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Anaerobic co-digestion of agro-industrial cashew nut wastes with organic matters for biogas production: case of cashew nut hull and cashew almond skin

Joseph B. SAWADOGO[1,2*], Narcis BARSAN[3], Mahamadi NIKIEMA[4], Emilian MOSNEGUTU[3], Dayéri DIANOU[5], Alfred S. TRAORE[2], Aboubakar S. OUATTARA[2] and Valentin NEDEFF[3]

[1]*Unité de Formation et de Recherche en Science de la Vie et de la Terre (UFR-SVT), Université Nazi BONI, 01 BP 1091 Bobo-Dioulasso 01, Burkina Faso.*

[2]*Centre de Recherche en Sciences Biologique, Alimentaire et Nutritionnelle (CRSBAN), Laboratoire de Microbiologie et Biotechnologie Microbienne (LAMBM), UFR-SVT, Université Joseph KI-ZERBO, 03 BP 7131 Ouagadougou, Burkina Faso.*

[3]*Faculty of Engineering, Vasile Alexandri University of Bacau, Calea Marasesti, n°157, 600115 Bacau, Romania.*

[4]*Université de Fada N'Gourma, 01 BP 54 Fada N'Gourma, Burkina Faso.*

[5]*Centre National de la Recherche Scientifique et Technologique (CNRST), 03 BP 7192 Ouagadougou, Burkina Faso.*

[*]*Corresponding author; E-mail: josephsawadogo@yahoo.fr ; Tel:+226 76683763*

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ABSTRACT

The cashew nut wastes (CNW), more released in the environment by cashew nut transforming units, are underused based on bioenergy. This study aimed at evaluating the biogas production by the anaerobic co-digestion of CNW with various organic feedstocks. Physicochemical parameters and lower heating value (LHV) of cashew nut hull (CH) and cashew almond skin (CS) were determined. Batch cultures of each waste, supplemented to pig manure (PM), cow dung (CD), fermentation sludge (FS), activated sludge (AS) and *Macrotermes bellicosus* termite gut homogenate (TGH), were performed in anaerobic and mesophilic conditions. The biogas and methane (CH_4) were measured. CNW were acid (pH 5.86-6.44), with 86.80-92.38% volatile solids (VS) and slightly high carbon/nitrogen ratio (31.94-37.79). The LHV was 23.094 MJ/Kg and 18.113 MJ/Kg for CH and CS, respectively. The highest yields were retrieved with the co-digestion PM-CH (189.16 L biogas.kg^{-1} VS, 130.89 L CH_4.kg^{-1} VS, and 69.2% CH_4) and CD-CS (159.85 L biogas.kg^{-1} VS, 99.58 L CH_4.kg^{-1} VS, and 62.3% CH_4). Therefore, to boost biogas and biomethane yield, it is necessary to adjust the C/N ratios to the optimal values, and maintain the pH to the neutral, and combine PM and CD as inoculum during the digestion process of CNW.

Keywords: Organic agri-food wastes, inoculums, anaerobic biodigestion, biogas yield, methane yield.

INTRODUCTION

Burkina Faso is part of main producers of oleaginous products in West Africa. Among those products, cashew nut (CN) is occupying the third exportation product after cotton and sesame. As an estimation, more than 129,000

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tons of brut CN were exported in 2018 against 100,000 tons in 2019 (Agro-pastoral, 2021). But only 10,000 tons/year of brut CN are transformed by processing units in Burkina Faso (SNV_CIR, 2017). That is ten times lower than non-transformed amounts for exportation. This contrast is due to the high cost of CN transformation compared to the cost of agricultural production of cashew trees. Indeed, transformation processing for a better and huge production of cashew almonds requests an important energy recovery and a sophisticated equipment.

Fewer industrial and some semi-industrial units use gas (butane) and/or electric ovens for shelling nut, peeling and drying almonds. However, with regards to inflation of energy cost during this last decade, most of CN transforming units meet some difficulties to recover the required energy. Thus, during CN transformation processing, most of artisanal and semi-industrial units use wood combined with cashew nut wastes (CNW), as alternative energy, to support the charge and cost in terms of energy recovery. The transformation of CN release 21% cashew almonds, 73% CN hull and 6% almond skin (Testa) (Tagutchou and Taquin, 2012). Thus, around 7,300 tons/year of CN waste are generated by units (SNV_CIR, 2017; Agro-pastoral, 2021), and subjected to combustion. Unfortunately, these organic wastes are underused or under valorized, and largely and continuously stocked on unit field. Consequently, this accumulation of CNW can contribute to (i) the pollution of soil, surface and underground water, (ii) degradation of air quality due to CN hulls combustion and affecting people health, and (iii) greenhouse gas emission into the atmosphere and climate warming (SNV_CIR, 2017).

