

Energetic Potential of Coffee Waste from Anaerobic Digestion and Combustion

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ABSTRACT

Coffee is present in every street in the world and is without a doubt one of the most consumed beverages. Moreover, it is the third most consumed drink in the world. Recent estimations from the International Coffee Organization put the world coffee production at about 6 million tons per year. Its uncontrolled disposal can cause environmental problems, but if handled properly, it can be processed into pellets, and used as an energy source. In the present study, the production of energy from coffee waste (CW) is an interesting alternative to traditional production lines. The objective of this study is to calculate the energetic potential (Ep), which can be generated by anaerobic digestion (AD) and thermochemical conversion (TC), of the organic fraction of CW in the city of Kenitra, Morocco. An elementary analysis allows us to estimate the calorific value by the TC. The lower and higher calorific values were estimated to be: 18.71 and 20.28 MJ/Kg, respectively. Ep results by AD and CT were 0.25 and 1.3 MWh/t, respectively.

Keywords: coffee waste; anaerobic digestion; thermochemical conversion; energetic potential.

INTRODUCTION

Coffee is one of the most popular drinks consumed worldwide and has one of the most developed marketplaces (Ait Lhaj Lahcen et al., 2021). The processing of coffee uses around half of the coffee produced worldwide (Schwankner et al., 2019). The fact that coffee contains organic molecules shows the economic benefits of valuing this resource. Morocco is a net coffee importer. About 28.000 tons are typically imported from Morocco each year.

Notably, Moroccans lose over 20 million tons of coffee waste annually, which has negative environmental effects (Magoum et al., 2021). Therefore, it is crucial to carry out the necessary procedures to valorize this waste. In general, many treatment techniques can valorize coffee waste. The wastes are treated using biological, chemical, physical, and combination treatment

techniques. Each method has its own peculiarities and end products. The desired product determines the treatment option.

Combustion or thermochemical conversion is one way of biomass valorization. Biomass is burned in a thermochemical conversion process to provide heat and energy. The calorific value, moisture, ash content, and elemental analysis of biomass are utilized to design and operate biomass combustion systems (Lahboubi et al., 2021). The “lower” value and the “higher” value are two ways to express calorific value. By measuring the enthalpy change between reactants and products with an adiabatic bomb calorimeter, it is possible to experimentally calculate the heating value (HV) of a biomass fuel (CEEAQ, 2014). Despite their relative simplicity, bomb calorimeters are not usually available to researchers. Many academics employ elemental analysis to calculate calorific values using empirical correlations to address this issue (Yin et al., 2011).

Additionally, anaerobic digestion (AD) could be used to recover coffee waste. The use of AD to treat organic pollutants is appealing (Ait Lhaj Lahcen et al., 2018) because it decreases the amount of material that must be removed, prevents groundwater contamination, and offers cheap, renewable energy. Methane, carbon dioxide, and a small amount of other polluting gases are present in the biogas produced by the process (Meres et al., 2005). Digestate is a product of AD, is rich in non-biodegradable materials, and can be used in agriculture as a soil amendment (Karouach et al., 2021). In place of fossil fuels, this biogas maintains the equilibrium of greenhouse gases like CO₂ in the atmosphere (Lahboubi et al., 2022). Generally speaking, anaerobic batch tests utilizing the accepted methodology were used to calculate the methane yield (Bakraoui et al., 2020). Some studies have used theoretical equations (Lahboubi et al., 2022; Lahboubi et al., 2021; Kerrou et al., 2021) to calculate theoretical methane production. The theoretical methane production (TMP) for AD was calculated using the Buswell equation. The elemental composition can be used in Buswell's equation to get the highest theoretical methane potential, presuming all components are converted [Bakraoui et al., 2020].

This study aims to determine the theoretical energy potential of Moroccan coffee trash using two different methods of recovery. Anaerobic digestion and thermochemical conversion are the recovery techniques used. TMP and theoretical HV are determined by elemental analysis and ultimate analysis, respectively. Using the findings from HV and TMP, the theoretical energy is computed.

MATERIALS AND METHODS

Preparation of the substrate

The substrate used in this work was coffee waste recovered from a coffee restaurant in the city of Kenitra, Morocco. The substrate is stored in bottles at a temperature of 4 °C until their use.

Analysis method

The dry matter content is expressed as a percentage of the sample weight. The total solid (TS) consists in drying the sample in an oven at 105°C for 24 hours until a constant mass is obtained. The mineral solid (MS) is determined by

burning the sample, which is previously dried in the muffle furnace at 550°C for 2 hours. The volatile solid (VS) (percentage of organic matter) is obtained by the difference between the mass of the sample burned at 550°C and the one dried at 105°C. Carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) elemental analyses are based on the procedures outlined in Annex IV of Regulation (EC) 2003/2003 and Annex VI of Royal Decree 506/2013 on June 28, 2013.

