Anaerobic Digestion Potential of Cocoa Pod Husk and Cocoa Bean Shell: Case of Gunung Kidul, Indonesia

Amelia Christina Atmowidjojo[1], Razif Harun[2], Francis M. C. S. Setyabudi[3](✉), Arini Wahyu Utami[4], and Syazwani Idrus[5]

[1] Department of Applied Life Sciences, Kyoto University, Kyoto 606-8502, Japan
[2] Department of Chemical and Environmental Engineering, Universiti Putra Malaysia, 43400 Serdang, Malaysia
[3] Department of Food and Agricultural Product Technology, Gadjah Mada University, 55281 Yogyakarta, Indonesia
`francis.setyabudi@ugm.ac.id`
[4] Department of Agricultural Socioeconomics, Gadjah Mada University, 55281 Yogyakarta, Indonesia
[5] Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Malaysia

Abstract. Biomass waste conversion to biogas through anaerobic digestion offers an array of benefits from disposal management, clean energy provision, and economic inclusion. Cocoa processing wastes are abundant, yet their recovery alternatives are still underexplored in Indonesia. Therefore, this study emerges to investigate the potential of utilizing cocoa pod husk (CPH) and cocoa bean shell (CBS) in a mono-digestion system. Waste characterization was done and continued with bio-methane potential test (BMP) with OLR 2.3 g COD/day for 22 days at 35 °C. Specific methane production (SMP) of CBS was higher (0.31 L methane/g COD) than CPH (0.19 L methane/g COD) possibly owing to CPH recalcitrant nature. To evaluate the biogas potential of cocoa farmers in Indonesia, theoretical biogas production was calculated by estimating CPH and CBS in Central Java, Special Regions of Yogyakarta, and Aceh obtained from literature study. CPH production of each cacao farmer in Indonesia ranging from 146 to 4,375 kg/month and the CBS from 5 to 138 kg/month. Using the biogas yield from the experimental work, this study calculated the theoretical potential to produce biogas within hydraulic retention time (HRT) 20 days *i.e.* as much as 2.54 to 76.22 m^3 from CPH and 0.1 to 4.0 m^3 from CBS. The finding highlights that the low availability of CBS might hinder the implementation despite CBS showed higher SMP. This aligns with the case study in Gunung Kidul, Indonesia in which CPH offers more biogas potential due to its abundance.

Keywords: anaerobic digestion · biogas · cocoa pod husk · cocoa bean shell

J. Sumantyo et al. (Eds.): ICoSIA 2022, ABSR 29, pp. 560–576, 2023.
https://doi.org/10.2991/978-94-6463-122-7_53

1 Introduction

The worsening effects of the high reliance to fossil fuels has called out the agenda of reducing carbon emissions, including Indonesia with goal of reducing its emissions by 29 percent in 2030 [1]. The national agenda takes course within sustainable development context in which environmental preservation has to walk hand-in-hand with economic growth and social inclusion. Accordingly, energy as a vital sector has been targeted to reach 23% of renewable energy share while focusing on rural energy security and access [2].

With mounting energy demand as reflected in the nation's economic growth, an alternative energy source becomes increasingly needed. As an agricultural country, Indonesia has an abundant agricultural biomass waste with potentials to be recovered as bioenergy source [3]. Being the sixth biggest global exporter of cocoa [4], Indonesia has a tremendous domestic cocoa production of more than 550 kilo tonnes cocoa beans [5]. From the production amount, it is estimated that as much as 1,680 to 2,088 kilo tonnes of cocoa pod husks (CPH) are generated each year [6]. Considering its large contribution to the small farmers welfare, which accounts for 97.29% of the nation's cacao farmers [5], cocoa processing waste utilization has a huge potential to promote energy security as well as economic inclusion in the rural areas of Indonesia.

Although the means of utilizing biomass for energy has long been known through combustion, anaerobic digestion (AD) is seen as an advantageous renewable technology for its higher carbon conversion efficiency, valuable products, flexibility, and low cost [7]. AD is a biological process that degrades organic materials in the absence of oxygen and produces biogas and digestate. The biogas can be used as an energy source for generating heat or electricity while the digestate recovers the material and minerals and can be used as soil fertilizer [8].

The process is proposed for its ability to accommodate a large amount of waste, return benefits directly to the cacao farmers, and promote community empowerment. Other valorisation methods are alternatively limited in total amount able to be utilized, *i.e.* CPH was reported to only be able to replace up to 20% of animal feeds or requiring complicated process, *e.g.,* as biofuels, soap, activated carbon, or to be extracted for the chemical compounds [6, 9, 10].

Therefore, this study emerges to explore the biogas production potentials by utilizing cocoa pod husk (CPH) and cocoa bean shell (CBS) in Indonesia. The present study analyses the technological feasibility to investigate the specific methane production as the conversion factor to calculate theoretical biogas production from CPH and CBS in a typical smallholder farmer. This study also takes a case study in Gunung Kidul, Yogyakarta to measure the potential substituted energy from the produced biogas.

2 Literature Review

2.1 Anaerobic Digestion Process

The world has called out for global carbon emission reduction, one of the agenda is to increase the renewable energy share. With expected share of renewable energy in 2050

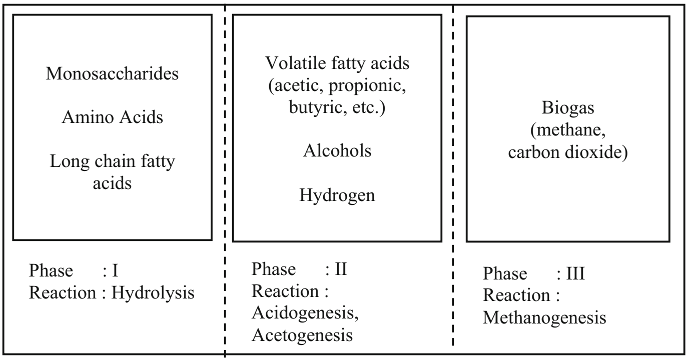

Fig. 1. Anaerobic digestion process [17].

reaching 86%, biogas along with liquid biofuels exerts its huge role by accounting for 10% from global total final energy consumption [15].

