# Estimation of biogas production and the emission savings from anaerobic digestion of fruit-based agro-industrial waste and agricultural crop residues

Sri Suhartini[1*], Irnia Nurika[1], Roshni Paul[2], and Lynsey Melville[2]
[1] Department of Agro-industrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Malang, East Java, Indonesia
[2] Centre for Resilient Environments, Faculty of Computing, Engineering and Built Environment, Birmingham City University, Birmingham, West Midlands, United Kingdom

(E-mail: ssuhartini@ub.ac.id; irnia@ub.ac.id; Roshni.Paul@bcu.ac.uk; Lynsey.Melville@bcu.ac.uk)

Corresponding author:
S. Suhartini, Department of Agro-industrial Technology, Faculty of Agricultural Technology, Universitas Brawijaya, Jl. Veteran Malang, 65145, Indonesia
E-mail: ssuhartini@ub.ac.id

**Abstract**

In this study, the biomethane potential of five agricultural crop residues (ACR's) (rice straw, vegetable waste, maize straw, coffee husk and oil palm empty fruit bunches (OPEFB)) and five Fruit-Based Agro-Industrial Wastes (FBAIW's) (jackfruit straw, banana, orange, apple and pineapple peel waste) were evaluated. The carbon and energy balance for each waste was also theoretically modelled for two biogas conversion scenarios (AD with CHP or biogas upgrading). A standard biomethane potential test (BMP) was operated over 30 days at 37$^{o}$C. Specific methane potential (SMP) of FBAIW's was generally higher than that of the ACR's, except for vegetable waste. Vegetable waste was identified as having the highest SMP (0.420 $m^3/kgVS_{added}$). With respect to ACRs, OPEFB and coffee husk had the lowest SMP values of 0.185 and 0.181 $m^3/kgVS_{added}$, respectively. This was attributed to the higher lignin content of these wastes which can impact on biodegradation and subsequent biogas production. Theoretical estimations showed a positive energy balance for all wastes tested. In terms of exportable energy, apple peel waste was shown to have the highest exportable energy potential. The FBAIW's also exhibited greater emissions savings than ACR's (with the exception of vegetable waste). This study concluded that there is good potential to valorise these wastes using AD and that this could address the challenges of waste management and clean energy provision in Indonesia.

**Keywords:** energy footprints; carbon footprints; waste to bioenergy; mono-digestion; anaerobic digestion modelling

## Introduction

According to the Ministry of Energy and Mineral Resources [1], 146.7 million tons of biomass (including municipal solid waste) is generated across Indonesia each year. This waste is currently underutilised and has wide ranging environmental and societal impacts. This waste resource offers great potential as a feedstock for bioenergy with an estimated energy equivalent of 32,653.8 MW. Currently, Indonesia is also experiencing an increase in energy demand, accompanied by a high price for fossil fuels and a decline in non-renewable energy supplies, particularly coal [2]. It is projected that energy demand in Indonesia will continue to increase to 450 billion kWh by 2026 [3]. Furthermore, energy demands continue to increase across a number of key sectors including industrial (276.3 GWh), commercial (226.8 GWh), residential (116.7 GwH) and public costumers (0.1

thousand GWh), respectively [4]. Efforts to develop new and renewable energy sources, such as those derived from biomass, are therefore critical. Indonesia, however, has various obstacles in valorising biomass as a bioenergy resource [5]. The report by Taylor et al [6] highlighted some key challenges e.g. high initial capital and operational costs and challenges of low feed in tariffs for electricity from biogas. Lack of biogas policy and development targets to reduce risk and uncertainty for stakeholders. Also, high fossil fuel subsidies inhibit further biogas development. Therefore, the Indonesian Government, through its National Energy Policy (NEP), has clearly stated several programmes to promote the production of renewable energy, including the production of bioenergy from biomass [1].

Biomass is defined as any organic, biodegradable materials originating from plants, animals, microorganisms or waste [1]. Agro-industrial waste, generated from commercial scale processing of fruits is an abundant resource in Indonesia. The sector makes an important contribution to the Indonesian economy, however, with little incentive to treat the waste streams from these processes, this material is often disposed of directly into the environment. This has various, deleterious impacts on land, water and air quality and can also pose a risk to human health (through pests, odour and pathogens) [7]. There are very few studies in the literature which illustrate the alternative sustainable uses for these organic wastes. A number of studies have shown that the material is suitable for animal feed and there are studies which have explored the utilization of organic waste for the production of sustainable materials, bio-absorbents [8] and high value compounds [9]. A study by Ugwanyi [10] reported that some agro-industrial wastes (such as citrus pulp, potato process slurries, cane process waste, apple pulp, pineapple waste, etc.) have the potential to be used as animal or cattle feed. Similarly, Jirapornvaree et al. [11] found that agro-industrial wastes such as pineapple waste can be valorised into biodegradable decomposable pots. Furthermore, a study by Bardiya et al. [12] illustrated that banana peels and pineapple wastes have promising potential for biomethanation. Various laboratory-scale studies have evaluated the biomethane potential of fruit and vegetable wastes, for example, Gunaseelan [13] reported that fruit wastes (such as orange peels, banana peels and pineapple peels) have high methane potential, and can therefore be used as potential feedstock for anaerobic digestion (AD). Energy production from these wastes offers an alternative treatment solution and, in comparison to other conversion platforms, is relatively low cost. As a valorisation pathway, this is attractive as it addresses the challenges of waste management, energy supply and offers opportunities for the production of bio-fertiliser.

Agricultural crop residues in Indonesia (such as oil palm residues, rice straw, maize straw and coffee husk) are abundant and offer huge potential as a feedstock for bioenergy [1]. Indonesia has a thriving palm oil production industry and in 2019 it was estimated that production of fresh fruit bunches (or FFB) was in excess of 42 million tons [14]. Assuming that processing of FFB generates about 21% (w/w) waste (referred to as oil palm empty fruit bunches or OPEFB) [15], the potential waste biomass generated is estimated to be 8.97 million tons. In addition, BPS-Statistics Indonesia [16] reported that dry unhusked rice production in 2019 was approximately 54.6 million tons, with the potential volume of waste rice straw estimated at 81.9 million tons. According to data from the Ministry of Agriculture Republic Indonesia [17], the area of maize cultivation in 2018 was 5,734,000, and approximately 2 - 4 tons of maize straw is produced per ha, giving a potential waste biomass resource in the range of 11.5 – 22.9 million tons. Maize straw is mostly used for cattle feedstock either with or without ensilage pre-treatment [18]. Indonesian coffee fruit production is estimated to be 750,000 tons per year [19], and 50-60% of the coffee fruit is coffee husk waste [20]. On this basis, it can be assumed that the potential volume of coffee husk waste per annum is in the range 375,000 – 450,000 tons per year. It is clear that agricultural waste is an abundant and currently underutilised biomass resource which could be further valorised, for generation of, for instance fuels. Small-scale, individual digesters are prevalent in Indonesia and have been widely introduced through biogas programmes (such as Simantri and Biru) to supply biogas to households [6]. Larger commercial-scale AD plants are less common but could offer long term benefits to industry both in terms of improved waste management practices and sustainable energy generation to support on-site processing.

Anaerobic Digestion is the biological degradation of organic material under anaerobic conditions, generating biogas, which mainly consists of methane ($CH_4$) and carbon dioxide ($CO_2$), as well as a residual organic fraction (i.e. digestate) [21, 22]. Biogas can be upgraded to achieve a higher methane content of 50-70% which then makes it suitable for direct combustion. It can be utilised directly for cooking or can be converted via a CHP engine to produce heat and electricity. Additionally, digestate from AD systems can be utilised as bio-fertiliser, cultivation media, or soil conditioner [3, 23]. According to Taricska [22], generally, AD systems incorporate one or two stages depending on their application. A single-stage AD system has only one digester, also known as a continuously stirred tank reactor (CSTR). These are considered more effective for waste fractions with a high moisture content (such as manure, food waste (FW), waste activated sludge (WAS), and silage) [22]. A two-stage AD system typically involves two digesters which separate the two phases of the digestion process (acidification and methanogenesis) and is the preferred configuration for feedstocks with higher ligno-cellulosic content such as those described herein. This enables greater process control and improved performance resulting in a shorter overall digestion times than the single-stage digester. The two-stage AD system, however, requires more advanced control and operation, as well as higher capital costs. Furthermore, many other factors affect the performance of AD including temperature, pH, feedstock composition and concentration, nutrients, hydraulic retention time, organic loading rate, mixing, and toxicity [21, 22].

