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Biogas Potential of Coffee Processing Waste in Ethiopia

Bilhate Chala [1,*], Hans Oechsner [2], Sajid Latif [1] and Joachim Müller [1]

[1] Institute of Agricultural Engineering, Tropics and Subtropics Group(440e), University of Hohenheim, 70599 Stuttgart, Germany; s.latif@uni-hohenheim.de (S.L.); joachim.mueller@uni-hohenheim.de (J.M.)

[2] State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim, 70599 Stuttgart, Germany; hans.oechsner@uni-hohenheim.de

* Correspondence: info440e@uni-hohenheim.de or bilhat@gmail.com; Tel.: +49-711-459-24759

Received: 27 June 2018; Accepted: 28 July 2018; Published: 31 July 2018

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Abstract: Primary coffee processing is performed following the dry method or wet method. The dry method generates husk as a by-product, while the wet method generates pulp, parchment, mucilage, and waste water. In this study, characterization, as well as the potential of husk, pulp, parchment, and mucilage for methane production were examined in biochemical methane potential assays performed at 37 °C. Pulp, husk, and mucilage had similar cellulose contents (32%). The lignin contents in pulp and husk were 15.5% and 17.5%, respectively. Mucilage had the lowest hemicellulose (0.8%) and lignin (5%) contents. The parchment showed substantially higher lignin (32%) and neutral detergent fiber (96%) contents. The mean specific methane yields from husk, pulp, parchment, and mucilage were 159.4 ± 1.8, 244.7 ± 6.4, 31.1 ± 2.0, and 294.5 ± 9.6 L kg^{-1} VS, respectively. The anaerobic performance of parchment was very low, and therefore was found not to be suitable for anaerobic fermentation. It was estimated that, in Ethiopia, anaerobic digestion of husk, pulp, and mucilage could generate as much as 68×10^6 m^3 methane per year, which could be converted to 238,000 MWh of electricity and 273,000 MWh of thermal energy in combined heat and power units. Coffee processing facilities can utilize both electricity and thermal energy for their own productive purposes.

Keywords: husk; pulp; parchment; mucilage; methane; renewable energy

1. Introduction

Coffee production is a livelihood for about 125 million people worldwide, particularly from developing countries [1]. Ethiopia is known to be the origin of and gene pool for coffee Arabica [2]. In the last decade, Ethiopia has been the largest coffee producer in Africa, and it remains fifth in the world, contributing a share of about 4.5% to the world production. Annual coffee production increased from 273,400 Mg in 2007 to 469,091 Mg in 2016, while the cultivation area increased from 407,147 ha to 700,475 ha (Table 1). The annual green bean production has increased in the last 4 consecutive years, but productivity (yield per harvest area) has declined in the same period. The amount of coffee by-products is directly related to coffee production. Coffee is Ethiopia's leading export commodity; and the livelihood of more than a million households depends on coffee production [3]. Coffee made up about 24% of the country's total export earnings for the fiscal period 2012/13 [4]. Ethiopian coffee is produced under forest, semi-forest, garden, and plantation production systems contributing 10, 35, 50, and 5% of the country's coffee production, respectively. Thus, about 95% of Ethiopia's coffee is produced by small holder farmers [2,4].

Table 1. Area, production, export, and yield of coffee in Ethiopia.

Year	Area (ha)	Yield (kg/ha)	Green Beans Production (Mg)	Green Beans Export (Mg)	Export Value (×1000 USD)
2007	407,147	671.5	273,400	158,467	417,323
2008	391,296	665.1	260,239	179,283	561,511
2009	395,003	672.1	265,469	129,833	365,689
2010	498,618	743.2	370,569	211,840	676,517
2011	515,882	730.4	376,823	159,135	844,555
2012	528,571	521.3	275,530	203,652	887,549
2013	538,466	728.0	392,006	218,937	803,965
2014	561,762	747.6	419,980	238,631	1,023,691
2015	653,910	698.9	457,014	234,218	1,018,149
2016	700,475	669.7	469,091	159,712	714,885

Adapted from www.faostat.org database [5].

In Ethiopia, the main regional states involved in coffee production are Oromia, Southern Nations Nationalities & People (SNNP), and Gambella. As of 2013/14, there were 1026 wet and 696 dry milling stations in these regions. About 60% of the wet milling and 79% of dry milling stations were located in SNNP and Oromia regions, respectively. Coffee milling stations are owned by private companies, cooperatives, or states. About 75% of the wet and 96% of the dry mills are owned by private firms. Cooperatives own 23% of wet and 3% of dry stations (Table 2) [5]. Unlike the dry milling stations, the majority of the wet mills are not connected to the electric grid; they are run on diesel engines for pulping and further processing steps. Replacing fossil fuels by bioenergy could be an option with ecologic and economic advantages.