Anaerobic digestion (AD) is seen as an advantageous renewable technology for its higher carbon conversion efficiency, valuable products, flexibility, and low cost [7]. It has been widely utilized for its benefits from a socio-economic point of view, AD not only significantly reduces the costs of organic waste disposal, but also being affordable for its low feedstock cost [16]. AD also offers environmental benefits for its role in green energy production, environmental protection, biogas-linked agrosystem, and GHG emission reduction [16].

AD is a biological process that degrades organic materials in the absence of oxygen and produces biogas and digestate. The biogas can be used as an energy source for generating heat or electricity while the digestate recovers the material and minerals and can be used as soil fertilizer [8]. The conversion process follows three steps as depicted in Fig. 1. To maintain the metabolic conditions for microorganisms within the three steps, several affecting factors need to be well considered; temperature ranging from 55–70 °C for thermophilic and 37 °C for mesophilic, ideal pH of 6.8–7.4, C/N ratio of between 20 and 30, OLR, and retention time of around 15–30 days [16]. Meanwhile, the nutrient resource could accommodate the regional resources of various arrays of potential feedstocks. The scale of AD application ranges from household to municipal with adjusted reactor types depending on the scale, the affecting factors, and the type of AD being employed.

2.2 Potential Biomass for Anaerobic Digestion

Bioenergy including biogas are often envisaged as a dilemmatic solution for sustainable development, considering the competition in using the agricultural land for growing the food or energy crops. This food-energy dilemmas have been approached by utilizing a large variety of waste or residues to produce biogas through AD [18]. The potential resources varied from agricultural residues, urban, and industrial organic waste as listed in Table 1. Biogas generated from these wastes can be considered as an interesting alternative to reduce GHG emissions while also sustains regulating services through the closing of agricultural cycles and avoids environmental effects derived from other uses of residual biomass.

Prior to AD, the wastes are to be considered for their total solids (TS) content, carbon-nitrogen (C/N) ratios, initial pH, and temperature. Necessary adjustments may be required to enhance the digestion process, *e.g.,* agricultural wastes with relatively high lignocellulosic contents are subjected to pre-treatment process to reduce their sizes or to break down the lignocellulose in aiding the hydrolysis process. Following the preparation step, the substrates are then fed into the digesters with an amount of inoculum to assist the microbial consortium during AD steps which resulted in biogas production, composed mainly of methane (CH_4) and carbon dioxide (CO_2) [19].

2.3 Cocoa Processing Waste

Cacao (*Theobroma cacao L*) is an important and economic crop in many developing countries. As much as 4.7 million tonnes of cocoa beans are produced worldwide within 2016–2017, 67% of them are contributed by the top three producers, *i.e.,* Cote d'Ivoire, Ghana, and Indonesia [9]. The big industry also produces a significant amount of wastes, in which during on-farm processing, about 80% of cocoa fruit is discarded as residual biomass.

After removal of cocoa beans from the cacao pods, the residues that remain consist mainly of three fractions: cocoa pod husks (CPH), cocoa bean shells (CBS), and cocoa sweatings. Farmers routinely discard these residues or by-products, occupying vast areas and raising social and environmental concerns. Inappropriate disposal potentially results in putrid odors and plant diseases from fungal contamination, *e.g.,* black pod rot disease [20, 21]. Utilization of CPH as a supplemental animal feed could only accommodate small fraction of the total waste, considering CPH contains theobromine, a detrimental compound in animal nutrition [20].

Among the three by-products, CPH contributes the most of the waste amount as it accounts for 67–76% of the cacao fruit. CBS is produced at cocoa and chocolate factories, and it forms 12–14% of the roasted cocoa bean [6]. Meanwhile, the sweating is often not collected and easy to dispose for its little amount and liquid nature. The composition of these cocoa processing waste offers the potential to be processed for other end products. The CPH is reported to contain a considerable amount of organic compounds such as (in %) 2.1 – 9.1 of protein, 6.4 – 14.1 moisture, 5.9 – 13.0 fat, 17.5 – 47.0 carbohydrates; while CBS contains approximately (in %) 15.0 – 18.1 protein, 7.7 – 10.1 moisture, 1.78 carbohydrates, and 0.66 fat (Figueroa et al., 2020). The organic contents in the cocoa processing waste are potential to be substrate for microorganisms, which in turn can produce valuable by-products such as biogas through the anaerobic digestion process.

2.4 Cocoa Processing Waste Recovery

The attractiveness of energy recovery potential from cocoa processing waste through AD has been proven by the efforts of past studies to assess the energy potential. CPH utilization as bioenergy has been explored in several countries, *e.g.,* in Uganda as electricity generation through direct combustion [29], in Ecuador with exploration over optimization pathways of AD, namely integration with slow pyrolysis, co-digestion,

Table 1. Potential biomass of AD

Waste	Feedstock	Substrate Characteristics	T (^{o}C)	HRT (d)	Reactor	Biogas (m^3/kg VS)	Methane (m^3/kg VS)	Reference
Agricultural	**Agricultural Wastes**							
	Agricultural residues							
	Rice straw	TS 14.60 g/L, VS 12.63 g/L	22 ± 2	120	Batch digesters	0.33–0.35	0.27–0.29	(Huang et al., 2009)
	Fallen leaves	TS 91.6 ± 0.0%, VS 85.1 ± 0.0, pH 6.8 ± 0.1	37	30	Batch digesters		0.082	(Liew et al., 2011)
	Animal Manure							
	Solid cow manure	TS 19.8 ± 1.3%, VS 85.7 ± 3.2%, pH 85.7 ± 3.2	38	28	Batch digesters (full-scale plant)	0.04	-	(Chiumenti et al., 2017)
	Chicken manure	TS 33.32 ± 0.2%, VS 25.6 ± 0.2%, pH 7.71 ± 0.2	35 ± 0.5	30	CSTR	0.2–1.2 (m^3/kg VS /day)	60%	(F. Wang et al., n.d.)
Municipal	**Solid Waste**							
	Organic Fraction	TS 35.6 ± 0.1%, VS 30.7 ± 0.17%,	55	14–18	Batch digesters	0.63–0.71	-	(Hartmann et al., 2005)
Industrial	**Wastewater**							
	Sewage sludge	TS 2.53 ± 0.01%, VS 2.06 ± 0.01%, pH 5.6 ± 0.1	35 ± 1	20	Batch digesters	0.48 ± 0.02 (m^3/day)	0.31 ± 0.01 (m^3/day)	(Arhoun et al., 2019)
	Solid/Liquid Waste							
	Slaughterhouse	TS 7.96%, VS 7.79%	35	35	Flasks	0.30 ± 1.1	0.2 (m^3/kg.day)	(Palatsi et al., 2011)