Several studies explored the thermochemical treatment of cashew nut, jatropha and shea hulls by using pyrolysis, gasification, and torrefaction for their energetical valorization (Ettien, 2010; Singh et al., 2006; Tagutchou and Naquin, 2012). However, these technologies are more expensive and not affordable for all CN transforming units. Yet, the energetical valorization of by-products of cashew nut in safe and cheapest conditions could help these units to cover their energy requirement. As an energetical and eco-friendly alternative to treat organic wastes, anaerobic digestion could be used to strengthen the energetical autonomy of CN transforming units. This biotechnology involves the skill of bacterial consortium for organic matter degradation to produce biogas. Biogas consists of mainly methane (55-75%) and carbon dioxide (25-45%). Methane is used as house gas, for engine combustion, and converted into electricity and heating by co-generation process. Because of the complexity of chemical composition of CN shells which contain cashew nut shell liquid (CNSL), anaerobic digestion of cashew nut waste is poorly documented so far. CNSL that consists of anacardic acid (70-90%), cardol (10-18%) and cardanol (5%) (Patel et al., 2006) strongly inhibits the methanogenesis process. However, some studies showed the occurrence of bacteria able to degrade recalcitrant compounds in CNSL (Prabha et al., 2011; Rajeswari et al., 2011).

Recent studies (Nikiema et al., 2020, 2021) also exhibited the ability to degrade CN shells by anaerobic digestion using thermal and biological treatments for fermentation culture. However, the experimental biogas yield was significantly lower than theorical estimation. In addition to cashew nut hull, there is cashew almond skin (CS), another by-product of CN transformation, which is not documented for its biogas potential so far. This study aimed at enhancing the biogas production by the anaerobic co-digestion of cashew nut wastes (CNW) with various organic feedstocks. Thus, CS as well as other feedstocks, like slurries and animal manures containing a microbial complex as staters, were used in this experiment.

MATERIALS AND METHODS

Collection and treatment of samples

4 years-aged cashew nut hulls (CH), and cashew nut almond skins (CS) were sampled in April 2016 from two cashew nut transforming units (SOTRIA-B and Association WOUOL) located in Banfora, at South-West of Burkina Faso. Samples were transported in May 2016 at

the laboratory of Faculty of Engineering, Vasile Alecsandri University of Bacau, Romania for further analysis. Samples were crushed using a knife grinder machine (GM 200 Retsch) and afterward sieved using a Lab screener machine (Retsch - AS 200) to obtain fine particles of 0.5 mm of diameter for further use. The experiment was carried out in two steps: i) physicochemical characterization of wastes, and ii) production of biogas. The analyzes were performed in triplicate.

Physicochemical parameters of substrates

pH

pH measurement was carried out according to Noutb et al. (1989) method. Fine samples (2.5 g) were homogenized in 22.5 mL distilled water and kept at rest for 2 h. pH was determined using pH meter (WTW pH340).

Moisture, Total solids and Volatile solids contents

These parameters were determined according to the standard procedures described by APHA (2005). For the moisture (or water content) and total solids (TS) determination, 2 g samples were taken in a crucible and oven-dried at 105 ± 2°C. The moisture and total solid contents were determined by weight measurement in a 3 h interval until a constant weight, and expressed in percent following Equations (1) and (2).

$$M = \frac{m0-m1}{m0} x\ 100 \qquad (1)$$

where *M* : Moisture or Water content (%)

M_0 : Fresh sample weight used before drying (g)

M_1 : Dry sample weight (g)

$$TS = 100 - M \qquad (2)$$

where *TS* : Total solid content (%)

M : Moisture (%)

As for the determination of volatile solid (VS) content, the oven-dried samples originated from the previous analyze were then heated in a muffle furnace at 550°C for 6 h. VS was determined based on the weight loss of dried sample [Equation (3)] and calculated according to Equation (4).

$$Wl(\%) = \frac{m1-m2}{m1} x\ 100 \qquad (3)$$

where *Wl* : Weight loss (%)

M_1 : Dry sample weight at 105°C (g)

M_2 : Heated sample weight at 550°C (g)

$$VS = Wl - M \qquad (4)$$

where *VS* : Total solid content (%)

Wl : Weight loss (%)

M : Moisture (%)

Total organic carbon

Total organic carbon (TOC) was determined from volatile solid content to use the common carbon proportion factor according to Equation (5) (Afilal et al., 2014).

$$TOC = \frac{VS}{1.74} x\ 100 \qquad (5)$$

where *TOC* : Total organic carbon content (%)

VS : Volatile solid content (%)

Total nitrogen

Total nitrogen (TN) was determined by Kjeldahl method as described by Afilal et al. (2014). This method was carried out as follows: (i) the digestion of samples during which the protein nitrogen of organic waste is transformed into ammonia nitrogen by oxidation of the organic matter in a concentrated sulfuric acid solution at 400°C in the presence of a catalyst ($CuSO_4$), and a salt (K_2SO_4); (ii) ammonia distillation, during which the ammonia is then distilled by water vapor, and trapped in a boric acid solution to form borate ammonium salts; and (iii) ammonia titration, during which the ammonium borate salts are titrated directly with a standard solution of hydrochloric acid (HCl), and a colored indicator.