Table 2. Wet and dry milling stations in Ethiopia (Ethiopian Ministry of Agriculture, coffee, tea, and spices directorate, 2015).

Regional State	Wet Milling Stations				Dry Milling Stations				Grand Total
	Private	Cooperative	State	Total	Private	Cooperative	State	Total	
Oromia	297	95	15	407	524	20	6	550	957
SNNP	470	146		616	136	4	–	140	756
Gambella	3	–	–	3	6	–	–	6	9
Total	770	241	15	1026	666	24	6	696	1722

Coffee cherries are collected from the coffee trees by selective harvesting (picking only the ripe fruits by hand) or strip harvesting (fruits striped at once with different maturity levels). The cherries are then processed to green beans following either the dry method or the wet method (Figure 1). In the wet method, the cherries undergo pulping, fermentation/washing, and peeling/polishing one after the other before producing the green beans in 7–12 days. The respective by-products are pulp (43% w/w), mucilage (12% w/w), and parchment (6.1% w/w) on the intrinsic fresh weight basis of coffee cherries [6]. On the other hand, the dry method uses hulling after drying the cherries to produce green beans. Husk is the major single by-product of the dry method. It represents about 50% w/w of the dry cherry. The dry method often requires up to 4 weeks from harvest to green beans [7]. Despite the higher water requirement (about 80 L kg^{-1} green beans) and disposal problems, green coffee beans from wet processing have a superior aroma and are sold with higher premiums [8]. Coffee by-products are dumped within the hosting community with virtually no economic benefits, thus causing severe environmental problems. The by-products are known to be rich in organic pollutants (e.g., proteins, sugars, and pectin), tannins, and phenolic compounds harmful to plants, humans, and aquatic biota [9,10]. Globally, coffee processing generates about 15 × 10^6 Mg (dry weight basis) of coffee residues, of which 9.4 × 10^6 Mg is pulp [11].

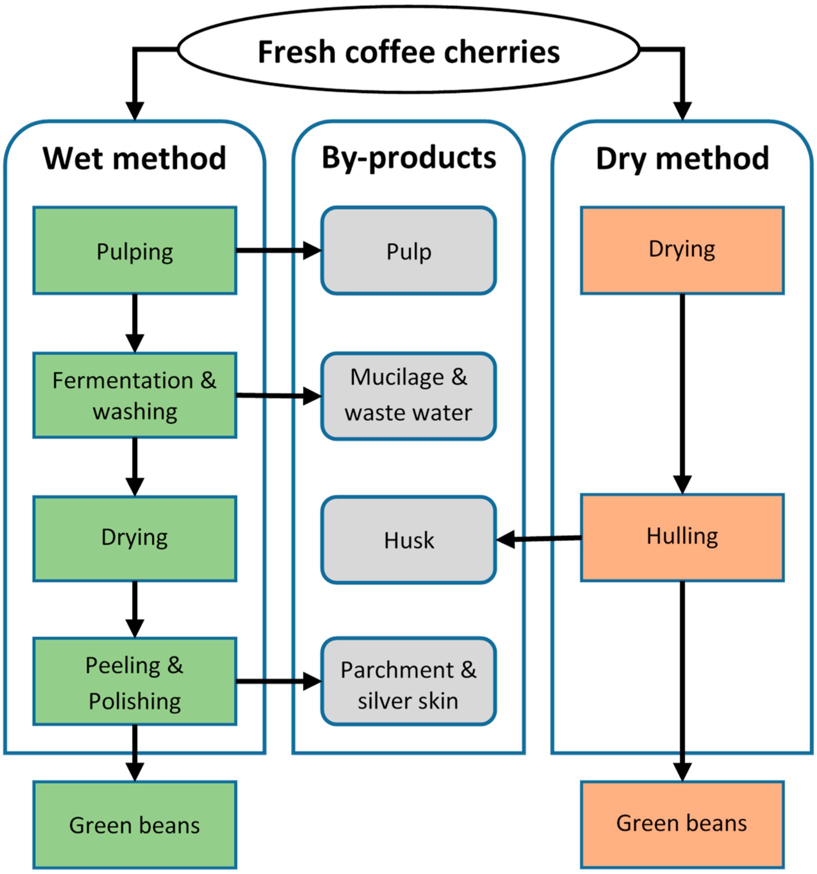

Figure 1. Primary coffee processing pathways to produce green beans following the dry and wet method.