nutrients supplementation, and electrochemical biogas upgrading [30], another study in Cote d'Ivoire used CPH as feedstock for alternative thermochemical and biochemical conversion processes [7]. Two studies of CPH utilization in Nigeria through AD have also been done. One study is by Dahunsi, Adesulu-dahunsi, et al. (2019) of CPH mono-digestion. Another study by Dahunsi, Osueke, et al. (2019) of CPH co-digestion with poultry manure put more highlight on seeking the optimal pre-treatment method and the process optimization to evaluate the energy producing potential of CPH.

Although several studies have been conducted in the two biggest cacao producing countries, *i.e.,* Ghana and Cote d'Ivoire, the potential of energy recovery from cocoa processing waste through AD in Indonesia as one of the biggest producers has only been little studied. The study is still limited to carbonization, which can only serve energy substitution through combustion [32]. The utilization of cacao husk in AD was only presented by Hermansyah et al. (2020). However, the practicality may be limited, since they used inoculum of cow rumen fluid from a slaughterhouse, which might be difficult to obtain in several areas in Indonesia. Moreover, in their study, the CPH was co-digested with cow manure, although availability and access to a quantifiable amount of cow manure might not always be fulfilled. This study also found that the use of cow manure as biogas feedstock potentially compete with the current use for bio-fertilizer.

Considering the huge amount of cocoa processing waste that could be utilized, Indonesia may miss its potential to kill two birds with one stone; to address the country's renewable energy share target and to support rural empowerment. Thus, the feasibility study is kept to the simplest technical requirements to ensure the applicability to small farmers across Indonesia. The utilization of CBS as feedstock for AD also has yet to be explored despite its potential organic content. Accordingly, this feasibility study will assess the utilization of cocoa processing waste, namely CPH and CBS, as single feedstock in an AD system with a case study in Gunung Kidul Regency, Special Region of Yogyakarta, Indonesia. In this research, a specific case study is considered as an example of the application of the proposed AD strategies, but we argue that the developed methodology can also be applied to other contexts and can help decision makers evaluating the most appropriate opportunity for their specific cases.

3 Materials

The cocoa processing waste (Criollo dan Forastero) consisted of two types; the pod and the bean shell. The cacao pod husk (CPH) includes the exocarp, mesocarp, and a layer of endocarp from the freshly harvested cacao fruit. The cocoa bean shell (CBS) was obtained from the desheller or dehulling process after the beans were roasted. The CPH and CBS were dried in the oven at 65 °C for a night before being subjected to a period of one month in room temperature for the purpose of shipment from the plantation area to the laboratory. The samples were then stored at 4 °C until it was time to be fed into the reactor. Prior to the feeding, the particle size was reduced by using a kitchen blender and mixed with water with ratio of samples to water for CPH 1:5 and CBS 1:2 until the texture was slurry-like.

4 Methods

4.1 Apparatus

The anaerobic digestion performance was studied in a set apparatus at Universiti Putra Malaysia, comprised of six batch reactors using 1 L Scotch Bottle which were submerged in a water bath at 35 °C. The treatments were: C1 (CPH + inoculum), C2 (CBS + inoculum), and blank (only inoculum). As much as 450 mL of seed sludge obtained from a running biogas digester treating food waste, and another 450 mL of substrate was fed into the reactor, leaving 100 mL for biogas space. The cocoa processing waste was introduced with OLR 1.15 g/L/day, which corresponds to 2.3 g COD/L. By taking into account the COD of the samples, the volume of CPH was 15.68 mL and CBS was 12.83 mL. The bottles were flushed with 100% nitrogen gas for 1 to 2 min to remove oxygen and then sealed with airtight rubber stoppers containing gas tube connected to the gas displacement cylinder. The biogas production was measured daily for 22 days by using water displacement method, in which the volume of water displaced in the container is equal to that of the volume of the gas.

4.2 Analysis

The analysis for sample characterization was conducted at Universiti Putra Malaysia. Total Solids (TS) and Total Volatile Solids (TVS) were analyzed according to APHA 21st edition. Chemical Oxygen Demand (COD) analysis followed the aforementioned method and Merck Method 14541. AOAC 20th edition analysis method was used for these analyses with code number as follows; total ash (923.03), moisture (950.46), total fat – soxhlet (991.36), and protein (981.10). Carbohydrate (by difference) analysis was based on Promerance Food Analysis: Theory and Practice, 2nd edition (pg 637). Energy (by calculation) analysis followed Pearson's The Chemical Analaysis on Foods (6th edition, pg 578). Finally, ammonia analysis as N was using Merch Method 14552. The biogas composition was analyzed using a gas chromatograph (HP 6890 N) (Agilent, Santa Clara, CA 95051, United States) equipped with a thermal conductivity detector (TCD) (Agilent, Santa Clara, CA 95051, United States). The column used was HP Molesieve (Agilent Technologies, Santa Clara, CA, United States) of 30 m length × 0.5 mm ID × 40 µm film thickness capillary column. The splitless inlet, oven, and TCD detector temperatures will be kept at 60 °C, 70 °C, and 200 °C. Argon was used as the carrier gas, while nitrogen was used as the makeup gas.