Lower heating value of samples

The lower heating value (LHV) or calorific value of a fuel is the amount of heat in a combustion process of one kilogram or one liter (Bouabid et al., 2013). The determination of LHV of samples was performed by calorimetry using a bomb calorimeter (CAL3K-U) as described by Bouabid et al. (2013). One gram (1g) of sample was introduced in the bomb filled with oxygen under pressure to ensure complete combustion. The bomb was immersed in a calorimeter containing an accurate amount of water used to determine the temperature of variation and then the amount of heat released during combustion. After combustion, the temperature of the calorimeter increases and stabilizes. Thus, the device displays the value expressed in megajoule per kilogram of fuel (MJ/Kg).

Anaerobic digestion and biogas production from samples

Inoculums for digestion process

The cow dung (CD), pig manure (PM), Termite gut homogenate (TGH), fermentation sludge (FS) and activated sewage sludge (AS) served as both inoculums (microbial sources) and co-substrates for anaerobic digestion of wastes. The CD and PM were collected from cattle and pig farmers around Bacau city (46.550209° N, 26.965780° W), Romania. The FS and AS were collected from the wastewater treatment plant in Bacau (46.536824° N, 26.937782° W). *Macrotermes bellicosus* termites were sampled from active termites in the botanic reserve of Somgandé (12°24’30 N, 1°29’30 W) in Ouagadougou, Burkina Faso, and brought to the Faculty of Engineering at the Vasile Alecsandri University of Bacau for experiment. As described by Sawadogo et al. (2013), termite guts (2 guts/mL) were degutted, mechanically crushed and in a physiological saline solution as a stock solution of termite gut homogenate (TGH). All inoculums freshly collected were kept at 4°C for further use.

Experimental setup

Erlenmeyer flasks were used as batch digesters for the biogas production test from each combination of substrate-inoculum at the ratio of 1:5. In 100 mL Erlenmeyer flasks, each waste sample, either cashew nut hulls (CH) or cashew almond skin (CS) (2%, w/v), was supplemented with inoculum/co-substrate (10%, w or v/v) and mixed in 88 ml of tap water. Before flask sealing, the pH of each mixture was measured and then adjusted at 7.0 ± 0.1 with NaOH (1N). Flasks were sealed with rubber septum. The designs were equipped with a hose for draining biogas, and a clamp serving as a valve (Figure 1). All batch digesters were incubated in a water bath maintained at 30°C for 24 days. During anaerobic digestion, biogas production was measured each 2 days, and bottles were hand-mixed daily for approximately 20 s. Biogas production was measured by a water displacement method as described by Bedoić et al. (2019) (Figure 1) and Sumardiono et al. (2022). Controls (without cashew nut waste) were carried out. Experiment was performed in duplicate.

Analytical measurements

The pH of each culture was measured at the end of experiment (24th day) to determine whether the initial adjusted pH is ranged or not. The pH meter probe was directly introduced into opened digesters for pH reading.

The volume of biogas that is formed during anaerobic digestion was measured at the intervals of 2 days by the technique of water displacement in the measurement tube (Sumardiono et al., 2022).

To determine the amount of methane (CH_4) and carbon dioxide (CO_2) from the biogas produced at the end of experiments, 4 mL of gas was withdrawn from the headspace of each digester across the rubber septum and transferred into 4 mL vacutainer tubes previously emptied by a vacuum pump. Gas samples were then transported at the Laboratoire de Microbiologie et Biotechnologie Microbienne (LAMBM), Université Joseph Ki-Zerbo in Ouagadougou, Burkina Faso for gas chromatography (GC) analysis. CH_4 and CO_2 were measured by a GC equipped with a thermal conductive detector (GC-TCD) according to the GC conditions described by Sawadogo et al. (2012).

Statistical analysis

StatPlus:mac software was used for statistical analysis. The mean values of physicochemical parameters, biogas production and yield, methane production and yield between these organic matters were subjected to the analysis of variance (ANOVA) using the Tukey HSD test at threshold $p = 0.05$.