Biogas technology was introduced to Ethiopia five decades ago. The technology is envisaged as a de-centralized energy source for improved livelihood and a source of organic fertilizer. The Ethiopian national biogas program installed about 8,000 household biogas units (4 to 10 m^3) in 2009–2013 [12,13]. Most of the biogas digesters are fed with cow dung or latrine waste. By-products of coffee processing, which are currently discarded as waste, could be an alternative feedstock.

The rates and extent of bio-degradation are crucial in anaerobic fermentation of agricultural residues, which in turn depend on lignocellulose contents and properties [14]. Higher cell contents (protein, carbohydrates, and fats) tend to ferment easily and result in higher methane production [15]. The complex interaction of hemicellulose and lignin often leads to a reduced cellulose hydrolysis. However, in a first approximation, lignin content in substrates has been proven to be a good predictor of methane potential from agro-industrial wastes [15,16].

The biogas yield from coffee processing by-products has been investigated by several researchers, but the bio-methane yield potentials reported vary substantially [17]. Ulsido, et al. [18] found a methane production potential of 132 L kg^{-1} VS from husk, while Kivaisi et al. [19] reported 650 L kg^{-1} VS of *Robusta* and 730 L kg^{-1} VS of *Arabica* mixed solid wastes (husk and pulp). Similarly, Baier and Schleiss [20] determined a biogas potential of 380 L kg^{-1} VS (57–66% methane) and 900 L kg^{-1} VS of pulp using batch assay and semi-continuous digesters, respectively. Adams and Dougan [21] reported the suitability of anaerobic conversion of coffee pulp and the waste water for waste treatment, and the generation of useful fuel, as high as 66 m^3 per ton of pulp digested. Variation in the bio-methane potentials of substrates could be attributed to the variety of coffee waste investigated and mode of fermentation. Chanakya and De Alwis [1] summarized several research and field trials on coffee processing wastes. Different types of reactors (batch, CSTR, UASB, and BIBR) were tested at varying scales of operation.

On the other hand, Franca and Oliveira [7] pointed out that, despite the bio-methane potential, coffee by-products are comparable to common agricultural residues, and that the lack of scientific studies hinders the wider utilization of the by-products for technical or economic reasons. Jayachandra, et al. [22] reported that the acidic pH and polyphenols in the coffee husk makes it resistant to anaerobic conversion. However, the treatment of husk with thermophilic fungus (*Mycotypha*) resulted in suitable pH levels for anaerobic conversion and thus increased the bio-methane yield considerably. Ensiled coffee pulp/husk presents an ideal method to preserve the substrate for longer periods of use in anaerobic digesters and reduces caffeine content (13–63%), total polyphenols (28–70%), and condensed polyphenols (51–81%) [23]. Seasonal availability of coffee by-products could be a limitation for continuous anaerobic fermentation.

Summary of bio-methane yields from typical anaerobic substrates is listed in Table 3. Municipal wastes tend to produce more methane than other substrate types. Despite frequent use of animal manure as biogas substrate, the methane production rate was relatively low.

Table 3. Methane yield potential of different substrates common to anaerobic digesters.

Substrates	Methane Yield (L kg^{-1} VS)	Reference
Basic substrates: farm manures		
Cattle	130–300	[24]
Pig	210–320	[24]
Poultry	250–400	[24]
Agricultural products		
Straw	71–240	[24]
Maize silage	320–400	[24]
Grass	286–324	[25]
Sunflower	235–347	[25]
Agro industrial wastes		
Potato pulp	250–400	[24]
Vegetable waste	400	[24]
Brewer grains	370–390	[24]
Municipal wastes		
Bio-wastes	200–600	[24]
Rumen content (slaughterhouse waste)	160–400	[24]
Kitchen waste	350–600	[24]
Sewage sludge	250–350	[26]

In 2015, Ethiopia had an annual electricity production of 10.08 TWh. The overall installed capacity was 2.7 GW, in which hydro, fossil fuel, and other renewables contributed 79.5%, 7.5%, and 13% of the installed capacity, respectively [27]. As of 2016, 85.4% of the urban and 26.5% of the rural population of Ethiopia had access to electricity [28].

To the authors' knowledge, no comprehensive study on the characterization and bio-methane potential of coffee husk, pulp, parchment, and mucilage has been published in the scientific literature. Electrical and thermal potentials (in Ethiopian context) of the bio-methane from husk, pulp, and mucilage were not reported either.

The objective of this study was to examine the physico-chemical characteristics and determine the anaerobic bio-methane potential of coffee husk, pulp, parchment, and mucilage generated from primary coffee processing in Ethiopia. Furthermore, the potential of the bio-methane from husk, pulp, and mucilage to generate electrical and thermal energy was estimated.