5 Results and Discussion

5.1 Anaerobic Digestion Performance of Cocoa Processing Waste

5.1.1 Characterization of Cocoa Processing Waste

For optimal biogas production, it is of utmost importance to supply adequate nutrients in the right proportion as substrate for the microbial communities. Table 2 presents the characteristics of cocoa pod husk (CPH) and cocoa bean shell (CBS). In comparison,

Table 2. Characteristics of the cacao processing waste in Gunung Kidul district, Sleman regency, Special Regions of Yogyakarta, Indonesia

Parameter	CPH	CBS
Total Solid (mg/L)	11,880	4,276
Volatile Solid (mg/L)	9,210	3,146
Total Nitrogen (g/L)	0.75	0.58
Moisture (g/100 g)	86.3	95.3
Protein (g/100g)	2.9	1.9
Total Fat (g/100g)	1.4	3.0
Total Carbohydrate (g/100g)	8.2	N.D (<0.001)
Ash (g/100g)	1.2	0.7
Energy (kcal/100g)	57	31
Sucrose (g/L)	N.D (<0.001)	N.D (<0.001)
Maltose (g/L)	6.2	N.D (<0.001)
Glucose (g/L)	3.8	N.D (<0.001)
Fructose (g/L)	0.2	N.D (<0.001)

CPH has higher nutritional composition which includes carbohydrate, protein, and fats. Substrates rich in lipids hold a greater potential for methane yield although its degradation releases long-chain fatty acids that could have detrimental effect on the microbial community and causes a drop in pH. Despite of its seemingly higher nutritional content, CPH is a lingo-cellulosic biomass comprising of cellulose, hemicellulose, and lignin which are less efficiently converted in anaerobic digestion due to their heterogenous structure, recalcitrant nature, and low accessibility by enzymes [34]. To render them degradable, many efforts have been made to investigate the suitable pretreatment mechanisms, including by Dahunsi, Osueke, et al., (2019) who used sulfuric acid and hydrogen peroxide for CPH pretreatment. However, considering the potential of future application in the villages and farms, pretreatment is not done in this study, thus only readily converted nutritional compositions were assessed.

5.1.2 Bio-Methane Potential Test Performance

Of both CPH and CBS, BMP test parameters result presented in Table 3. The pH did not deviate far from 7 which was recommended by UNEP (2013) and is said to be a conducive pH for methanogenic bacteria [7]. The C/N ratio of the two cocoa processing waste was alternatively higher than the optimal C/N ratio for high methane yield considered around 25 to 32 [35]. Thus, CPH and CBS should be a good substrate for co-digestion with waste of lower C/N ratio such as food waste (15.2) [34].

The biogas production from CPH and CBS reached 735 mL and 870, respectively, within 22 days of hydraulic retention time (HRT) (Fig. 2). Compared to CPH, CBS was a more efficient substrate considering its higher degradability seeing from its organic

Table 3. Bio-methane potential test results

Parameter	C1 (CPH + inoculum)	C2 (CBS + inoculum)
COD raw (g/L)	66	80.68
Volume Feeding (mL)	15.68	12.83
COD out (mg/L)	330.6	181.4
% COD removal	85.6	92.1
pH	6.6	6.7
Alkalinity (IA/PA)	0.308	0.323
Ammonium Nitrogen (mg/L)	45	30
Volume of biogas (mL)	735	870
% Methane	48.9	59.2
% TS removal	74.6	68.1
% VS removal	82.7	88.0
C/N ratio	88	139
Specific Methane Production (L methane/g COD added)	0.19	0.31

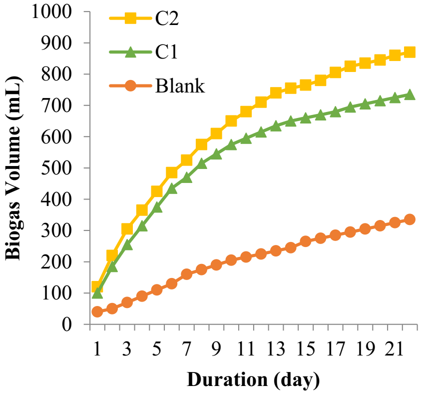

Fig. 2. Daily biogas production volume (mL) for C1 C1 (CPH + inoculum), C2 (CBS + inoculum), and blank (inoculum only).

content removal percentage of COD and VS, *i.e.,* 92.1% and 88.0%. CBS also resulted in higher biogas production, methane percentage, and consequently higher specific methane production. The lower methane yield production might be attributable to the CPH lignin content. As cited from the literature, an increase of lignin content by 1% caused a reduction of, on average, 7.49 L CH4/kg total solid [36]. Overall, CPH and CBS showed a comparable specific methane production to other wastes as listed in Table 4.

Table 4. Specific Methane Production comparison of various wastes

Waste	SMP (LCH4/gCOD)	References
Raw sugar cane residue	0.1	[37]
Pineapple husk extract	0.13	[38]
Wheat straw	0.29	[39]
Sweet Potato & cassava residues	0.23	[37]
Food waste	0.35	[40]
Cacao pod husk (C1)	**0.19**	**This study**
Cocoa bean shell (C2)	**0.31**	**This study**

5.1.3 Anaerobic Digestion Stability

According to Filer et al. (2019), anaerobic digestion system is more likely to suffer from acidification under high OLRs, where volatile fatty acid (VFA) accumulation and pH decline can suppress the microbial activity and digestion efficiency. An increase in OLRs, will increases gas production in the initial stages of anaerobic digestion but further increase in loading inhibits gas production and this is attributed to VFA accumulation in the digester. VFA concentration, pH, and alkalinity (ALK) are usually used as the parameters to evaluate the digestion process stability.

Regarding alkalinity, which was measured in intermediate/partial alkalinity (IA/PA) in this study (Table 3), the stability limit values are diverse. One study suggested IA/PA ratio of 0.9 in order to maintain total VFAs below 2.5 g/L in thermophilic reactors treating sewadge sludge [42]. Another study that used organic fraction of municipal solid wastes recommends IA/PA ratio below 0.3 to maintain total VFAs between 2.5 and 3.5 kg/m^3 within a long HRT of up to 281 days [43]. As this study conducted digestion in mesophilic condition within short HRT, the IA/PA ratio was compared to the proposed IA/PA ratio of 0.4. This number follows Balaguer et al. (1992), whose research treated potato-starch wastewater in a mesophilic lab-scale UASB for HRT of 5.6 days, that total VFAs below 2.5 g/L needs to maintain in order to assure a stable reactor performance.