Emperical heating value

There are two ways to describe a fuel's heating value: "lower" (LHV) and "higher" (HHV) (Bakraoui et al., 2020). In this study, to predict HHV, we used a correlation based on ultimate analysis as shown in eq (1) (Yin et al., 2011).

$$\text{HHV (MJ/kg)} = 0.2949C + 0.8250H \quad (1)$$

where: C – is the carbon content (%),
H – is the hydrogen content (%).

The LHV is determined from the HHV value according to the following equation (2) (Bakraoui et al., 2020):

$$\text{LHV (MJ/kg)} = \text{HHV} - 2.766 \cdot W \quad (2)$$

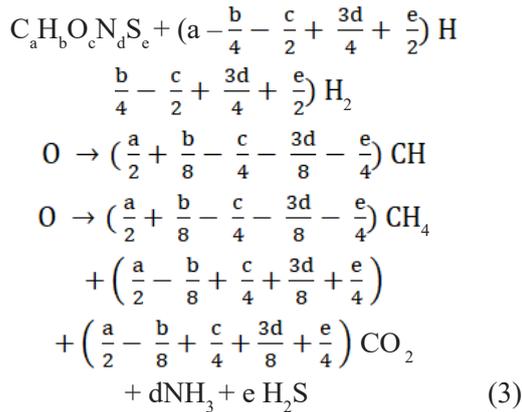
where: *W* – moisture content,
2.766 MJ/kg – heat coefficient of evaporation (enthalpy of vaporization).

Theoretical biogas potential

In 1952, Buswell and Mueller proposed a method to determine the products of anaerobic digestion of organic matter based on their elemental composition, as shown in equation 3. The total stoichiometric conversion of organic matter to CH₄, CO₂, NH₃, and H₂S can be calculated using Buswell equation (3) (El Bari et al., 2018):



Figure 1. Coffee waste



The degradation of carbon in the substrate studied is represented by equation 5 above. The coefficients a, b, c, d, and e are dimensionless and can be evaluated from the approximated ratio of each component’s number of moles to the minimum number of moles among all the components (Sawyer et al., 2019):

$$\begin{aligned}
 a &= \frac{\%C}{\frac{MC}{e}} \\
 b &= \frac{\%H}{\frac{MH}{e}} \\
 c &= \frac{\%O}{\frac{MO}{e}} \\
 d &= \frac{\%N}{\frac{MN}{e}} \\
 e &= \frac{\%S}{MS} \tag{4}
 \end{aligned}$$

where: %C, %H, %O, %N, and %S – represent the composition of C, H, O, N and S in the organic matrix,
 MC, MH, MO, MN – are the molar mass of elements: C, H, O and N.

Theoretical methane production

The volume of methane produced during anaerobic digestion of waste is initially approximated using theoretical methane production. In the database shown in Table 1, the elemental composition (C, H, O, S, and N) of coffee waste was used to calculate TMP using the Buswell formula given by Eq. 5. (Yeqin et al., 2013; Buswell et al., 1952):

$$TMP = \frac{22.4 * 1000 * \left(\frac{a}{2} + \frac{b}{8} - \frac{c}{4} - \frac{3d}{8} - \frac{e}{4} \right)}{12a + b + 16c + 14d + 32e} \tag{5}$$

Biodegradability

As shown in equation 6, the biodegradability of coffee waste is calculated from the ratio between the experimentally observed methane potential (EMP) and the theoretical methane potential (TMP) (Semaan et al., 2022):

$$Bd (\%) = \frac{EMP (mL/g VS)}{TMP(mL/g VS)} * 100 \tag{6}$$

Anaerobic digestion energy

The potential electrical energy E_{AD} (MWh/t) produced from methane is estimated according to Equation 7 (Bakraoui et al., 2020):

$$E_{AD} = q \cdot YCH_4 \cdot ECH_4 \cdot \eta_e \tag{7}$$

where: q – represents the annual available mass of biomass (T of dry matter),
 YCH_4 – represents the methane yield of substrate (m^3),
 ECH_4 – represents the methane electrical value (9.36 kWh/ m^3) (Hasbi et al., 2020),
 η_e – represents the biogas engine-generator efficiency (30%).

The potential of electrical energy ETC (MWh/t) produced from combustion is estimated according to Equation 8 (Matteson et al., 2007):

$$E_{Com} = \frac{q_i * LHV * \eta_b}{3600} \tag{8}$$

where: q_i – represents the annual available mass of biomass (T of dry matter),
 LHV – represents the low heating value of substrate (MJ/kg),
 η_b – represents the conversion efficiency of dry matter to electricity (25%).