The Biochemical Methane Potential (BMP) test is a standard method which can be used to measure the conversion of organic matter into methane. It is a relatively quick and simple batch test which is used to assess the biodegradability of a substrates under controlled conditions by monitoring the cumulative biogas or methane production over the test period [24]. This measurement can provide data and information beneficial for evaluation, design, and optimisation of the AD process [25]. Furthermore, the BMP test is also applied to calculate the amount of residual organic material available for further anaerobic treatment, the remaining fraction of the non-biodegradable material, and the potential efficacy of the AD process generally [24, 25]. Angelidaki et al. [26] developed guidelines to standardise the procedures in the BMP tests, with various aspects to be considered such as inoculum activity, macro- or micro-nutrients, mixing arrangement, particle size of the tested substrates, as well as characteristics and composition of the tested substrates. Several studies have utilised BMP testing to investigate the biogas potential of additional biomass feedstocks, such as fruit wastes [23]; OPEFB [27]; coffee husk [28]; and straw [29]. Studies which focus on the aforementioned agro-industrial and agricultural crop residues relevant to Indonesia are currently limited.

This study aimed to investigate the biogas potential of agricultural crop residues (ACRs) and fruit based agro-industrial waste (FBAIWs) as single feedstocks into AD with a view to identifying the most appropriate applications and commercial opportunities. The results will contribute to the development of a bioresource database for Indonesia which will help to inform future waste and energy policy and practices. This work will also demonstrate the potential benefits of valorising these wastes and identify key operational considerations. This will aid with translation of the work to commercial scale applications. Fostering and nurturing bio-based economies and promoting wider adoption of bioenergy are important if Indonesia is to achieve its Sustainable Development Goals. In particular, SDG12 which aims to reduce agricultural losses and achieve sustainable management and efficient use of natural resources and SDG7 to ensure access to affordable, reliable and clean energy for all.

## Materials and methods

### Feedstocks and inoculums

Five Fruit Based Agro-industrial Waste (FBAIW) samples were collected from five commercial sites in Batu City and Malang City, East Java, Indonesia. These wastes included jackfruit waste (or jackfruit straw), as well as orange, apple, banana and pineapple peelings. A number of Agricultural Crop Residue (ACR) samples (such as rice straw, maize straw, vegetable waste, coffee husk and OPEFB) were also collected directly from their respective production sources. All raw material samples were cut and ground using a commercial food mixer to smaller particle size. The samples were immediately stored in plastic containers and refrigerated at 4 $^{o}$C (for FBAIW and vegetable waste) or stored at room temperature (~28$^{o}$C) (for rice straw, maize straw, coffee husk and OPEFB) upon arrival at the Bioindustry Laboratory, Universitas Brawijaya. Subsequent proximate analysis was carried out including total solids (TS), volatile solids (VS), moisture content (MC), and ash.

Digestate, as inoculum, was taken from a full-scale mesophilic AD treating cattle manure at *Balai Besar Pelatihan Peternakan* (BBPP) in Batu City. The collected digestate was then sieved through a 1 mm screen to remove larger particles. Digestate was de-gassed for 48 hours at 37 $^{o}$C to reduce any residual biogas, as recommended by Strömberg et al. [30]. The inoculum used in this study has the following characteristics: pH of 7.6; TS of 1.37 %WW; VS of 0.88 %WW; VS of 63.93 %tS; MC of 98.63%WW; and ash of 0.49 %WW, respectively.

### Biochemical methane potential test set-up

The BMP test was carried out in triplicate over 30 days using a manual BMP system heated by a water bath maintained at 37±0.5 °C. The BMP test methodology was performed in accordance with Suhartini et al. [27], and used 250 mL serum bottles with a working volume of 40 mL. Control blanks (inoculum only) were used to measure the initial methane production from the inoculum. Positive controls (α-cellulose) were used to test the inoculum activity. Waste samples and inoculum were added to each reactor with an inoculum to substrate ratio (I/S ratio) of 6:1. Samples were added to each bottle with an organic loading rate (OLR) of 3 kg VS/L/day. The serum bottles were placed in a water bath at 37 $^{o}$C without mixing arrangement. Pressure was measured on a daily basis using a Digitron 2026P absolute pressure meter (Electron Technology, UK). Biogas production was calculated at standard temperature and pressure (STP) using the formula in Suhartini et al. [31]. The net biogas production was calculated by subtracting the average gas production of the samples from that of the blank controls over the same period. The specific methane potential (SMP) was calculated using the formula below [30]:

$$SMP = \frac{V_S - V_B \frac{m_{IS}}{m_{IB}}}{m_{VS,sS}} \quad [1]$$

Where: SMP is the normalised methane volume (L $CH_4$/kg VS), $V_S$ represents the mean value of the accumulated methane volume from the reactors containing inoculum and substrate (mL), $V_B$ represents the mean value of the methane volume from control blank (mL), $m_{IS}$ is the weight of VS of added inoculum in the sample (gVS), $m_{IB}$ is the weight of VS of added inoculum in the blank sample (gVS), and $m_{VS,sS}$ is the weight of VS of substrate added in the reactor (gVS).

Specific biogas production (L biogas/kg VS), was calculated using equation 1, by replacing the volume of methane with the volume of biogas.

**AD modelling scenario**

The AD modelling considered two scenarios, which consisted of AD with a combined heat and power (CHP) unit (AD-CHP), and AD with a biogas upgrading unit (AD-BU). These two scenarios were considered to be particularly relevant to potential future applications in Indonesia because of the need to co-locate energy use with energy production geographically. The CHP technology transforms the biogas produced during AD into electricity and heat, while biogas upgrading converts the biogas produced into biomethane. The carbon and energy balance of these scenarios was calculated using the AD Assessment Tool (ADAT) software created and developed by the University of Southampton (http://www.bioenergy.soton.ac.uk/AD_software_tool.htm), as well as a model developed by Salter and Banks [32] with an organic loading rate (OLR) of 3 kg VS/L/day, equating to that used in the BMP test. The system was operated under mesophilic conditions. The parameters used in the model were based on data obtained from experimental work and from the literature review, as shown in Table 1.

**Analytical methods**

pH was measured using a digital pH meter, previously calibrated in buffers at pH 7 and 9.2, following the standard procedure [33]. Total solids (TS), volatile solids (VS), moisture content (MC) and ash content was determined based on Standard Method 2540 G [33]. The calorific value (CV) of each biomass feedstock tested was measured using a bomb calorimeter. Theoretical methane content was calculated using the Buswell equation, assuming 100% organic biomass breakdown [34]. The C, H, N and S content for substrate samples used in Buswell calculation was determined from the biomass and waste database of ECN Phyllis2 (https://phyllis.nl/), except for banana peels [35]; jackfruit straw [36]; vegetable waste [37], as shown in Table 2.

**Statistical analysis**

Mean and standard deviation (error bars) were calculated using Microsoft Excel software. The Cronbach's Alpha reliability test was carried out using R Software to analyze the reproducibility in the BMP experiments. The reliability test was performed on all replication in BMP test with 95% confidence boundaries. If the Chronbach's Alpha value is within 0.70-0.99, then the experimental measurement is reliable and valid [38].