2. Materials and Methods

2.1. Raw Materials

Coffee husk, pulp, parchment, and mucilage were collected from Gomma-2 estate coffee farm (7°55′16.32″ N, 36°37′06.62″ E) about 400 km South-West of Addis Ababa, Ethiopia. The pulp was collected right after pulping of the cherries, from consecutive processing days of a month. The pulp then was spread on a plastic sheet for 3–4 days of sun drying. The pulp was shuffled in regular intervals, in order to dry evenly. The mucilage was fetched from a second fermentation pit, poured on a plastic sheet, and left to dry under the sun for 5–6 days. The parchment and husk were collected from the same farm, without the need for further drying. All samples underwent a size reduction to pass 1 mm pores, packed in polyethylene bags, and shipped to the University of Hohenheim, Germany. The samples were stored in a cool and dry place until further use.

2.2. Inoculum

The inoculum was obtained from the State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim. It consists of dairy manure and energy crops pre-digested in laboratory reactors, cultivated under the institute's standard procedure for bio-methane potential (BMP) assays [29]. Prior to the BMP assay, the inoculum was digested at 37 °C to degas and allow temperature adaptation of the anaerobic bacteria for further experimental assays. The inoculum had a total solids and volatile solids content of 5.0% and 61.6% (of TS), respectively.

2.3. Chemical Analysis

Moisture, volatile matter, and ash contents of samples were determined according to DIN EN 14774-3:2010-02, DIN EN 15148:2010-03 and DIN EN 14775:2010-04, respectively. Neutral detergent fiber (NDF), acid detergent fiber (ADF), acid detergent lignin (ADL), and crude fiber contents were determined by AOAC Official Method 973.18 (FibreBag Analysis System, Gerhardt, Königswinter, Germany). Sugar (sucrose, glucose, and fructose) and acid (lactic acid, formic acid, acetic acid, and propionic acid) contents of the samples were determined with HPLC (Bischoff, Leonberg, Germany) equipped with RI detector. Samples were separated on a Bio-Rad Aminex HPLC organic acid column (HPX—87H 300 $\times$ 7.8 mm^2) at 35 °C with a mobile phase of 0.02 N H_2SO_4, at a rate of 0.6 mL min^{-1} and pressure 6.0 MPa. Sugar and acid contents were analyzed at the laboratory of the State Institute of Agricultural Engineering and Bioenergy, University of Hohenheim. Elemental composition of the samples was analyzed by the State Institute of Agricultural Chemistry, University of Hohenheim, and by the laboratory of Schaumann Bioenergy GmbH.

2.4. Anaerobic Batch Digestion Tests

The Hohenheim Biogas Yield Test (HBT) is a laboratory batch method used to determine the methane and biogas yield potential of substrates [30], which is mentioned in the German Engineers Association (VDI) Guideline 4630 [31], as one of six recommended methods for BMP assays. The trial was carried out using 100 mL calibrated glass syringes as fermenters (Figure 2). The syringes were fitted to a motorized rotor to enable continuous mixing of the samples. The fermentation was operated for duration of 35 days at a temperature of 37 °C. At the beginning of the process, 30 g of inoculum was placed inside a glass syringe with 0.4 g of ground and dried samples [29,31]. Reference samples (hay and concentrate) of known methane yield were used in order to verify the quality of the inoculum and the reliability of the digestion process [29]. The blank (zero variant) fermenter was filled with about 50 g of inoculum alone (Table 4). Biogas and methane yields were obtained by deducting the proportional biogas and methane yields from the zero variant. The biogas volume was measured according to the volume difference before and after emptying the gas inside the syringe. While emptying the syringes, biogas was injected into the methane sensor (Advanced Gasmitter, Pronova, Berlin, Germany), which was calibrated with ambient air and gas (~60% CH_4). The fermenter temperature (mostly 2 °C less than the digestion temperature) and ambient air pressure were measured during the gas measurement and used to normalize the gas yield at STP (101.325 kPa, 273 K). The specific methane yield (L CH_4 kg^{-1} VS added) is the net normalized methane yield divided by the amount of organic dry matter of substrate added.