In the HPLC chromatogram, there is only peak of solvent (water) for each sample and VFA concentration is not detected (N.D., or no presence at all). Thus, our result agrees with Wang et al.'s (2014), that VFAs consumption was observed owing to microbial metabolism or the participation of VFAs consumers, such as hydrogen production by the mesophilic acidogenic culture. Notably, the BMP studies is one-time feed process, which the archaea consume all intermediate products and produce final products of CH_4 and CO_2.

5.2 Theoretical Potential Biogas Production

5.2.1 Biogas Production Potential from Cocoa Processing Waste in Indonesia

To generalize the results and make them applicable to other contexts, the calculations were applied to an extended range of input based on the cocoa farmers data in Central

Table 5. Cocoa plantation data in several regions in Indonesia

Region	Plantation area	Cocoa Beans Productivity	Reference
Sidomulyo village, Lebakbarang district, Pekalongan regency, Central Java, Indonesia	1000 m^2	500 kg/ha	[11]
Nglanggeran Agricultural Technology Park, Patuk sub-district, Gunung Kidul district, Special Region of Yogyakarta, Indonesia	$<$1000 m^2 1000–3000 m^2 3000–9000 m^2 (23.33%) $>$1 ha (3.33%)	588.41–744.20 kg/ha	[12]
Banjarasri village, Kalibawang district, Kulon Progo regency, Special Regions of Yogyakarta, Indonesia	$<$1000 m^2 (44.29%) 1000–3000 m^2 (45.71%) $>$3001 (8.57%)	$<$500 kg/ha (34.28%) 510–1000 kg/ha (22.86%) 1001–1500 kg/ha (20%) $>$1500 kg/ha (22.86%)	[14]
Matang Kuli and Tanah Luas district, North Aceh regency, Aceh Province, Indonesia	1600 m^2	900–1000 kg/ha	[13]

Java, Special Region of Yogyakarta, and Aceh. The majority of the cacao plantation area is around 1000 m^2 of each farmer based on the data listed in Table 5. While the productivity of cocoa beans from smallholder farmers in Indonesia is 500–1000 kg/ha [5].

As adapted from Gaumpe (2012), cacao harvest in Peleru village, North Mori district, Morowali regency, Sulawesi Tengah province is done in two seasons, namely peak season and semester season. The peak season occurs from April to June, while the latter is on August to November. The intensity of the peak season can reach 3–4 times (40% of respondents) and 5 times or more (60% of respondents), while for semester season can reach 3–4 times (23.3% of respondents) and 5 times or more (70% of respondents). Within each harvest period per month, the farmer can harvest their plantation twice. As majority has twice harvest frequency each month [14, 46], the farmers have approximately 8 to 14 times of harvest period each year [46]. The finding does not highlight any stark difference of harvest intensity during peak season and semester season with total average dried cocoa fruit production for both seasons as much as 1.6 tons/year. In this study, the median of harvest frequency range is used to estimate the yearly CPH and CBS production.

As the bean only accounts for around 22% of the fresh fruit bunch (FFB), estimations are made by following the cacao fruit structures data from Figueroa et al. (2020), in which the CPH accounts for 70% and the CBS accounts for 2.2% of the FFB. Therefore, the

Table 6. Cocoa pod husk and cocoa bean husk estimated production per year per farmer

Case	Plantantion area (ha)	Cocoa beans productivity (kg/ha)	Cocoa beans production per harvest (kg)	Cocoa beans production per year (kg/year)	Fresh fruit bunch per year (kg/year)	Cocoa pod husk per year (kg/year)	Cocoa bean shell per year (kg/year)
Small plantation area, low productivity	0.1	500	50	550	2,500	1,750	1,750
Small plantation area, high productivity	0.1	1,500	150	1,650	7,500	5,250	5,250
Big plantation area, low productivity	1	500	500	5,500	25,000	17,500	17,500
Big plantation area, high productivity	1	1,500	1,500	16,500	75,000	52,500	52,500

calculation will be applied to an extended range of average CPH production ranging 146–4,375 kg/month and the CBS ranging 5–138 kg/month (Table 6). Based on this estimate, theoretical potential biogas production from cocoa processing waste of a cacao farmer in Indonesia is calculated (Table 7). From result, the theoretical biogas potential for CPH is as much as 2.54 to 76.22 m^3 and 0.1 to 4.0 m^3 for CBS. CBS only offers low potential due to its lower availability, therefore its implementation might only be fit in terms of economics of scale in a bigger producer *e.g.* chocolate industry or large farmer group.

5.2.2 Biogas Production Potential from Gunung Kidul, Yogyakarta

In this study, several possibilities of biogas production are made based on the data obtained during survey in the case study area, Gambiran hamlet as one among seven hamlets in Bunder Village, Patuk Sub-district, Gunung Kidul Regency, Yogyakarta Special Region, Indonesia. Cacao is a relatively new commodity in the area compared to the seasonal food crops, being started only in 2004, with a total area of 2–3 hectares. In one of the farmers case, cacao fruits are harvested twice a month, on the 15th and the 30th in the regular season, obtaining about 50 kg of fresh cacao fruit. During the peak season between July and September each year, the harvest is done weekly, and collects as much as 200 kg of fresh fruit per week. In each processing line, as much as 15 to 40 kg or in average 25 kg of CBS are produced.