RESULTS AND DISCUSSION

Characterization of the substrate

The physico-chemical characteristics of the substrate used are presented in Table 1. As shown in the table, the percentages of the different elements for C, H, N and S are 48.9, 7.11, 2.50, and 0.36% respectively. These results are within the range of values for coffee waste reported in the literature (Mendoza et al., 2019). The oxygen content was calculated by the difference. These results can be used to estimate HHV and TMP. One of the most crucial factors for biogas production

Table 1. Physicochemical and ultimate analysis of coffee

Parameters	Values
TS (%)	34.13
VS (%TS)	96.68
Moisture (%)	65.87
pH	5.35
C (%)	48.9
H (%)	7.11
N (%)	2.50
S (%)	0.36
O (%)	41.13
C/N	19.56

Table 2. Results of HHV and LHV estimation

Calorific value	Value (MJ/Kg)
HHV	20.28
LHV	18.71

from lignocellulosic biomass is the relationship between its carbon and nitrogen content (Ulsido et al., 2016; Sawatdeenarat et al., 2015; Luz et al., 2017; Selvankumar et al., 2017). Studies have shown that controlling specific parameters, such as the C/N ratio, can improve the CH₄ yield of coffee waste in the AD process (Atelge et al., 2021). In our case, the carbon/nitrogen ratio of the coffee dregs is 19.56.

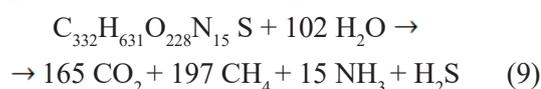
Calorific value

Table 2 presents the results of the HHV and LHV of the coffee waste using the information in Table 1 and equations (1) and (2). Figure 4 shows the variation in the calorific value for the high

and low heating values of coffee waste during anaerobic digestion. These correlations gave results of 20.28 and 18.71 MJ/kg, respectively. These results can provide a preliminary assessment of significant energy potential.

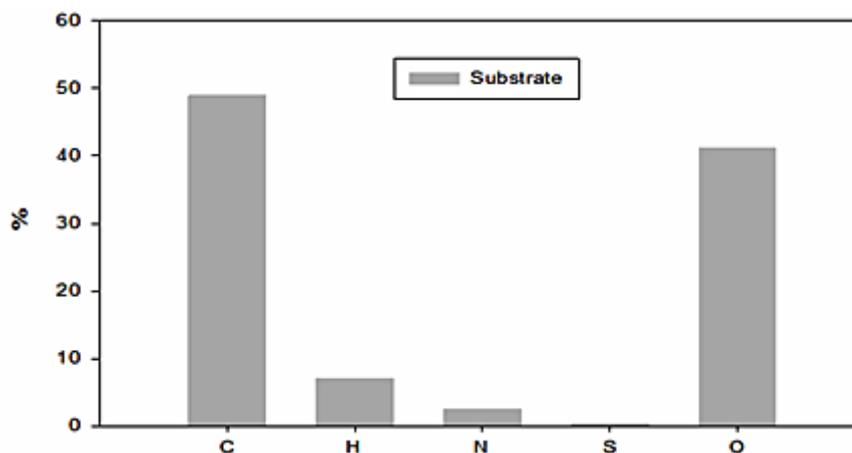
Theoretical of the biogas

The theoretical biogas production (Bth), the theoretical methane production (TMP) and the theoretical composition of each biogas product can be calculated from the results of the database and Buswell's equation. The results for Bth and TMP are presented in Table 3. The estimated theoretical composition of the biogas is presented in Table 4.



The experimental results can be compared with the theoretical results obtained. The use of coffee waste gave the best results in our base-line analyses; the maximum methane production potential is 497 m³/ton VS. Our result is higher than that reported by the researcher [Nzaka et al., 2014], who states that the maximum production potential of coffee pulp is about 370 m³/ton VS.

It can be seen from the results below that the composition of the biogas during the analysis was 52.61% CH₄, 43.14% CO₂, and 4.23% NH₃, with a H₂S concentration of 0.26% which is in perfect agreement with recent laboratory studies (Bakraoui et al., 2020; Elida et al., 2016). The TMP result of our study is 0.497 m³ CH₄ /kgVS. This theoretical potential is higher than the theoretical potential of date palm waste in Morocco (0.405 m³ CH₄ /kgVS) (Li et al., 2013).