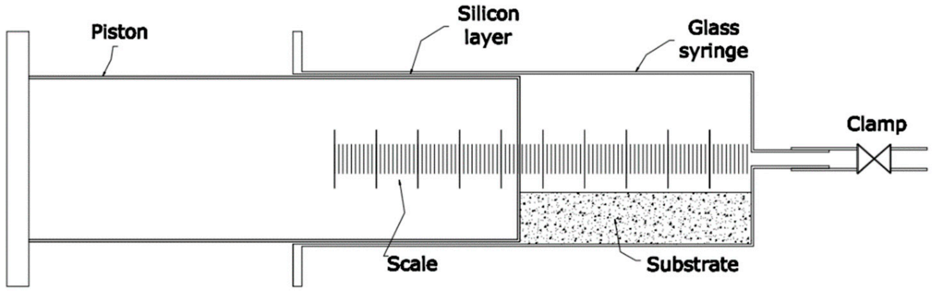

Figure 2. Glass syringe to determine the bio-methane potential in HBT anaerobic batch assay (adapted from Mittweg, et al. [29]).

Table 4. Inoculum and substrate inputs in HBT batch assay.

Variant	Inoculum (mg)	Substrate (mg)	TS (% FM)	VS (% TS)
Blank	50,000	—	4.99	61.55
Hay standard	30,000	400	90.56	89.99
Pulp	30,000	400	91.62	88.26
Husk	30,000	400	92.65	93.09
Parchment	30,000	400	95.44	99.59
Mucilage	30,000	400	94.38	85.99

The degree of degradation (η_{oDM}) was evaluated according to the mass ratio of gas produced m_{biogas} to volatile solids loaded (Equation (1)).

$$\eta_{oDM} = \frac{m_{biogas}}{m \cdot c_{VS}} \quad (1)$$

in which m is the dry mass of substrate added and c_{VS} is the concentration of volatile solids in the substrate.

The molar masses of methane (M_{CH_4}) and carbon dioxide (M_{CO_2}) were used to determine the mass of the biogas (Equation (2)) based on their respective concentrations in the biogas, assuming the biogas was composed of methane and carbon dioxide only [31,32].

$$m_{biogas} = V_{biogas} \cdot \left(\frac{M_{CO_2} \cdot c_{CO_2}}{22.4 \cdot 100} + \frac{M_{CH_4} \cdot c_{CH_4}}{22.4 \cdot 100} \right) \quad (2)$$

in which V_{biogas} is the volume of biogas measured, c_{CO_2} is the concentration of carbon dioxide in the biogas, and c_{CH_4} is the concentration of methane in the biogas.

The energy recovery (ER) rate was determined by the ratio of calorific values of the methane generated to the calorific value of input substrates in the batch assay. The gross energy (GE) of substrates can be estimated using results from Weende feed analysis and applying the Equation (3) [33].

$$GE = \left(0.0239 \text{ MJ g}^{-1} \cdot XP + 0.0398 \text{ MJ g}^{-1} \cdot XL + 0.0201 \text{ MJ g}^{-1} \cdot XF + 0.0175 \text{ MJ g}^{-1} \cdot NfE \right) \quad (3)$$

in which XP is crude protein, XL is crude fat, XF is crude fiber, NfE is nitrogen free extract (NfE) (g kg^{-1}, dry mass basis), and GE is gross energy (MJ kg^{-1}). The specific energy content of component parameters has certain differences, as shown in the fixed coefficients of the equation.

The theoretical energy potential of by-products from coffee processing was calculated under the following scenario: (1) that all the husk, mucilage, and pulp generated in a harvest season is recovered and utilized in biogas digesters (the parchment was excluded from calculation), (2) the electric conversion efficiency in a CHP is 35% electricity and 40% thermal energy that could be used for coffee drying, and (3) the lower methane heating value of 9.968 kWh m^{-3} is used to calculate the primary energy yield.

Statistical analysis was made using Microsoft Excel (2013) to determine the mean and standard deviation of SMY of substrates and other parameters related to physico-chemical characterization.

3. Results and Discussion

3.1. Chemical Composition

There were certain differences in the chemical composition between coffee husk, pulp, parchment, and mucilage (Table 5). The parchment showed the highest proportion (76.9%) of crude fiber contents, followed by husk (39.9%), pulp (24.8%), and mucilage (19.4%). NDF, ADF, and ADL contents in parchment were also considerably higher than in husk, pulp, and mucilage. Non-fiber carbohydrates (sugar, starch and pectin) in mucilage were about 28.8%, while husk and pulp showed comparable NFC of 16.2% and 17.6%, respectively. Hemicellulose contents in parchment, husk, pulp, and mucilage were 20%, 15%, 8%, and 1%, respectively. However, cellulose contents in pulp, husk, and mucilage were roughly the same (32%), while the parchment showed higher values (45%). The lignin in the parchment was about two times higher than for husk and pulp, each. Parchment exhibited the highest lignin content (32%) among the by-products. Samples were also examined for their sugar (sucrose, glucose, and fructose) and organic acid (lactic, formic, acetic, and propionic) contents (Table 5). The highest sugar content was obtained from husk, followed by pulp and mucilage. Fructose was the main component in the sugar analysis. Mucilage had the highest content in organic acids, while husk and pulp contained little amounts of the acid fractions. Lactic acid was the main component in the acid analysis. There was neither detectable sugar nor organic acids in the parchment. Carbon to nitrogen ratio (C:N) in husks showed an ideal value for anaerobic digestion of 25. Mucilage, however, showed lower than the recommended optimum value of 20–30, which might need co-digestion with other substrates with a fairly higher C:N ratio. The parchment, on the other hand, showed the highest C:N ratio (190) [34].

