |
|-------------|-----------------|--------------|
| TS (%WW)    | 90.07           | 51.74        |
| VS (%WW)    | 84.77           | 48.86        |
| VS/TS (%TS)| 94.12           | 94.45        |
| MC (%WW)    | 9.93            | 48.26        |
| Ash (%WW)   | 5.30            | 2.88         |

The structural of OPEFB before and after fungal pre-treatment is shown in Figure 1. It can be seen that after 14 days of incubation time, there was no significant breakdown of OPEFB was evident. This may indicate that longer incubation is needed to have more lignin degradation. The previous study revealed that OPEFB digestibility increased by 4.5 fold after fungal pre-treatment with incubation time of 4 weeks [23, 24]. Therefore, future research on more prolonged incubation and its impact on biogas production are necessary.
Figure 1. SEM images of untreated and treated OPEFB

3.2. Methane potential

The BMP test results demonstrated that the SMP of control inoculum and control positive was 0.026 m³ CH₄/kg VS added and 0.394 m³ CH₄/kg VS added, respectively. A lower SMP value of control inoculum indicated that the inoculum activity is needed to be improved, possibly due to lack of handling or poor trace element content [25]. A study on BMP test with modification of inoculum condition may be needed. Furthermore, as shown in Figure 2, untreated OPEFB was found to have lower SMP compared to that of fungal pre-treated OPEFB. This indicated that an increase in organic content was correlated to an increase in digestibility and bioenergy potential, as previously stated in various studies [16, 17].

Figure 2. Average SMP of treated and untreated OPEFB

3.3. Energy balance

The AD model, as shown in Table 2, shows that despite a higher SMP value of treated OPEFB than untreated OPEFB, the biogas or methane potential was much lower. This was possibly due to a lower TS and higher MC content in treated OPEFB. This is parallel to the previous study which found that
the nature and composition of biomass feedstock in AD system may influence the biogas and methane production [26]. The data also showed that an increase in OLR led to a reduction in the retention time and the number of digesters needed in the AD of untreated and treated OPEFB.

**Table 2.** Summary of biogas and methane production and digestate produced

| Details                          | OLR of Untreated OPEFB (kgVS/ m³/day) | OLR of Treated OPEFB (kgVS/ m³/day) |
|----------------------------------|--------------------------------------|--------------------------------------|
|                                  | 2         | 3         | 4         | 5         | 2          | 3          | 4          | 5          |
| Digester input (tonnes/yr)       | 100,000   | 100,000   | 100,000   | 100,000   | 100,000    | 100,000    | 100,000    | 100,000    |
| Total digester capacity required (m³) | 127,741   | 85,161    | 63,871    | 51,097    | 73,637     | 49,092     | 36,819     | 29,455     |
| Retention time (days)            | 424       | 283       | 212       | 170       | 244        | 163        | 122        | 98         |
| Biogas (m³/yr)                   | 21,913,249| 21,913,249| 21,913,249| 21,913,249| 16,043,598 | 16,043,598 | 16,043,598 | 16,043,598 |
| Methane produced (m³/yr)         | 11,614,022| 11,614,022| 11,614,022| 11,614,022| 8,503,107  | 8,503,107  | 8,503,107  | 8,503,107  |
| Methane available (m³/yr)        | 11,497,882| 11,497,882| 11,497,882| 11,497,882| 8,418,076  | 8,418,076  | 8,418,076  | 8,418,076  |
| VS destroyed (tonnes/yr)         | 28,565    | 28,565    | 28,565    | 28,565    | 20,914     | 20,914     | 20,914     | 20,914     |
| Digestate (tonnes/yr)            | 71,435    | 71,435    | 71,435    | 71,435    | 79,086     | 79,086     | 79,086     | 79,086     |
| Number of digester (unit)        | 10        | 6         | 6         | 5         | 6          | 4          | 4          | 3          |

The energy balance of AD with the CHP scenario of untreated and treated OPEFB at different OLR is illustrated in Figure 3. Figure 3a shows that the total exportable energy balance as electricity and heat form untreated OPEFB (2.9-3.0 GJ/tonne waste) was higher than that of treated OPEFB (2.0 GJ/tonne waste). It may result from more energy are needed for pre-treatment processing, as well as due to a lower biogas or methane available from treated OPEFB, which have previously explained. A similar trend was also found for the exportable energy electrical, with the value in the range of 0.9-1.0 GJ/tonne waste (untreated OPEFB) and 0.6 GJ/tonne waste (treated OPEFB) (Figure 3b). The model also indicated that an increase in OLR has resulted a slight increase in the energy balance.
3.4. Carbon emission saving

Total emissions from AD with CHP scenario were in the range of 8,424.1 – 8,798.6 tonne CO$_2$eq/tonne waste for untreated OPEFB and 6,948.1-7,166.9 tonne CO$_2$eq/tonne waste for treated OPEFB, respectively. The model shows that increasing OLR causes a reduction in the total emission. This was possibly due to a decrease in the number of digester and retention time needed, thus reducing energy requirement for AD operation. The previous study by Budzianowski and Postawa [27] reported that different configuration and operational parameters on AD plant may have an impact on the energy outcome and carbon emission. Figure 4 shows that potential carbon emission savings for untreated OPEFB were higher than that of treated OPEFB. Furthermore, an increase in OLR was also parallel to a slight increase in the total emission saving, possibly due to higher energy generated.
4. Conclusions
This study revealed that fungal pre-treatment has ability to enhance the organic content of OPEFB. Fungal pre-treated OPEFB has higher biogas and methane production, due to a reduction in lignin content and an increase in organic matter. The AD modelling also revealed that OPEFB is the potential to be used as feedstock for biomethanisation. However, the AD modelling scenario indicated that fungal pre-treated OPEFB with 14-day incubation still has lower energy balance and carbon emission savings than untreated OPEFB. This finding indicated that longer incubation for fungal pre-treatment is required for higher and better digestibility of OPEFB. Therefore, improving the efficiency of AD of OPEFB is still critical due to the problem of high lignin content, by alternate other biological pre-treatment strategies and/or co-digestion strategies.

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