**Table 1.** Parameters applied to AD model

| Parameters | Unit | Value |
|---|---|---|
| Input OLR | kgVS/m$^3$/day | 3 |
| Digester temperature | $^oC$ | 37 |
| Digester construction | - | Steel with height to width ratio of 0.4 |
| Digester operational life span | years | 30 |
| Type of separator | - | Belt press |
| Pasteuriser | - | Width to height ratio of 0.5 (Post-pasteurisation) |
| Pasteuriser temperature | $^oC$ | 70$^oC$ |
| Pasteurisation time | hours | 1 |
| Gas holder | - | Separate gas holder for storage 2 hours |
| Digestate storage construction | - | Steel with roof membrane |
| Digestate storage capacity | months | 6 |
| Biogas capture | - | Included with height to width ratio of 0.2 |
| Biogas losses | % | 1 |
| CHP electrical efficiency | % | 35 |
| CHP heat efficiency | % | 50 |
| Boiler efficiency | % | 85 |
| Percent methane lost upgrading | % | 2 |
| Electrical energy upgrading biogas | kWh/m$^3$ | 0.3 |
| Electrical energy compressing methane | kWh/m$^3$ | 0.3 |
| CHP load factor | yours/year | 8300 |
| CHP operational lifespan | years | 15 |
| Alternate heat energy sources | - | Diesel oil |
| Heat energy source replaced | - | Natural Gas |
| Ambient temperature | $^oC$ | in the range of 27-31 |
| TS | %WW | as stated in Table 2 |
| VS | %TS | as stated in Table 2 |
| Proportion fixed carbon | % | 0.4-0.5 |
| Specific methane potential | % | Based on BMP test results |
| $CH_4$ concentration | % | as stated in Table 2 |
| Type of composter | - | Open system |
| Composter mass reduction | % | 50 |
| Type of transportation | - | Artic > 33t for feedstock<br>Artic < 33t for digestate/compost |
| Distance of transportation | km | 10 km for digestate to agricultural land<br>50 km for feedstock to AD plant |

## Results and discussion

### Physical characteristics of selected fruit-based agro-industrial waste and agricultural crop residues

The characteristics of the wastes used in this study are shown in Table 2. For all of the wastes tested the ratio of VS to TS was in the range 82-99%TS (apart from for rice straw which was 49.49 %TS), indicating their suitability as AD feedstocks. These findings indicated that all tested samples are suitable as feedstock for AD systems. Gelegenis et al. [39] noted that for a given wet weight of feedstock, the VS content is usually positively correlated to specific biogas or methane production. Gunaseelan [13] tested 54 fruits and vegetable wastes using BMP test, and typically, specific methane production is attributed to the extent and rate conversion of the organic fraction. Similarly, our study has indicated that both fruit and vegetable waste were found to be potentially useful substrates in single- or co-digestion AD systems.

**Table 2.** Characteristics and average of SMP of waste samples

| Waste type | TS (%WW) | VS (%WW) | VS/TS (%TS) | MC (%) | Ash (%WW) | CV (MJ/kg TS) | C* (%TS) | H* (%TS) | O* (%TS) | N* (%TS) | S* (%TS) | Theoretical $CH_4$ (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Fruit-based agro-industrial wastes* | | | | | | | | | | | | |
| Orange peels | 19.72±0.344 | 18.83±0.420 | 95.49±0.957 | 80.28±0.344 | 0.89±0.184 | 2.24 | 46.4 | 5.7 | 46.33 | 1.52 | 0.05 | 48.6 |
| Banana peels | 19.14±0.280 | 15.75±0.146 | 82.25±0.448 | 80.86±280 | 3.40±0.135 | 1.77 | 35.65 | 6.19 | 55.47 | 1.94 | 0.75 | 44.9 |
| Pineapple peels | 15.89±0.236 | 15.34±0.216 | 96.55±0.075 | 84.11±0.236 | 0.55±0.020 | 2.28 | 47.30 | 6.03 | 45.33 | 1.13 | 0.21 | 50.3 |
| Apple peels | 21.63±0.344 | 21.29±0.360 | 98.45±0.471 | 78.37±0.344 | 0.34±0.103 | 2.44 | 49.56 | 8.43 | 40.99 | 0.97 | 0.05 | 59.4 |
| Jackfruit straw | 15.17±0.140 | 14.06±0.126 | 92.70±0.155 | 84.83±0.140 | 1.11±0.028 | 2.06 | 41.77 | 6.36 | 48.84 | 2.47 | 0.56 | 48.9 |
| *Agricultural crops residues* | | | | | | | | | | | | |
| Rice straw | 42.02±0.609 | 20.80±0.079 | 49.49±0.910 | 57.98±0.609 | 21.23±0.894 | 2.31 | 48.16 | 5.62 | 45.13 | 0.94 | 0.15 | 49.3 |
| OPEFB | 88.59±0.299 | 81.26±0.609 | 91.73±0.411 | 11.41±0.299 | 7.33±0.346 | 2.01 | 41.61 | 5.92 | 51.26 | 0.23 | 0.98 | 47.8 |
| Maize straw | 24.93±2.133 | 21.97±1.700 | 88.13±0.776 | 75.07±2.133 | 2.96±0.438 | 2.23 | 46.5 | 5.81 | 47.02 | 0.56 | 0.11 | 49.4 |
| Vegetable waste | 7.91±0.240 | 7.11±0.258 | 89.91±0.640 | 92.09±0.240 | 0.80±0.036 | 2.53 | 52.4 | 6.5 | 40.00 | 1.1 | 0 | 53.6 |
| Coffee husk | 89.36±0.831 | 81.24±0.487 | 90.91±0.668 | 10.64±0.831 | 8.12±0.654 | 2.21 | 46.38 | 4.86 | 47.58 | 0.59 | 0.59 | 46.0 |

Note: *References used for C, H, O, N, S value of banana peels [35]; jackfruit [36]; vegetable waste [37] and other biomass samples are from https://phyllis.nl/.

**pH profiles before and after BMP testing**

Before and after the BMP tests, the pH and temperature of the control blank, p control α-cellulose and sample reactors were measured to determine whether there was any likely impact or hindrance on the AD process. There were no significant changes in pH before and after the BMP test and all pH values were in the range of 7.0-7.7, well within the ideal range of 6.8 – 8.0 for optimal AD [40]. The results also suggested there was no major inhibition as a result of pH in these batch tests.

**Specific biogas and methane production**

Fig. 1 shows the potential biogas or methane produced based on the organic matter content (or VS content) in each biomass samples (also known as specific biogas production/SBP and specific methane production/SMP) over 28 days. The figures indicate that FBAIWs have higher biogas and/or methane potential than that of ACRs, except for vegetable waste. The figure indicates that almost all samples produce gas rapidly in the first 2 days. After that, the rate of gas production in most cases is reduced. For several waste types (i.e. banana peels, apple peels, and jackfruit straw), both SBP and SMP increased moderately until day 15 and reached a plateau where methane production was relatively constant. For rice straw, maize straw, OPEFB and coffee husks, the trend shows lower methane production overall, and the rate of methane production was very slow from day 2 to day 13. All of these wastes fall into the category of agricultural waste and exhibit high lignin and fiber contents, which is known to impact on biogas and methane production. Lignin, a recalcitrant fraction of ligno-cellulosic biomass has a complex structure, which limits the digestibility and conversion of the biomass to biogas using AD system [41].

In this study, α-cellulose was used as a positive control sample to confirm the efficacy of the consortia of microorganisms in the inoculum to degrade organic matter. If the SMP value is close to the theoretical value, it indicates that the consortiums of microorganisms are optimal for the degradation of organic matter without the addition of supplementary nutrients. It also indicates that there are no inhibitory compounds/conditions present that would negatively influence biogas production. Thus, the inoculum can be used as a starter for testing the potential of biogas/methane. If the SMP value is much lower than the theoretical value, it indicates a lack of microbial activity and inability of the inoculum to degrade organic matter in the samples. This study found that the methane production from the control inoculum and control α-cellulose were lower than theoretical (at the value of 0.026 $m^3$ $CH_4$/ $kgVS_{added}$ and 0.368 $m^3$ $CH_4$/ $kgVS_{added}$, respectively). The SMP of control α-cellulose is still below the theoretical SMP of 0.415 $m^3$ $CH_4$/ $kgVS_{added}$, calculated based on its molecular composition ($C_6H_{10}O_5$). However, this SMP value is slightly higher than that of the SMP of α-cellulose samples reported in Chynoweth et al. [42] which reported value of 0.370 $m^3$ $CH_4$/ $kgVS_{added}$.