**Figure 2.** Ultimate analysis of coffee waste

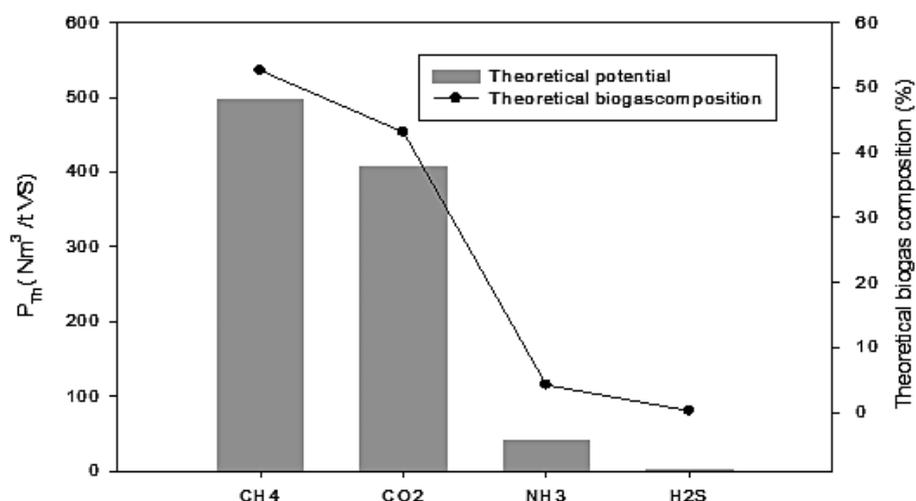


Figure 3. Theoretical potential and biogas composition of coffee waste using Buswell equation

Table 3. Theoretical biogas and methane production using Buswell’s equation.

Empirical formula	B_{Th} (m ³ /kgVS)	TMP (m ³ /kgVS)
$C_{362}H_{631}O_{228}N_{15}S$	0.91	0.497

Table 4. Estimated Theoretical potential and biogas composition

Biogas component	P_{Th} (Nm ³ /ton VS)	Theoretical biogas composition (%)
CH ₄	497.339	52.61
CO ₂	407.807	43.14
NH ₃	40.026	4.23
H ₂ S	2.521	0.26

Biodegradability

From the experimental results of a previous study, the value of methanogenic potential of coffee waste in mesophilic conditions was 234 NmLCH₄/g SV (m³CH₄/t) (Ait Lhaj Lahcen et al., 2018). In our case, we find that the TMP calculated using Buswell’s equation was 497 m³/tonVS. The experimental biodegradability in our case is 47%. According to our previous study; the biodegradability result was higher with the experimental result (81%) (Ait Lhaj Lahcen et al., 2018), than with the theoretical obtained in this study (47%). Semaan et al. (2007) obtained scaled biodegradabilities of 40.6–79%. In our study; the value of methanogenic potential is intermediate between this value and 47%.

Experimental electrical energy potential

From the previous study, the value of methanogenic potential of coffee waste was 234 NmLCH₄/g SV (m³/t) (Ait Lhaj Lahcen et al.,

2018). For one ton of fresh material in the coffee waste we find 0.3299 ton VS, which is equivalent to a methane volume of 77 m³. Using equation 8, and electrical potential generated from 1 m³ of methane (9.36 kWh) (Matteson et al., 2007), the experimental potential of electrical energy using anaerobic digestion was 0.25 MWh /t, considering an engine-generator efficiency of 30%.

Theoretical electrical energy potential

From equation 7 and database from Table 3, we can calculate the theoretical energy from anaerobic digestion. The theoretical energy generated from 0.497 m³ CH₄/kgVS is 1.03 MWh/t. This value is higher 4 times than the experimental value. This explained by the fact that theoretical methane yield was generated with a 100% biodegradability of the substrate.

Empirical energy potential

Equation 8 is used to determine the empirical energy potential of CW. The empirical energy