Table 5. Chemical composition of husk, pulp, parchment, and mucilage; values on % DM basis, unless stated. n = 3, mean ± std.

Substrate	DM (% FM)	VS	XA	XP	XL	XF	NfE	NDF	ADF	ADL	NFC	GE (MJ kg^{-1})	C:NRatio	Sugars *	Organic Acids **
Husk	93.5 ± 0.0	92.9 ± 0.1	7.2 ± 0.05	11.1 ± 0.0	1.5 ± 0.0	39.9 ± 0.1	40.4 ± 0.0	64.0 ± 1.1	49.5 ± 0.0	17.5 ± 1.6	16.2 ± 1.1	18.8 ± 0.0	24.9	4.45	1.22
Pulp	92.3 ± 0.1	88.3 ± 0.2	11.7 ± 0.2	14.1 ± 0.0	1.0 ± 0.1	24.8 ± 1.2	48.5 ± 0.0	55.6 ± 1.4	47.1 ± 0.1	15.5 ± 1.6	17.6 ± 1.4	17.4 ± 0.0	18.4	1.73	0.13
Parchment	96.0 ± 0.1	99.6 ± 0.1	0.45 ± 0.0	1.6 ± 0.0	0.9 ± 0.1	76.9 ± 0.3	20.1 ± 0.0	96.8 ± 0.3	76.9 ± 0.2	32.2 ± 0.0	0.3 ± 0.3	19.7 ± 0.1	190	0	0
Mucilage	94.8 ± 0.0	85.1 ± 0.1	14.9 ± 0.1	18.5 ± 0.0	0.1 ± 0.1	19.4 ± 0.4	47.1 ± 0.0	37.7 ± 1.2	36.9 ± 0.6	5.0 ± 0.3	28.8 ± 1.2	17.7 ± 0.1	14	0.46	5.19

FM = fresh matter; DM = dry matter; VS = volatile solid; XA = crude ash; XP = crude protein; XL = crude fat; XF = crude fibre; NfE = nitrogen free extract; NDF = neutral detergent fibre; ADF = acid detergent fibre; ADL = acid detergent lignin; NFC = non-fiber carbohydrate; GE = gross energy * sucrose, glucose, and fructose; ** lactic, formic, acetic, and propionic acid; NFC = 100-NDF-XA-XL-XP.

3.2. Elemental Analysis

The elemental analysis of husk, pulp, parchment, and mucilage showed that the substrates might exhibit a deficiency in some important trace elements required for optimal and stable biogas production, as illustrated in Table 6, compared to the range of values suggested by Oechsner, et al. [35]. Mucilage was deficient in Mo, Se, and W, pulp in Mn and Co., and husk in all analyzed trace elements besides Co. The deficiency of Mo in mucilage, pulp, and husk was as high as 70%, 80%, and 90%, respectively, compared to minimum trace element requirements. Ni and Se were also deficient with 60% and 55%, respectively, both in husk and pulp. Fe, which is required in a higher amount than other trace elements, was available 29% in husk and 65% in pulp compared to the minimum requirements. Shortage of trace elements often causes a decline in biogas production due to the loss of a stable digestion process and eventually leads to a lower substrate feeding rate [36–39]. Full scale anaerobic digestion of coffee by-products thus requires supplementation of trace elements through co-digestion with animal manure or commercial formulas.

Table 6. Elemental composition of the husk, pulp, parchment, and mucilage in terms of manganese (Mn), zinc (Zn), cobalt (Co.), molybdenum (Mo), iron (Fe), nickel (Ni), selenium (Se), and tungsten (W) [mg kg^{-1} DM].