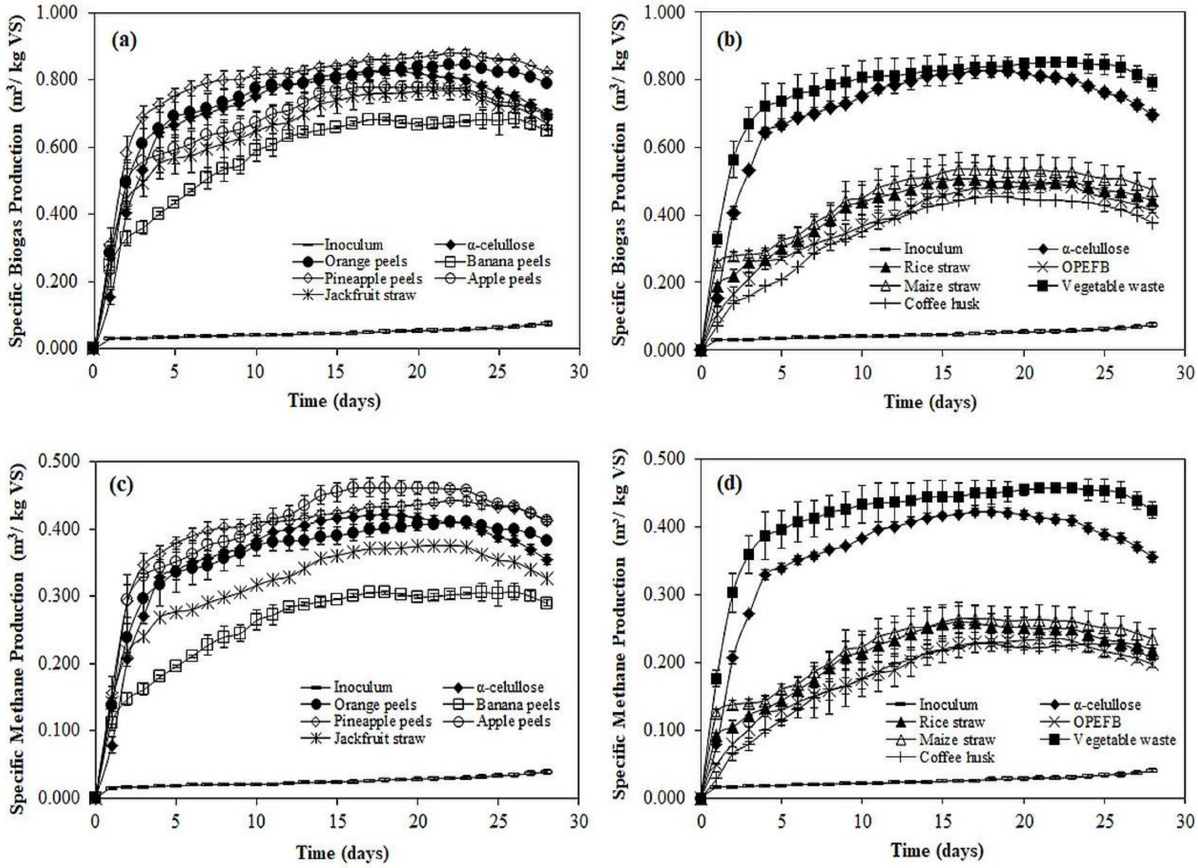


**Figure 1.** Specific biogas and methane production from fruit-based agro-industrial waste and agricultural crops residues. Error bars represent standard deviation from three measurements. Error bars represent standard deviation from three measurement.

This study shows the SMP value for the inoculum was lower than the average reported in other studies [23, 42]. This issue may arise due to poor sampling, poor storage/handling of inoculum, as well as a lack of trace element in the inoculum  In this study, it is believed that trace elements were insufficient as sampling and handling were carried out according to the standard procedures as described in Angelidaki et al. [26]. Other potential explanations need to be investigated such as poorly performing digesters, inoculum source and ratio of inoculum to substrate [29]. The results in this study confirmed that future modifications to the BMP test is necessary. For example,  through the addition of trace elements or other essential nutrient in order to enhance the metabolism of the anaerobic microbial consortia, as suggested by Angelidaki et al. [26], with the aim of enhancing the ability of the microbial consortia in the inoculum to degrade the organic material in the tested biomass samples. Jensen et al. [24] suggested that, because the quality of the inoculum has a great impact on the BMP test, sufficient quantity should be collected from an anaerobic digester plant fed with complex material in order to provide a diverse and balanced microbial population. This approach improves the chances for a complete breakdown of the degradable portion of the sample material. The same inoculum was used for all samples tested within this study, therefore, despite the insufficient trace element composition the results remain comparative.

Despite the aforementioned limitations of the inoculum used in this study, all samples tested exhibited significant biogas and methane production. On average, Fig. 2a shows that the sample with the highest SBP was pineapple waste (0.817 $m^3$ biogas/kg$VS_{added}$) followed by vegetable waste (0.800 $m^3$ biogas/kg$VS_{added}$), orange peels (0.771 $m^3$ biogas/kg $VS_{added}$), apple peels (0.702 $m^3$ biogas/kg $VS_{added}$) and jackfruit straw (0.677 $m^3$ biogas/kg $VS_{added}$). The SBP value of jackfruit straw in this study was slightly higher than reported in previous studies of 0.551-0.610, for example, as shown in Table 3 [43]. With the exception of vegetable waste, other agricultural crop residue samples, (which are considered lignocellulosic biomass), produced much lower SBP and SMP. The study shows that coffee husks produced the lowest SBP giving a value of 0.366 $m^3$ biogas/kg$VS_{added}$, followed by OPEFB (0.397 $m^3$ biogas/kg$VS_{added}$). These findings are in agreement with previous work that shows that lignocellulosic materials are resistant to biological conversion and require pre-treatment to optimise microbial degradation [41].

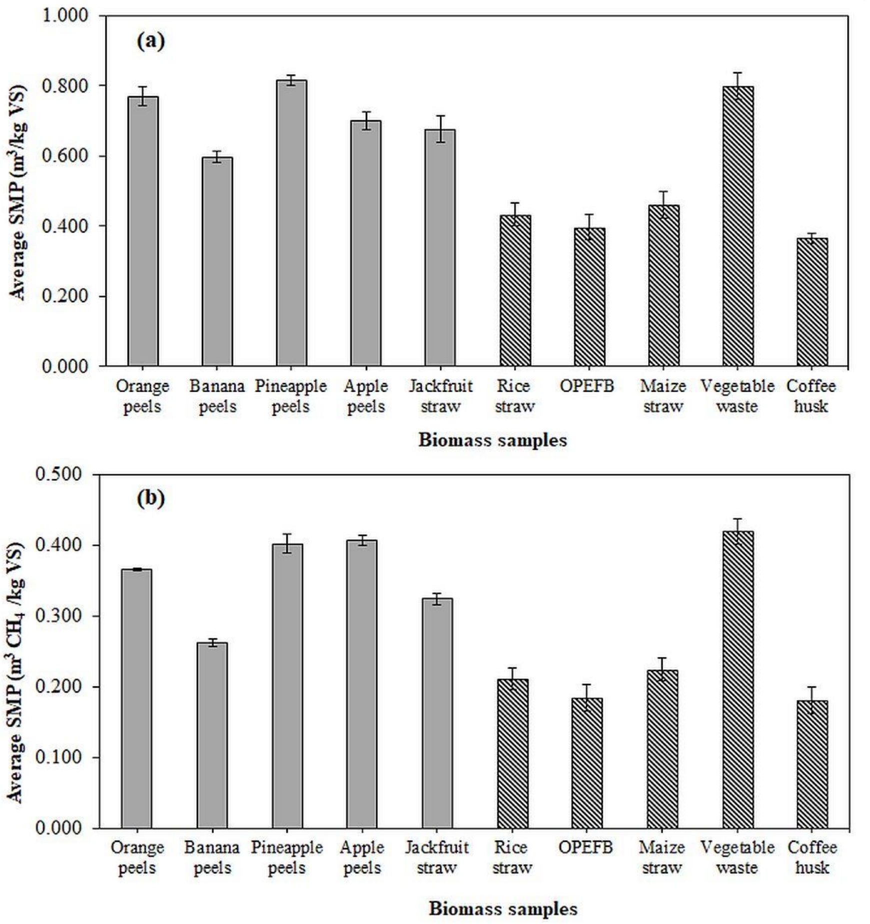


**Figure 2.** Average SBP and SMP from fruit-based agro-industrial waste and agricultural crops residues. Error bars represent standard deviation from three measurements. Error bars represent standard deviation from three measurement.