After calculating the CPH amount from the generated fresh fruit bunch, several cases are made to estimate the biogas production (Table 8). In case I, an average production of 151.67 kg CPH/month and 75 kg CBS/month is used by assuming the wastes would be

Table 7. Theoretical biogas production calculation

	Cocoa Pod Husk (CPH)				**Cocoa Bean Shell (CBS)**			
Average Production (kg/month)	**146**	**438**	**1,458**	**4,375**	**5**	**14**	**46**	**138**
Average Production (kg/day)	4.87	14.6	48.60	145.93	0.17	0.47	1.53	4.60
Temperature (^{o}C)	34	34	34	34	34	34	34	34
HRT (days)	20	20	20	20	20	20	20	20
Flowrate (m^3/day)	0.02	0.07	0.24	0.71	0.001	0.003	0.01	0.03
Total Vol. of Bioreactor (m^3)	0.48	1.43	4.74	14.24	0.02	0.06	0.18	0.55
Biogas Produced (m^3/day)	0.13	0.38	1.27	3.81	0.01	0.02	0.07	0.20
Biogas Produced (m^3)	2.54	7.63	25.38	76.22	0.1	0.4	1.3	4.0
Cooking Gas (kg)	0.06	3.51	11.68	35.06	0.00	0.19	0.61	1.83
Electricity (kWh)	15.25	45.75	152.30	457.31	0.87	2.42	7.96	23.88
Kerosene (L)	1.58	4.73	15.74	47.26	0.09	0.25	0.82	2.47
Solar (L)	1.32	0.31	13.20	39.63	0.07	0.21	0.69	2.07
Gasoline (L)	2.03	1.33	20.31	60.97	0.12	0.32	1.06	3.18
Firewood (kg)	8.90	26.69	88.84	266.76	0.50	1.41	4.64	13.93

collected during harvest and kept as feedstock throughout the year. The case II assumes the production of 1,200 CPH/month as the maximum waste can be put inside a 4 m^3 bioreactor. The consideration over using a 4 m^3 bioreactor is based on the ready-made bioreactor design available in Indonesia's market. In case III and IV, the production reaches 140 kg CPH/month during normal season and 560 kg CPH/month in the peak season. Finally, case V is also taken into account to give a view of the maximum potential of the AD system, in which the assumption is made for the full (100%) energy substitution including electricity. The data for electricity substitution is not shown as the implementation would require further assessment on the conversion efficiency. In the last case, the farmers group is expected to gather additional wastes from the farmers in other nearby villages.

In the case of CBS, each month the cacao farmers in Gambiran hamlet collect their cacao beans to be processed by the Sari Mulyo farmer group. The farmer group conducts chocolate processing 2–3 times a month despite the harvest season, it is assumed that CBS production per month is 75 kg. Due to its lower availability, CBS is not taken into account in the cases. Considering its theoretical biogas potential, it can only substitute as much as 16% of the cooking gas need of the farmer.

Lastly, considering the result of the theoretical biogas production potential in Gunung Kidul, Yogyakarta, we are seeking for a smaller scale bioreactor design to assess the applicability of using CPH fully as feedstock. We have been implementing the biogas system in a collaborative project with an NGO that is focusing on sustainability initiatives in Indonesia. The success of the field implementation study will be further reported in another article.

Table 8. Theoretical biogas production in Gambiran hamlet, Gunung Kidul, Yogyakarta

Parameters	**Case I**	**Case II**	**Case III**	**Case IV**	**Case V**
	CPH	**CPH**	**CPH**	**CPH**	**CPH**
Average Production (kg/month)	151.67	1,200	140	560	3,425
Average Production (kg/day)	5.06	40	4.67	18.67	114.17
Temperature (^{o}C)	34	34	34	34	34
HRT (days)	20	20	20	20	20
Flowrate (m^3/day)	0.01	0.20	0.02	0.09	0.56
Total Vol. of Bioreactor (m^3)	0.49	3.90	0.46	1.82	11.14
Biogas Produced (m^3/day)	0.13	1.04	0.12	0.49	2.98
Biogas Produced (m^3)	2.64	20.89	2.44	9.75	59.63
Cooking Gas Produced (kg)	1.21	9.61	1.12	4.48	27.43
Substituted Cooking Gas (%)	20	100	18	73	100

6 Conclusion

Cocoa processing waste comprised of cocoa pod husk (CPH) and cocoa bean shell (CBS) are shown to be promising feedstock for biogas production even in a simplest system without pretreatment. From the bio-methane potential test, specific methane production of CPH and CBS observed were 0.19 L methane/g COD and 0.31 L methane/g COD, respectively. The difference may be accounted to the recalcitrant nature of CPH that hinder efficient biogas production although the availability of CPH is more abundant. The conversion obtained from the experimental work was used to calculate the theoretical potential biogas production of each cacao farmer in Central Java, Special Regions of Yogyakarta, and Aceh. From the available data, CPH production was estimated to be 146 to 4,375 kg/month and the CBS from 5 to 138 kg/month for each cacao farmer. Accordingly, the potential biogas production for HRT 20 days was as much as 2.54 to 76.22 m^3 from CPH and 0.1 to 4.0 m^3 from CBS. Although CBS was converted to biogas more efficiently, the low availability hinders its potential as it might not reach the economics of scale. Theoretical biogas production was also calculated in a study case area in Gambiran hamlet, Gunung Kidul, Yogyakarta in which 20% cooking gas substitution from average CPH production, or ranging from 18 to 73% during normal harvest season to peak season, respectively. Further research to investigate the feasibility of field implementation is needed as well as the variability of the system to be replicated for cacao farmers in other regions.

Acknowledgement. We are grateful for the support of the Southeast Asian University Consortium for Graduate Education in Agriculture and Natural Resources for providing the research funding under the University Consortium Seed Fund for Collaborative Research Grants.