		Mn	Zn	Co.	Mo	Fe	Ni	Se	W
Husk		83	4.4	0.5	0.1	440	1.2	0.09	<0.05
Pulp		159	21.7	0.5	0.2	969	1.2	0.09	<0.05
Mucilage		149	125.5	1.0	0.3	1719	3.7	0.12	<0.05
Parchment		12	6.8	0.1	<0.05	47	0.1	<0.05	<0.05
Optimum values	Min.	100	30	0.4	1.0	1500	3.0	0.20	0.1
	Max.	1500	300	5.0	6.0	3000	16.0	2.00	30.0

3.3. HBT Analysis

The mean SMY from husk, pulp, parchment, and mucilage was examined at 37 °C for 35 days following the HBT batch assay protocol (Table 7). The SMY from husk was 159 L kg^{-1} VS, and the average methane content of biogas was 56.8%. The energy recovery rate of husk was 34%, which indicates a fairly low anaerobic performance. Mönch-Tegeder, et al. [33] demonstrated similar results from batch fermentation of horse dung. The pulp showed SMY of 245 L kg^{-1} VS with a methane quality of 51.5%. Parchment exhibited the lowest SMY of 31 L kg^{-1} VS. The result suggested that coffee parchment is not suitable for anaerobic conversion. The highest recalcitrant content in the parchment could be attributed to the lowest SMY. Previous research demonstrated that a higher lignin content was one of the main reasons for lower bio-methane conversion [26,40–42]. Mucilage yielded SMY of 294 L kg^{-1} VS with about 55.4% of methane from the biogas. Thus, the mucilage showed the highest SMY methane yield among the coffee by-products, followed by pulp and husk. The degradability of pulp and mucilage was 63% and 68%, respectively. Higher SMY recovered from mucilage among all examined substrates can be attributed to higher soluble cell-contents (62.3%), as well as lower lignin (5%) and hemicellulose (0.8%) contents. Moreover, the organic acid content of mucilage was much higher than that of the other substrates [43]. Furthermore, the SMY and quality of the biogas from husk, pulp, and mucilage was comparable to common agro-industrial wastes and some energy crops [25] as depicted in Table 3. Khan, et al. [44] determined a SMY of 256 L kg^{-1} VS–349 L kg^{-1} VS from different fractions of banana waste, and Haag, et al. [45] demonstrated SMY 228 L kg^{-1} VS–261 L kg^{-1} VS from different varieties of cup plants (*Silphium perfoliatum*) under batch assay.

Table 7. Specific methane yield (SMY, mean ± STD, n = 6), degradability, and energy recovery rate of husk, pulp, and mucilage from HBT batch assay.

Substrate	SMY (L kg^{-1} VS)	Methane Content (%)	Degradability (%)	Methane Energy (MJ kg^{-1} VS)	Energy Recovery
Husk	159.4 ± 1.8	51.5	35.3	6.33	33.7%
Pulp	244.7 ± 6.4	56.8	63.0	9.75	56.1%
Parchment	31.1 ± 2.0	84.2	3.4	1.12	5.7%
Mucilage	294.5 ± 9.6	55.5	68.0	11.7	66.1%

The energy recovery rate ranges from 4.6% (parchment) to 66% (mucilage), while pulp and husk showed 56% and 33%, respectively. The lowest recovery rate was expected from parchment due to the very high recalcitrant contents in the biomass. Since the ash content of the parchment is very low, it might be suitable for other types of energy conversion technologies, like pelleting and briquetting. The husk is basically a combination of pulp, mucilage, and parchment; hence, it reflects intermediate values of the components.

3.4. Energy Potential of Coffee by-Products in Ethiopia

About 70% of Ethiopian coffee is produced following the dry method and 30% by the wet method. The average green coffee bean production for the past 3 harvest years (2014–2016) was 448,695 Mg year^{-1} (Table 1). For each unit weight of green coffee beans produced, 0.6 kg of pulp and 0.103 kg of mucilage (DM basis) are generated from the wet method, and 0.933 kg of husk from the dry method. This translates to an average generation of 312,060 Mg DM and 289,748 Mg VS of husk, 85,976 Mg DM and 75,925 Mg VS of pulp, and 14,764 Mg DM and 12,564 Mg VS of mucilage a year. Considering the SMY obtained at the end of the digestion period (35 days) in the BMP assay, the energy potential per year from husk, pulp, and mucilage was estimated to be 160,729 MWh, 64,898 MWh and 12,887 MWh, respectively (Table 8). Since the pulp and mucilage are both available in a single wet processing station, their respective energy potential could be combined. The aggregate methane estimate can produce 238,000 MWh of electricity and 272,586 MWh of thermal energy, provided a CHP unit (total conversion efficiency 75%) is applied. The diesel equivalent of the total bio-methane estimated from the husk, pulp, and mucilage was 68,365 m^3, which costs about 40.3 million USD, based on the current fuel retail price in Ethiopia. The bio-methane could displace fossil fuel, which is often used by coffee processing facilities. The diesel is mainly used to run pulping machines and pump water for coffee processing. In Ethiopia, the average diesel consumption by farmers' cooperatives to process 1 Mg of fresh coffee cherry into parchment coffee was 2.8 L. However, in large estate coffee farms, the consumption was very low (0.9 L Mg^{-1} fresh cherry). Furthermore, the thermal energy from the CHP units could be utilized in drying parchment coffee or fresh cherries. Therefore, it would be a supplement for open-air drying and reduce labor costs and weather risks faced by traditional coffee drying. Fischer, et al. [17] estimated a potential of 18MW_{el} from anaerobic fermentation for the Kenyan coffee sector, with an installed capacity of 50 kW_{el} for coffee cooperatives and 250 kW_{el} for large estate farms.