**Table 3.** Comparison of other studies investigating BMP fruit-based agro-industrial waste and agricultural crops residues

| | SMP values in other studies ($m^3CH_4$/kg $VS_{added}$) | | | | | | This study | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Gunaseelan [13] | Chala et al. [28] | Chen et al. [29] | Suksong et al. [53] | Umeghalu et al. [43] | Zheng et al. [44] | Ave. SMP ($m^3CH_4$/ kg $VS_{added}$) | Ave. SBP ($m^3$ Biogas/ kg $VS_{added}$) | Cronbach's alpha reliability for SMP | Cronbach's reliability alpha for SBP |
| BMP's operational condition | Samples were dried and ground (2 mm mesh). BMP test was carried out with inoculum concentration of 20% (v/v) and total volume of 135 mL, at 35 ± 1◦C, and operated for 100 days. | Coffee husk was ground (1 mm size). BMP was carried out with addition of 0.3 g substrate and 30 g inoculum in 100-mL calibrated glass syringes with continuous mixing, at 37°C, and operated for 35 days. | Samples were BMP with addition of 7.5 g VS and the working volume of 450 ml (total volume of 500 ml), at 37 ± 1 °C using a water-bath pot, and daily shaken at 140 rpm | OPEFB was dried and cut (size of 0.5–1.0 cm length). BMP was carried out at $R_{I/S}$ of 2 with the working volume of 200 mL (total volume of 500 mL), at 40°C using incubator, and operated for 60 days. | Jackfruit waste was cut (~2-3 cm. BMP was carried out with addition of 150 g substrate, 150 g inoculum, and 600 g water, at mesophilic condition, daily stirred, and operated for 35 days. | Samples were dried and ground (1 mm). BMP was carried out with addition of 100 g inoculum, 400 g of nutrient medium and 10 g orange peel (or 5 g for banana peels and apple peels) and total volume of 1 L, at 35 °C, and shaken once each day. | All biomass samples were ground to reduce particle size. BMP test was carried out at 250 mL bottle with working volume of 40 ml. $R_{I/S}$ of 6:1, OLR of 3 kg VS/L/day, at 37±0.5 °C using static water bath, shaken once each day, and operated for 28 days | | | |
| Orange peels | 0.455-0.486 | - | - | - | - | 0.277 | 0.366±0.013 | 0.771±0.028 | 0.99 | 0.99 |
| Banana peels | 0.243-0.322 | - | - | - | - | 0.227 | 0.262±0.007 | 0.597±0.016 | 0.99 | 0.99 |
| Pineapple peels | 0.357 | - | - | - | - | - | 0.402±0.008 | 0.817±0.015 | 0.99 | 0.99 |
| Apple peels | - | - | - | - | - | 0.277 | 0.407±0.015 | 0.702±0.025 | 0.99 | 0.99 |
| Jackfruit straw | - | - | - | - | 0.551-0.610* | - | 0.324±0.019 | 0.677±0.039 | 0.99 | 0.99 |
| Rice straw | - | - | 0.263 | .- | - | - | 0.211±0.016 | 0.433±0.032 | 0.99 | 0.99 |
| OPEFB | - | - | - | 0.149 | - | - | 0.185±0.018 | 0.397±0.037 | 0.99 | 0.99 |
| Maize straw | - | - | 0.287 | - | - | - | 0.224±0.019 | 0.462±0.038 | 0.99 | 0.99 |
| Vegetable waste | 0.190-0.400 | - | - | - | - | - | 0.420±0.020 | 0.800±0.038 | 0.99 | 0.99 |
| Coffee husk | - | 0.159 | - | - | - | - | 0.181±0.007 | 0.366±0.015 | 0.99 | 0.99 |

Note. *SBP value in $m^3$ Biogas /kg $VS_{added}$

With regards to SMP, the differences in methane content evolved from the samples was believed to be due to variations in elemental content of C, H, O, N, S of tested biomass, as shown in Table 2. The results show that, on average, the highest SMP value was produced from vegetables waste and apple peels, with values of 0.420 and 0.407 $m^3$ $CH_4$/ $kgVS_{added}$ respectively (Fig. 2b). This was followed by pineapple peels (0.402 $m^3$ $CH_4$/ $kgVS_{added}$), orange peels (0.366 $m^3$ $CH_4$/ $kgVS_{added}$), jackfruit straw (0.324 $m^3$ $CH_4$/ $kgVS_{added}$), banana peels (0.262 $m^3$ $CH_4$/ $kgVS_{added}$), maize straw (0.224 $m^3$ $CH_4$/ $kgVS_{added}$) and rice straw (0.211 $m^3$ $CH_4$/ $kgVS_{added}$). Both OPEFB and coffee husk samples produced the lowest SMP, with the values of 0.185 and 0.181 $m^3$ $CH_4$/ $kgVS_{added,}$ respectively. Other studies have also reported variation of results in biogas and methane potential of agro-industrial waste and agricultural crops residues (Table 3). For example, Zheng et al. [44] reported that apple peels, banana peels and orange peels have SMP of 0.277, 0.227, and 0.277 $m^3$ $CH_4$/ $kgVS_{added}$, lower than the SMPs found in this study. According to Ahmed et al. [45], differences in the physicochemical characteristics of biomass can influence the physiological process and ability of microbial consortia to adapt to different substrates, which may impact on the rate of methane production.

The findings in this study indicate that both FBAIWs and ACRs (particularly vegetable waste) offer good potential to be used as a feedstock for biogas production. There is adequate evidence in the literature that supports the translation of BMP batch test results to prediction of full-scale biomethane production in continuously fed full-scale AD plants. For example, Strömberg et al. [30] reported that the SMP values obtained from BMP tests can provide a good indication of biodegradation rates and can therefore be used when selecting the most suitable biomass feedstock for AD. Hollinger et al. [46] demonstrated that methane production calculated from BMP tests compared well with the measured methane production at two full-scale operational AD plants. However, the authors stated that the BMP test tended to overestimate productivity and that application of an extrapolation coefficient of 0.8-0.9 was recommended. The authors also confirmed that this comparison (and moderate overestimations of full scale productivity) were in agreement with other previous studies [21, 47]. It should be noted, however, that BMP tests, while providing a good estimation of biogas potential (and can identify potential toxicity issues) they cannot provide information on longer term process stability, optimal organic loading rates or hydraulic retention times for full scale operation [25].

The results of this study also highlighted that some of the ACRs tested (i.e. coffee husk, OPEFB, maize straw, and rice straw) are not suitable as a primary feedstock for AD. When compared to other biomass feedstocks studied here, ACRs such as maize straw, rice straw, coffee husk and OPEFB have low specific biogas production due to their high lignin content. Therefore, co-digestion with other biomass feedstocks or pre-treatment prior to the AD process is recommended. Previous studies have also demonstrated the successful co-digestion of fruit and vegetable wastes in semi-continuous trials with concomitant improvements in biogas production compared with mono-digestion of these wastes [48, 49]. An in-depth investigation of suitable co-digestion feedstocks is also necessary to enhance the biogas production from these feedstocks.

The reliability test results showed that all tested samples have Cronbach's alpha values higher than 0.6 both for specific biogas and methane potential from each biomass samples tested (Table 3). This finding indicates that the degree of reproducibility and consistency of the BMP test from all samples were acceptable and reliable, as stated by Fraenkel and Wallen [43].

The values produced from the BMP test were used to theoretically estimate the energy potential, energy saving and carbon saving, as well as the nutrient footprint from the AD of these FBAIWs and ACRs according to the two scenarios mentioned previously.

**Volatile solids (VS) destruction**

This study indicates that, theoretically, the degradation rate of organic matter (known as VS destruction percentage) for all tested wastes was higher than 80%, indicating they offer good potential as a feedstock for AD. Despite the previously identified limitations with the inoculum the VS removal observed in the control sample (Cellulose) was 99.57%. This is owing to the fact that cellulose is readily biodegradable. As previously mentioned, optimal AD performance is reliant on an inoculum which contains sufficiently abundant and active anaerobic consortia.

In the case of FBAIW, for most of the samples a VS destruction in the range of 90% to 95% was observed. For agricultural crop residues, the VS destruction was in the range of 80-98%. This finding provides further confirmation that both sources of wastes are suitable for AD feedstock. This is in agreement with research by Menardo and Balsari [50], who found that some agricultural crops residues and organic wastes were a feasible alternative to energy crops for bioenergy production. The high VS destruction observed in this study is a good indication that AD is a viable pathway for the treatment of these wastes. This offers considerable environmental benefits over disposal to land. The energy production potential provides a significant economic driver for implementation of AD. However, further measures are required to enhance the degradation process, which will have a positive correlation in increasing the biogas and methane production.