References

1. A. Wijaya *et al.*, "How Can Indonesia Achieve Its Climate Change Mitigation Goal? An Analysis Of Potential Emissions Reductions From Energy And Land-use Policies," *World Resour. Institute.*, no. September, p. 36, 2017, doi: https://doi.org/10.4155/cmt.13.77.
2. BAPPENAS and GGGI, "Bagaimana Pertumbuhan Ekonomi Hijau Membantu Indonesia Memenuhi Kebutuhan Infrastruktur untuk Meningkatkan Pembangunan Daerah ? Bagaimana Pertumbuhan Ekonomi Hijau Membantu Indonesia Memenuhi Kebutuhan Infrastruktur untuk Meningkatkan Pembangunan Daerah ?," pp. 1–13, 2017.
3. S. Dani and A. Wibawa, "Challenges and policy for biomass energy in Indonesia," *Int. J. Business, Econ. Law*, vol. 15, no. 5, pp. 41–47, 2018.
4. "Cocoa Prepared by Foresight," 2020.
5. Badan Pusat Statistik Indonesia, *Statistik Kakao Indonesia.* 2018.
6. K. H. N. Figueroa, N. V. Mendoza Garcia, and R. Campos Vega, "Cocoa By-products," *Food wastes by-products nutraceutical Heal. potential*, pp. 373–411, 2020.
7. D. Maleka, "Assessment of the implementation of alternative process technologies for rural heat and power production from cocoa pod husks," 2016.
8. A. Wu, D. Lovett, M. McEwan, F. Cecelja, and T. Chen, "A spreadsheet calculator for estimating biogas production and economic measures for UK-based farm-fed anaerobic digesters 3," p. 778507, 2013.
9. F. Lu *et al.*, "Valorisation strategies for cocoa pod husk and its fractions," *Curr. Opin. Green Sustain. Chem.*, vol. 14, pp. 80–88, 2018, doi: https://doi.org/10.1016/j.cogsc.2018.07.007.
10. S. O. Dahunsi, A. T. Adesulu-dahunsi, and J. O. Izebere, "Cleaner energy through liquefaction of Cocoa (Theobroma cacao) pod husk: Pretreatment and process optimization," *J. Clean. Prod.*, vol. 226, pp. 578–588, 2019, doi: https://doi.org/10.1016/j.jclepro.2019.04.112.
11. A. Rahmawati and E. Hartulistiyoso, "Analisis Potensi dan Peluang Pengembangan Kakao Desa Sidomulyo, Kecamatan Lebakbarang, Kabupaten Pekalongan," *J. Pus. Inov. Masy.*, vol. 2, no. 3, pp. 330–337, 2020.
12. W. A. Saputro and O. Helbawanti, "PRODUKTIVITAS TANAMAN KAKAO BERDASARKAN UMUR DI TAMAN TEKNOLOGI PERTANIAN NGLANGGERAN," *Paradig. Agribisnis*, vol. 3(1), no. September, pp. 7–15, 2020.
13. Bumoe Malikussaleh and Y. P. Yayasan Agro Bina Mandiri, "HASIL ASESSMENT PROSES PENGOLAHAN DAN PASCA PANEN KAKAO," 2015.
14. Veronika Reni Wijayanti, "Usaha Tani Kakaodan Tingkat Ekonomi Petani Di Desa Banjarsari Kecamatan Kalibawang Kabupaten Kulon Progo," *Pendidik. Geogr.*, pp. 17–18, 2010.
15. International Renewable Energy Agency, *IRENA (2019), Global Energy Transformation: A Roadmap to 2050.* 2019.
16. C. Mao, Y. Feng, X. Wang, and G. Ren, "Review on research achievements of biogas from anaerobic digestion," *Renew. Sustain. Energy Rev.*, vol. 45, pp. 540–555, 2015, doi: https://doi.org/10.1016/j.rser.2015.02.032.
17. S. Wainaina, Lukitawesa, M. Kumar Awasthi, and M. J. Taherzadeh, "Bioengineering of anaerobic digestion for volatile fatty acids, hydrogen or methane production: A critical review," *Bioengineered*, vol. 10, no. 1, pp. 437–458, 2019, doi: https://doi.org/10.1080/21655979.2019.1673937.
18. E. Tamburini, M. Gaglio, G. Castaldelli, and E. A. Fano, "Biogas from agri-food and agricultural waste can appreciate agro-ecosystem services: The case study of Emilia Romagna region," *Sustain.*, vol. 12, no. 20, pp. 1–15, 2020, doi: https://doi.org/10.3390/su12208392.
19. Z. M. A. Bundhoo, S. Mauthoor, and R. Mohee, "Potential of biogas production from biomass and waste materials in the Small Island Developing State of Mauritius," *Renew. Sustain. Energy Rev.*, vol. 56, pp. 1087–1100, 2016, doi: https://doi.org/10.1016/j.rser.2015.12.026.