Table 8. Energy potential of coffee husk, pulp, and mucilage from one-year harvest.

Substrate	SMY (m^3 Mg^{-1} VS)	Residues Production Ratio (RPR) kg VS kg^{-1} GB [a]	Biomass Yield (Mg VS $year^{-1}$)	Methane Yield (m^3 $year^{-1}$)	CHP Production (MWh/year)		Diesel [b] Equivalent (m^3)	Saved Fuel Cost [c] (USD)
					Electricity (MWh_{el} $year^{-1}$)	Heat (MWh_{Th} $year^{-1}$)		
Husk	159	0.923	289,748	46,069,906	160,729	183,690	46,070	27,181,244
Pulp	245	0.564	75,925	18,601,671	64,898	74,169	18,602	10,974,986
Mucilage	294	0.093	12,564	3,693,742	12,887	14,728	3,694	2,179,308

[a] Green coffee beans and [b] diesel calorific value = 10.25 kWh/L. [c] The diesel cost was estimated as 0.59 $/L based on the current retail price in Ethiopia.

4. Conclusions

Ethiopia's coffee processing sector generates a huge amount of by-products, both in liquid (mucilage) and solid (pulp, parchment, and husk) forms. The current electricity shortage coupled with the environmental issues associated with coffee waste disposal make anaerobic conversion technology a benign intervention. Coffee by-products are rich in lignocellulosic contents with different proportions of cell contents and cell wall (cellulose, hemicellulose, and lignin) contents. The by-products exhibited promising bio-methane potential (BMP) comparable to common agro-industrial residues and some energy crops. The specific methane yield was highest in mucilage followed by pulp and husk. The BMP from parchment was very low, thus implying that it is not suitable for anaerobic conversion. It was estimated that anaerobic fermentation of coffee processing by-products generated by the Ethiopian coffee sector has significant potential to generate methane as high as 68×10^6 m^3 per year, which can produce 238,000 MWh_{el} of electricity and 272,586 MWh_{th} thermal energy. Most coffee processing facilities could recover bio-methane from their own by-products, which would be sufficient to run the processing activities. Seasonal availability of coffee by-products, particularly from the wet method, could limit a year-round utilization. Ensiling, however, enables longer storage periods. Policy instruments like the feed-in tariff (FIT) are suggested to encourage private investors to produce electricity/thermal energy from coffee by-products and also promote renewable energy production. The FIT offers long-term (15–25 years) guaranteed purchase contract and cost-based compensation to renewable energy producers. Further research on the performance of coffee by-products in combination with other biomass sources should be investigated.

Nomenclatures

Symbol	Definition
η_{VS}	Degree of volatile solids degradation
c_{VS}	Concentration of volatile solids in dry substrate
m_{biogas}	Mass of biogas
M_{CH_4}	Molar mass of methane
M_{CO_2}	Molar mass of carbon dioxide
c_{CH_4}	Concentration of methane in the biogas
c_{CO_2}	Concentration of carbon dioxide in the biogas
GE	Gross energy of substrate
SMY	Specific methane yield

Author Contributions: Conceptualization, B.C. and J.M.; Methodology, B.C., H.O., and J.M.; Investigation, B.C. and H.O.; Writing—Original Draft Preparation, B.C.; Writing—Review & Editing, B.C. and J.M.; Project Administration, S.L.

Funding: This research was funded by the German Federal Ministry of Education and Research (BMBF) within the framework of the GlobE program in conjunction with the BiomassWeb project, grant number 031A258F.

Acknowledgments: The authors are grateful to the State Institute of Agricultural Engineering and Bioenergy and the laboratory staff members (University of Hohenheim) for the batch assay trials and physico-chemical analysis. In addition, we thank Schaumann Bioenergy, GmbH (Germany) for conducting elemental sample analyses. Authors are indebted to Stiftung Fiat Panis, Germany for financial support. Authors are thankful to Sabine Nugent for language editing.

Conflicts of Interest: The authors declare no conflict of interest.

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