The moisture content of a biomass can also impact upon the degree of VS destruction. According to Le Hyaric et al. [51], specific methanogenic activity in an anaerobic digester decreased linearly with a decrease in MC value. As shown in Fig. 3, this trend was also observed in this study where dried biomass samples (such as OPEFB and coffee husks) with a higher % dry matter (TS) (or a lower MC value) subsequently exhibited lower methane potentials, indicating lower biodegradability. Based on the SMP values reported in this study, vegetable waste has superior potential for biogas and methane production compared with OPEFB or coffee husk. This shows that the fraction of organic matter available in biomass feedstock may have more impact on the rate of biogas production, and therefore the implied biodegradation rate [50]. Furthermore, rate of biogas production is also dependent upon the availability of the organic matter to the microbes. If the cellulose is encased in lignin, biodegradation rate can be inhibited. Mancini et al. [41] stated that lignin and hemicellulose physically encase the cellulose, thus hindering cellulose to be easily accessible and making it highly resistant to degradation.

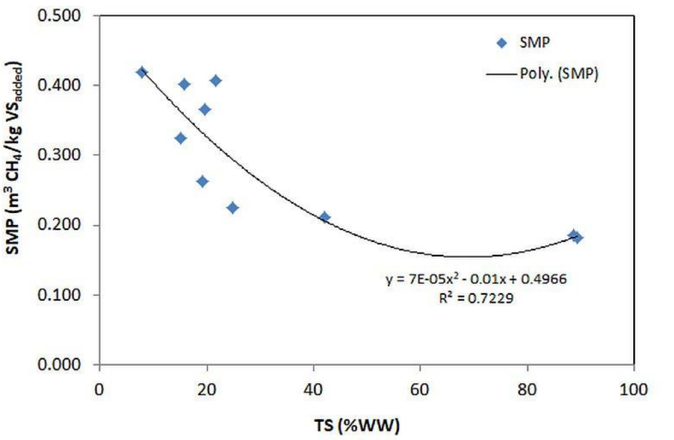


**Figure 3.** Correlation between TS content and SMP of all tested biomass samples

### *AD Modelling*

**Boundary system**

This study defined both potential scenarios as complex systems which included the following: the anaerobic digestion plant, transportation, biogas converting unit, digestate treatment facilities (i.e. pasteurisation unit, dewatering, and composting unit). The system boundary used in this study is shown in Fig. 4. The model considers various inputs to the system such as materials, energy, construction materials, equipment, and etc. while the outputs include energy produced (i.e. electricity, heat, biomethane) and emission savings (i.e. $CO_2$ emission). This study considered the use of a complex system, where solid fractions of digestates were composted in an enclosed composting unit for bio-fertiliser production with the aim of replacing synthetic fertiliser.

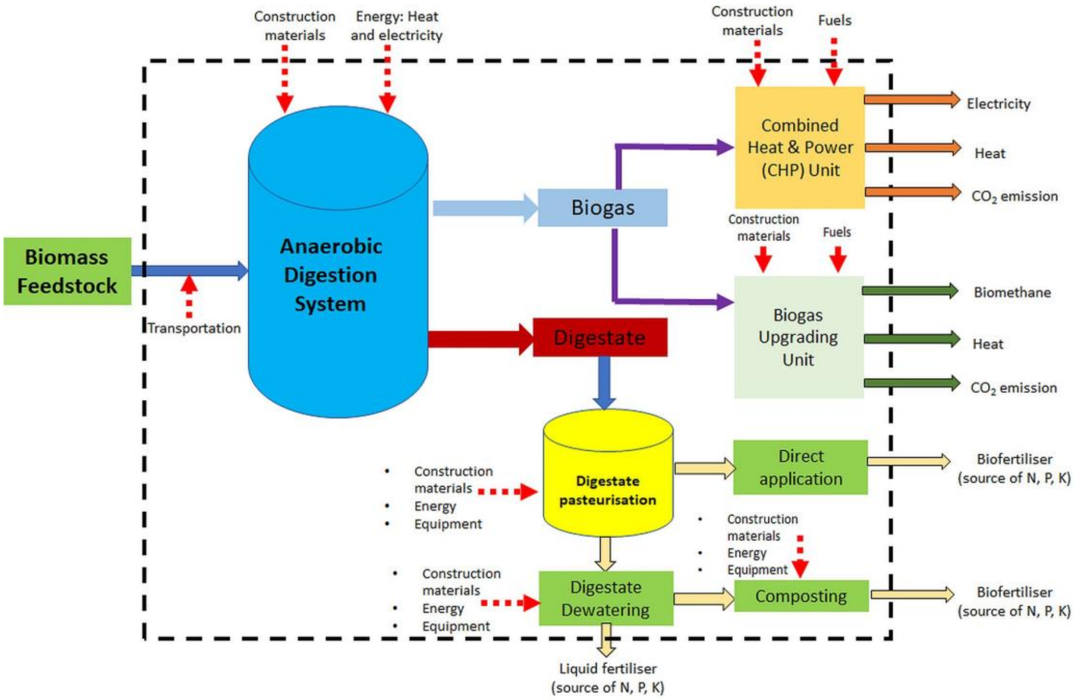


**Figure 4.** The boundary system in AD of fruit-based agro-industrial waste or agricultural crops residues or in complex system

In this study, the feedstock input to the digester (used in all scenarios) was 10,000 tonnes per year (based on wet weight) of all the biomass feedstocks studied based on their supply availability. Several design parameters used in the model include the operating temperature of 37 $^{o}$C, OLR of 3 kg/m$^3$/day, digester construction made of steel, a post pasteurisation unit operating at 70 $^{o}$C for 1 hr, a biogas holder of 2 hrs worth of gas, digestate storage made of steel with 6-month of storage capacity, and digester operational lifespan of 30 years. Details of the parameters used in the model are outlined in Table 1.

Table 4 shows the summary of the scenario for digester input, potential biogas, methane produced, methane available and upgraded methane for both scenarios in all selected biomass feedstock. The model showed that total digester capacity required is influenced by the content of TS, MC, and VS of each substrate. As the SMP of each biomass feedstock varied, it also caused a variation in potential biogas or methane. Table 4 also showed that, OPEFB and coffee husk require a longer retention time of 271 days which correlated to their high lignin or fiber content.

**Table 4.** Summary of digester capacity, potential biogas/methane, methane available and upgraded methane (both scenarios)

| Waste type | Total Digester Capacity (m$^3$) | Retention Time (days) | Potential Biogas (m$^3$/tons TS/yr) | Methane Produced (m$^3$/tons TS/yr)* | Methane Available (m$^3$/tons TS/yr)* | Upgraded Methane (m$^3$/tons TS/yr)* | $VS_{destroyed}$ (tons ww/yr)** | Digestate (tons ww/yr)** |
|---|---|---|---|---|---|---|---|---|
| | | | | *Fruit-based agro-industrial wastes* | | | | |
| Orange peels | 1,888 | 63 | 0.715±0.026 | 0.349±0.012 | 0.346±0.012 | 0.339±0.012 | 1.908±0.068 | 8.092±0.068 |
| Banana peels | 1,587 | 53 | 0.482±0.012 | 0.217±0.005 | 0.215±0.005 | 0.210±0.005 | 1.294±0.032 | 8.706±0.032 |
| Pineapple peels | 1,537 | 51 | 0.773±0.015 | 0.387±0.007 | 0.383±0.007 | 0.376±0.007 | 1.646±0.032 | 8.354±0.032 |
| Apple peels | 2,139 | 71 | 0.679±0.025 | 0.401±0.015 | 0.397±0.015 | 0.389±0.014 | 1.799±0.067 | 8.201±0.067 |
| Jackfruit straw | 1,417 | 47 | 0.614±0.036 | 0.301±0.018 | 0.298±0.017 | 0.292±0.017 | 1.263±0.074 | 8.737±0.074 |
| | | | | *Agricultural crops residues* | | | | |
| Rice straw | 2,088 | 69 | 0.213±0.016 | 0.105±0.008 | 0.104±0.008 | 0.101±0.007 | 1.210±0.089 | 8.790±0.089 |
| OPEFB | 8,171 | 271 | 0.354±0.034 | 0.170±0.017 | 0.168±0.017 | 0.165±0.016 | 4.291±0.417 | 5.709±0.417 |
| Maize straw | 2,211 | 73 | 0.404±0.033 | 0.198±0.016 | 0.196±0.016 | 0.192±0.016 | 1.358±0.113 | 8.642±0.113 |
| Vegetable waste | 713 | 24 | 0.700±0.034 | 0.377±0.018 | 0.374±0.018 | 0.251±0.018 | 0.715±0.035 | 9.285±0.035 |
| Coffee husk | 8,155 | 270 | 0.358±0.013 | 0.165±0.006 | 0.163±0.006 | 0.160±0.006 | 4.451±0.160 | 5.549±0.160 |