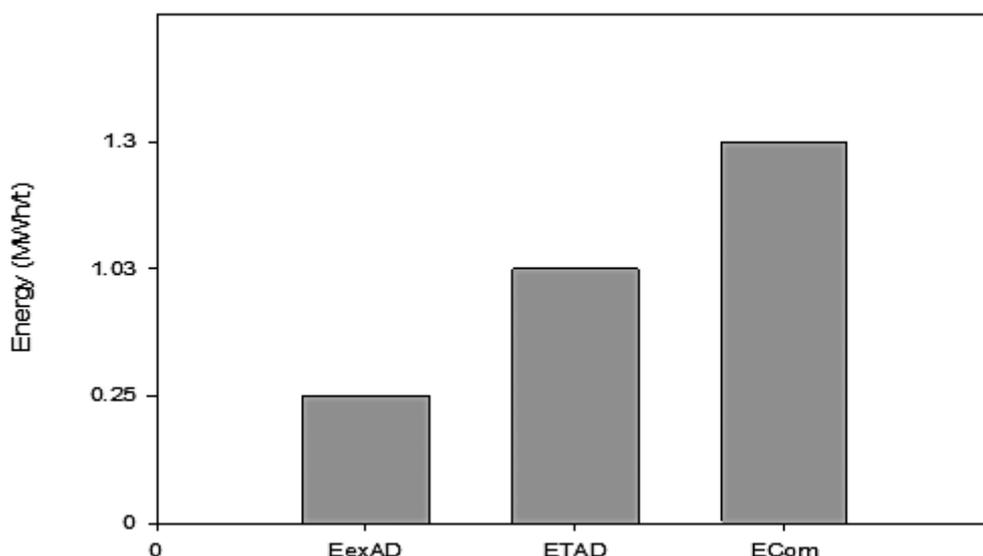


Figure 4. Energy results from anaerobic digestion and thermochemical conversion of coffee waste

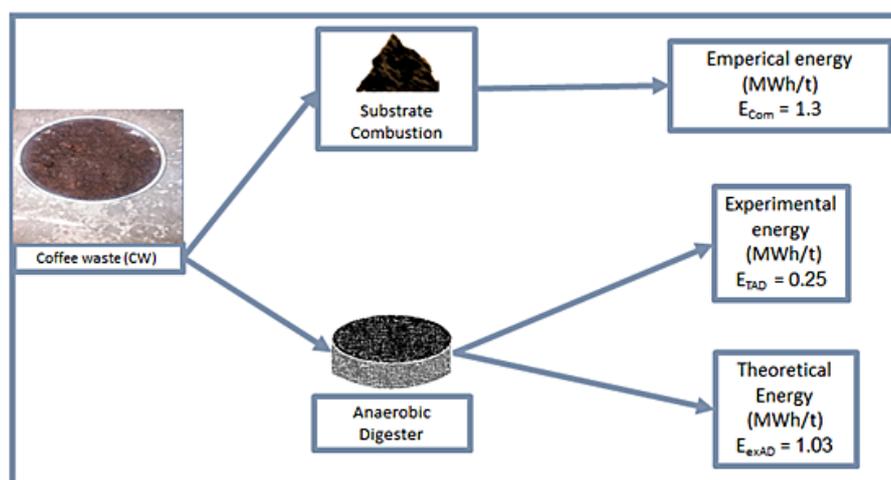


Figure 5. Energy result of coffee waste using anaerobic digestion and combustion

results are presented in Table 5. As shown, the empirical energy potential from combustion for one ton of coffee waste is 1.3 MWh/t. There is a difference between the predicted and measured energy potential. The experimental electrical energy potential was lower (0.25 MWh/t) than the theoretical electrical energy potential E_{TAD} (1.03 MWh/t) produced from methane, and empirical energy generated from combustion of the substrate (1.3 MWh/t).

In a study using coffee pulp, the energy potential per year production from AD for 85.976 t dry matter of pulp is 64.898 MWh (Chala et al., 2018), which corresponds to 0.75 MWh/t. The energy produced using combustion is higher than that

Table 5. Estimated energy results from AD and TC

Energy	Value (MWh/t)
EexAD	0.25
E_{TAD}	1.03
E_{Com}	1.3

produced by the AD process. But the latter is cleaner and more environmentally friendly and energy efficient so it is a practical method to manage coffee grounds and exploits renewable energy at the same time (Oliwit et al., 2019). Indeed, AD converts part of the organic matter into biogas while retaining the majority of the fertilising elements in the digestate. This digestate

frequently offers an intriguing agronomic utility as a fertiliser as well as an as an organic amendment (Bernet et al., 2015).

Figure 4 shows that the coffee waste has a high energy potential and can be used for anaerobic digestion and combustion. The energy potential values were 0.25 and 1.3 MWh/t, respectively.

CONCLUSIONS

Anaerobic digestion is a recommended technology to reduce the amount of waste produced by the population and to produce methane as a renewable energy source that we can use in different ways. The biomass remaining in the coffee production chain can be considered as a suitable raw material for thermochemical conversion processes. This study aimed to identify and calculate the energy potential of anaerobic digestion and thermochemical conversion of coffee waste. The TC process showed an expected high calorific value of 20.28 MJ/kg and an energy potential of 1.3 MWh/t and the AD process also produced a significant theoretical biogas potential of about 0.91 m³ CH₄/kgVS, of which the energy potential found was in the order of 0.25 MWh/t.

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