20. Z. S. Vásquez *et al.*, "Biotechnological approaches for cocoa waste management: A review," *Waste Manag.*, vol. 90, pp. 72–83, 2019, doi: https://doi.org/10.1016/j.wasman.2019.04.030.
21. Y. Acebo-Guerrero, A. Hernández-Rodriguez, M. Heydrich-Pérez, M. El Jaziri, and A. N. Hernandez-Lauzardo, "Management of black pod rot in cacao (Theobroma cacao L.): A review," *Fruits*, vol. 67, no. 1, pp. 41–48, 2012, doi: https://doi.org/10.1051/fruits/2011065.
22. C. Huang, M. hua Zong, H. Wu, and Q. ping Liu, "Microbial oil production from rice straw hydrolysate by Trichosporon fermentans," *Bioresour. Technol.*, vol. 100, no. 19, pp. 4535–4538, 2009, doi: https://doi.org/10.1016/j.biortech.2009.04.022.
23. L. N. Liew, J. Shi, and Y. Li, "Bioresource Technology Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment," *Bioresour. Technol.*, vol. 102, no. 19, pp. 8828–8834, 2011, doi: https://doi.org/10.1016/j.biortech.2011.07.005.
24. A. Chiumenti, F. Borso, and S. Limina, "Dry anaerobic digestion of cow manure and agricultural products in a full-scale plant : Efficiency and comparison with wet fermentation," *Waste Manag.*, 2017, doi: https://doi.org/10.1016/j.wasman.2017.03.046.
25. F. Wang, M. Pei, L. Qiu, Y. Yao, and C. Zhang, "Performance of Anaerobic Digestion of Chicken Manure Under Gradually Elevated Organic Loading Rates."
26. H. Hartmann and B. K. A. Ã, "Anaerobic digestion of the organic fraction of municipal solid waste : Influence of co-digestion with manure," vol. 39, pp. 1543–1552, 2005, doi: https://doi.org/10.1016/j.watres.2005.02.001.
27. B. Arhoun *et al.*, "Anaerobic co-digestion of municipal sewage sludge and fruit/vegetable waste: effect of different mixtures on digester stability and methane yield," *J. Environ. Sci. Heal. Part A*, vol. 0, no. 0, pp. 1–7, 2019, doi: https://doi.org/10.1080/10934529.2019.1579523.
28. J. Palatsi, M. Viñas, M. Guivernau, B. Fernandez, and X. Flotats, "Bioresource Technology Anaerobic digestion of slaughterhouse waste: Main process limitations and microbial community interactions," *Bioresour. Technol.*, vol. 102, no. 3, pp. 2219–2227, 2011, doi: https://doi.org/10.1016/j.biortech.2010.09.121.
29. G. Kilama, P. O. Lating, J. Byaruhanga, and S. Biira, "Quantification and characterization of cocoa pod husks for electricity generation in Uganda," *Energy. Sustain. Soc.*, vol. 9, no. 1, 2019, doi: https://doi.org/10.1186/s13705-019-0205-4.
30. N. K. A. Ortiz, *Anaerobic digestion of cocoa waste within a circular economy context*. 2019.
31. S. O. Dahunsi, C. O. Osueke, T. M. A. Olayanju, and A. I. Lawal, "Co-digestion of Theobroma cacao (Cocoa) pod husk and poultry manure for energy generation : Effects of pretreatment methods," vol. 283, no. March, pp. 229–241, 2019, doi: https://doi.org/10.1016/j.biortech.2019.03.093.
32. M. Syamsiro, H. Saptoadi, B. H. Tambunan, and N. A. Pambudi, "A preliminary study on use of cocoa pod husk as a renewable source of energy in Indonesia," *Energy Sustain. Dev.*, vol. 16, no. 1, pp. 74–77, 2012, doi: https://doi.org/10.1016/j.esd.2011.10.005.
33. H. Hermansyah, F. F. Fedrizal, A. Wijanarko, M. Sahlan, T. S. Utami, and R. Arbianti, "Biogas production from co-digestion of cocoa pod husk and cow manure with cow rumen fluid as inoculum," *AIP Conf. Proc.*, vol. 2255, no. September, 2020, doi: https://doi.org/10.1063/5.0017383.
34. N. Nwokolo, P. Mukumba, K. Obileke, and M. Enebe, "Waste to energy: A focus on the impact of substrate type in biogas production," *Processes*, vol. 8, no. 10, pp. 1–21, 2020, doi: https://doi.org/10.3390/pr8101224.
35. UNEP, "Converting Waste Agricultural Biomass into a Resource," 2013.
36. N. Xu *et al.*, "Biomethane production from lignocellulose: Biomass recalcitrance and its impacts on anaerobic digestion," *Front. Bioeng. Biotechnol.*, vol. 7, no. AUG, pp. 1–12, 2019, doi: https://doi.org/10.3389/fbioe.2019.00191.

37. A. T. Oliwit, R. D. A. Cayetano, G. Kumar, J. S. Kim, and S. H. Kim, “Comparative evaluation of biochemical methane potential of various types of Ugandan agricultural biomass following soaking aqueous ammonia pretreatment,” *Environ. Sci. Pollut. Res.*, vol. 27, no. 15, pp. 17631–17641, 2020, doi: https://doi.org/10.1007/s11356-019-07190-8.
38. N. S. Rosli, S. Idrus, A. Md Dom, and N. N. Nik Daud, “Potential of pineapple waste extract (PWE) as co-substrate in anaerobic digestion of rice straw washwater (RSWW): enhancement of biogas production,” *Lect. Notes Civ. Eng.*, vol. 9, pp. 1479–1493, 2019, doi: https://doi.org/10.1007/978-981-10-8016-6_107.
39. S. Idrus, C. J. Banks, and S. Heaven, “Assessment of the potential for biogas production from wheat straw leachate in upflow anaerobic sludge blanket digesters,” *Water Sci. Technol.*, vol. 66, no. 12, pp. 2737–2744, 2012, doi: https://doi.org/10.2166/wst.2012.511.
40. A. Zainal, R. Harun, and S. Idrus, “Performance Monitoring of Anaerobic Digestion at Various Organic Loading Rates of Commercial Malaysian Food Waste,” *Front. Bioeng. Biotechnol.*, vol. 10, no. March, pp. 1–12, 2022, doi: https://doi.org/10.3389/fbioe.2022.775676.
41. J. Filer, H. H. Ding, and S. Chang, “Biochemical methane potential (BMP) assay method for anaerobic digestion research,” *Water (Switzerland)*, vol. 11, no. 5, 2019, doi: https://doi.org/10.3390/w11050921.
42. I. Ferrer, F. Vázquez, and X. Font, “Long term operation of a thermophilic anaerobic reactor: Process stability and efficiency at decreasing sludge retention time,” *Bioresour. Technol.*, vol. 101, no. 9, pp. 2972–2980, 2010, doi: https://doi.org/10.1016/j.biortech.2009.12.006.
43. L. Martín-González, X. Font, and T. Vicent, “Alkalinity ratios to identify process imbalances in anaerobic digesters treating source-sorted organic fraction of municipal wastes,” *Biochem. Eng. J.*, vol. 76, pp. 1–5, 2013, doi: https://doi.org/10.1016/j.bej.2013.03.016.
44. M. D. Balaguer, C. Cassú, T. Vicent, and J. M. París, “Start-up of an UASB reactor treating potato-starch wastewater using an alkalimetric follow-up procedure,” *Biomass and Bioenergy*, vol. 3, no. 6, pp. 389–392, 1992, doi: https://doi.org/10.1016/0961-9534(92)90034-N.
45. K. Wang, J. Yin, D. Shen, and N. Li, “Anaerobic digestion of food waste for volatile fatty acids (VFAs) production with different types of inoculum: Effect of pH,” *Bioresour. Technol.*, vol. 161, pp. 395–401, 2014, doi: https://doi.org/10.1016/j.biortech.2014.03.088.
46. F. A. Gaumpe, “Produksi, Pemasaran, dan Pendapatan Petani Kakao: Studi di Desa Peleru Kecamatan Mori Utara Kabupaten Morowali Provinsi Sulawesi Tengah,” Satya Wacana Christian University, 2012.