Note: digester input for all biomass feedstock is 10,000 tonnes wet weight per year; * values are in thousands m$^3$ per tons TS per year; ** values are in thousands tons wet weight per year

**Energy balance from the AD modelling scenario**

Figure 5 shows the summary energy balance for all biomass samples tested using the AD-CHP (MCE) and AD-BU (MCB) scenario with an OLR of 3 kg VS/m$^3$/day. The results show that energy available from the AD of selected FBAIWs and ARCs is sufficient to provide heat and electricity for operating the digester plant. In general, the model shows the positive values of the exported electricity and heat from the biogas produced. The data illustrates that, with the exception of vegetable waste, the total energy balance for FBAIW is generally higher than for ACR's. Such differences and potential were potentially influenced by the characteristics and the composition found in those biomass samples. For example, in the case of OPEFB and coffee husk, both samples were found to have a relatively high VS content, therefore improving the methane potential. With regards to vegetable waste, the amount of carbohydrates was relatively higher, indicating a high availability of easily degradable organic materials. Banana peels produced the lowest total and electrical energy balances compared to other waste samples.

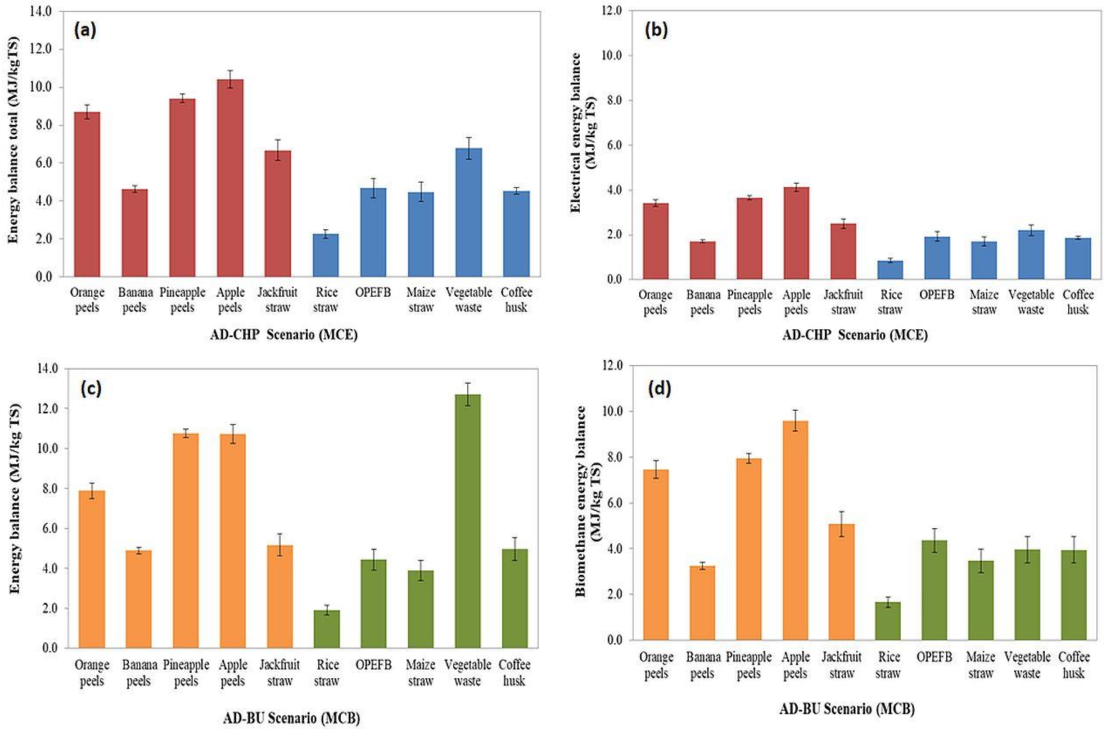


**Figure 5.** Comparison of energy balances for electricity and biomethane production from AD of fruit-based agro-industrial waste and agricultural crops residues: (a) electrical energy and heat; (b) electrical energy only; (c) biomethane and heat; and (d) biomethane only. Error bars represent standard deviation from three measurement.

Fig. 5a and 5b compares the energy balances obtained from the AD-CHP scenario. The total energy available for export ranged from 2.267-10.411 MJ/kg TS. Electricity alone as the exportable energy was in the range of 0.852-4.141 MJ/kg TS. The figure also indicates that apple peels, pineapple peels, orange peels and vegetable waste have the highest potential to be valorised for biogas and rice straw has the lowest potential. Despite an electricity potential from OPEFB and coffee husk, the model also indicated that, under the same feeding rate of 3 kg VS/L/day, longer retention times are required compared to that of the other feedstock, as shown in Table 3. Such findings demonstrated that both OPEFB and coffee husk has a slow biodegradation process. This is in agreement with other studies which have found that digesting OPEFB and coffee husk present various challenges, in particular a slow breakdown process due to high lignin content. For instance, Nieves [52] and Suksong et al. [53] reported that the lignin content in OPEFB was high (23.00-28.3%); thus, it is difficult to degrade and limits the biogas production. Therefore, future studies on co-digestion with other biomass feedstock or on the impact of pre-treatment in improving biogas and methane potential is crucial.

It can be seen that, in all AD-BU scenarios, the trends were similar which indicated potential purification of biogas to produce biomethane.  Fig. 5c and 5d show comparisons of energy balances from AD-BU scenarios, which indicates that the exportable energy as biomethane and heat was high in the range of 1.901-12.705 MJ/kg TS. Biomethane alone as the exportable energy was ranged from 1.663-9.596 GJ/kg TS. In general, all samples provide positive energy balance and biomethane energy balance. However, five biomass materials were found to have the greatest potential of all the biomass samples tested, including apple peels, pineapple peels, orange peels, vegetable waste, and jackfruit straw again the biomass with the lowest potential was rice straw.

These findings confirm that FBAIWs and ARCs offer good potential as feedstocks for producing electricity, heat or biomethane. The excess energy produced from these AD system scenarios can be used to substitute fossils fuels. Previous studies have reported, for instance, that 1 tonne of OPEFB generated biomethane can substitute about 337 L of fossil fuels [52]. Furthermore, the data shows that excess heat generated from AD-CHP scenario has potential to be exported. For AD-BU scenario biogas was upgraded to biomethane and no excess heat was produced. Previous studies reported that AD of OPEFB can generate electricity and heat from biogas, which provides renewable energy for the operation of the plant and contributes additional energy for public facilities in nearby areas [52, 53]. The most appropriate conversion pathway may be dependent upon the location of the AD plant and the energy requirements of the communities and/or industries it will serve. According the Global Methane Initiative, there were 608 Palm oil mills in Indonesia in 2015 and of these only 6% had adopted AD technologies to treat waste [54]. This study shows that AD is a viable and potentially profitable pathway for the valorisation of FBAIW and ACRs in Indonesia.

**Emissions balance from the AD modelling scenario**

Table 5 shows the emissions balances (as $CO_{2eq}$) from AD-CHP and AD-BU scenarios at an OLR of 3 kg VS/m$^3$/day. The total emissions from the AD-CHP scenario were in the range of 0.111-0.489 kg $CO_2$ eq/kg TS, while the AD-BU scenario showed slightly lower emissions ranging from 0.086-0.495 kg $CO_2$ eq/kg TS. In the case of total emissions saving, however, the data showed that the AD-CHP scenario saved carbon emission in the range of 0.610-2.414 kg $CO_2$ eq/kg TS. The AD-BU scenario can generate emission savings between 0.145-1.690 kg $CO_2$ eq/kg TS. Despite a lower value in total emissions, the findings indicated that the AD-CHP scenario had better emission saving and thus has potential to generate a lower carbon footprint compared to another counterpart scenario.

Fig. 6 shows that the AD-CHP scenarios has much higher total GHG emission savings (electricity and heat) than that of the AD-BU scenarios. The potential emission saving for the AD-CHP scenario was in the range of 0.315-1.146 kg $CO_{2eq}$/kg TS (from electricity production) and in the range of 0.499-2.106 kg $CO_{2eq}$/kg TS (from electricity and heat production). While, the AD-BU scenario the potential emission savings from biomethane production was in between 0.101-0.557 kg $CO_{2eq}$/kg TS and from biomethane and heat production was in the range of 0.140 - 0.631 kg $CO_{2eq}$/kg TS, respectively. The findings demonstrated that using apple peels as feedstock in AD generated higher emission savings, followed by pineapple peels, orange peels and vegetable waste. Such findings can provide an overview that producing biogas, which further can be transformed into electricity or biomethane, could be an alternative route to substitute the use of fossil fuels or other non-renewable energy sources, thereby GHG emissions can be reduced. Under the same operational condition in the model, lignocellulosic biomass such as rice straw, OPEFB, coffee husk and maize straw have lower emission saving, which was parallel to lower biogas and methane potential, as previously explained. Previous studies have highlighted the potential emission savings from AD of OPEFB [15, 52]. However, in practice, the use of OPEFB or coffee husk as feedstock in AD may results in technical challenges of low biodegradation due to its high lignin content, as previously described. Despite a high potential and availability of OPEFB or coffee husk in Indonesia, more improvement prior AD system is advisable, such as through chemical and biological pre-treatment [52, 53] or co-digestion with other biomass feedstocks [28]. Such strategies are essential for treating lignocellulosic biomass feedstock with AD technology, aiming for improvement of biogas and methane generation.

**Table 5.** Summary emissions from AD-CHP and AD-BU scenarios at OLR of 3 kg VS/m$^3$/day

| Scenario | Emission (kg $CO_{2\ eq}$/kg TS) | | | |
|---|---|---|---|---|
| | Total emissions | Emission saving (total) | Emissions balance (electricity or biomethane) | Emissions balance (electricity + heat or biomethane + heat) |
| | | *AD-CHP scenario* | | |
| MCE Orange peels | 0.295±0.006 | 2.085±0.077 | 1.146±0.046 | 1.790±0.071 |
| MCE Banana peels | 0.236±0.003 | 1.263±0.033 | 0.648±0.020 | 1.027±0.031 |
| MCE Pineapple peels | 0.342±0.003 | 2.302±0.045 | 1.252±0.027 | 1.960±0.042 |
| MCE Apple peels | 0.309±0.007 | 2.414±0.092 | 1.354±0.055 | 2.106±0.0485 |
| MCE Jackfruit straw | 0.308±0.008 | 1.761±0.110 | 0.920±0.066 | 1.454±0.101 |
| MCE Rice straw | 0.111±0.004 | 0.610±0.048 | 0.315±0.029 | 0.499±0.044 |
| MCE OPEFB | 0.114±0.008 | 1.033±0.103 | 0.595±0.062 | 0.918±0.095 |
| MCE Maize straw | 0.198±0.008 | 1.165±0.102 | 0.612±0.061 | 0.966±0.094 |
| MCE Vegetable waste | 0.449±0.009 | 2.146±0.114 | 1.025±0.069 | 1.657±0.106 |
| MCE Coffee husk | 0.112±0.003 | 1.001±0.037 | 0.575±0.022 | 0.889±0.034 |
| | | *AD-BU scenario* | | |
| MCB Orange peels | 0.257±0.003 | 0.488±0.034 | 0.436±0.022 | 0.516±0.022 |
| MCB Banana peels | 0.233±0.001 | 0.481±0.009 | 0.198±0.009 | 0.280±0.009 |
| MCB Pineapple peels | 0.302±0.002 | 0.982±0.013 | 0.466±0.013 | 0.563±0.013 |
| MCB Apple peels | 0.240±0.003 | 0.755±0.026 | 0.557±0.026 | 0.631±0.026 |
| MCB Jackfruit straw | 0.293±0.004 | 0.321±0.031 | 0.304±0.031 | 0.406±0.031 |
| MCB Rice straw | 0.107±0.002 | 0.145±0.013 | 0.101±0.013 | 0.140±0.013 |
| MCB OPEFB | 0.086±0.004 | 0.264±0.029 | 0.251±0.029 | 0.274±0.029 |
| MCB Maize straw | 0.186±0.004 | 0.282±0.029 | 0.208±0.029 | 0.274±0.028 |
| MCB Vegetable waste | 0.495±0.004 | 1.690±0.033 | 0.254±0.033 | 0.440±0.032 |
| MCB Coffee husk | 0.086±0.002 | 0.413±0.010 | 0.241±0.010 | 0.263±0.010 |

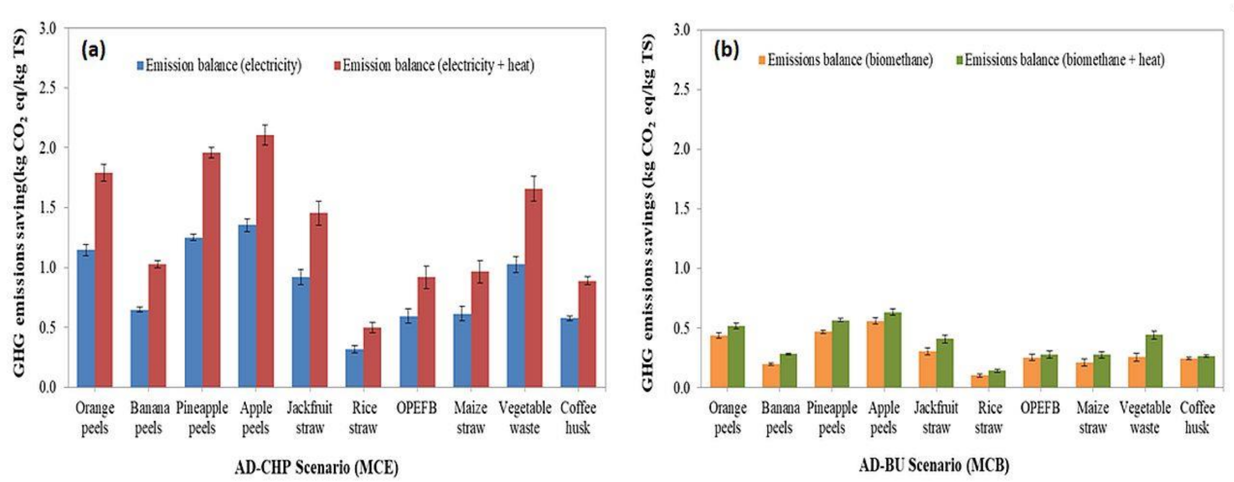


**Figure 6.** Potential emission savings from electricity (a) and biomethane (b) production with and without use of heat. Error bars represent standard deviation from three measurement.

## Conclusions

All wastes tested in this study were shown to have physico-chemical characteristics that were suited to AD, particularly in terms of high volatile solids. Vegetable waste exhibited the highest methane potential (measured as SMP) of all the wastes tested and FBAIWs exhibited higher methane potentials than the ACR's overall. This was attributed to the fibrous nature of ACR wastes and an increased ligno-cellulosic content which can negatively impact on the rate and overall production of biogas. The findings confirmed that the energy and heat produced during the digestion of these wastes was sufficient to meet the parasitic energy requirements of the AD plant. The additional energy generated (in the form of heat, electricity and/or biomethane) can be exported providing an additional income to operators. Generally, FBAIW was shown to have greater potential than for ACR's in terms of energy available for export (electricity or biogas) and also offered higher emission savings. The exception was vegetable waste which has a higher carbohydrate content and thus higher SMP. Further work is required to understand long term stability of digesters and optimal operational conditions. Work is also required to explore pre-treatment technologies and AD configurations to improve the digestibility of crop residues.

## Conflicts of interest

The authors declare no conflict of interest.

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