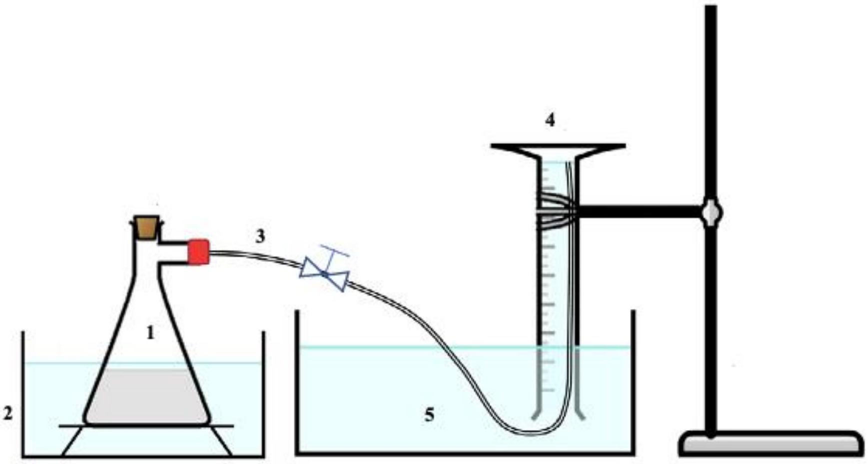

Figure 1: Experimental setup of Laboratory scale anaerobic digestion and liquid displacement method. Adapted from Bedoic et al. (2019).
1: biodigester with mixture; **2**: temperature-controlled water bath; **3**: outlet hose for biogas; **4**: graduated measuring cylinder; **5**: water tank for displacement technique.

RESULTS

Physicochemical characteristics of cashew nut hull and cashew nut skin

The mean values of physicochemical parameters of the studied wastes are depicted in Table 1. The pH of samples was acid, and ranged from 5.86 ± 0.03 for cashew almond skin (CS) to 6.44 ± 0.01 for cashew nut hull (CH). pH of CS was significantly acid than that of CH ($p < 0.001$).

The moisture content of wastes ranged from 6.96 ± 0.06% to 10.35 ± 0.10%, and was significantly different ($p < 0.001$). The low value was found in the CH samples (6.96 ± 0.06%) while the high value in the CS samples (10.35 ± 0.10%).

The total solid (TS) content was high in both wastes (93.04 ± 0.06 % and 89.65 ± 0.08%). The CH residues presented the significant higher TS value (93.04 ± 0.06 %) compared to CS 89.65 ± 0.08%) ($p < 0.001$).

The results showed that the volatile solid (VS) content was also high in both residues although significantly different ($p < 0.001$). The VS was an order of magnitude greater in CH waste (92.38 ± 0.18%) than in CS waste (86.80 ± 0.28%).

All samples presented high levels of total organic carbon (TOC). The CH samples showed a higher significant TOC content in order of 53.09 ± 0.10% than that of CS samples (49.88 ± 0.16%) ($p < 0.001$).

However, the total nitrogen (TN) content was very lower in all samples compared to TOC values mentioned above. The smallest value of TN was found in CS (1.32 ± 0.14%) residues while the CH samples contained a slightly high value (1.67 ± 0.12%) ($p < 0.05$).

Thus, the carbon/nitrogen ratio (C/N) showed significant values ranged from 31.79:1 ± 0.83 to 37.79:1 ± 1.14 ($p < 0.05$).

As shown in Table 1, the lower heating value (LHV) was significantly higher in CH samples (23.094 ± 0.340 MJ/kg) than the one in CS samples (18.113 ± 0.210 MJ/Kg).

Biogas and methane potential of cashew nut wastes

The biogas production showed an increasing variation during biodigestion process (Figure 2). The co-digestion of cashew nut wastes (CNW) with pig manure (PM) enabled a quick production of biogas from 2 days of incubation. The biogas production from

CNW was the highest along the co-digestion process with pig manure, and the stability of biogas production was noted from 16th day of incubation. In second place, the co-digestion of CNW with cow dung (CD) showed an increasing and continual trend in the biogas production until 24 days of incubation (Figure 2). A low biogas production from the co-digestion of CNW with activated sewage sludge (AS). No biogas production was observed from the co-digestion of CNW with fermentation sludge (FS) and termite gut homogenate (TGH) as well the FS digestion (control without CNW) (Figure 3).

Furthermore, based on amount of cumulated biogas and biogas yield over 24 days, the addition of animal manures (PM and CD) to CNW significantly increased the biogas production comparatively to controls (inoculum without CNW), and setups CNW supplemented with termite guts (TGH) and wastewater treatment plant slurry (AS) ($p < 0.001$) (Figure 3, Table 2). Indeed, the highest amount of cumulated biogas and biogas yield were retrieved in pig manure with cashew nut hull (PM-CH) setup (349.5 ± 6.36 mL and 189.16 ± 3.44 L/kg VS). On the other hand, the lowest values were found in activated sewage sludge with cashew almond skin (AS-CS) setup (28.5 ± 4.24 mL and 16.13 ± 2.45 L/kg VS). However, biogas yield was not significantly different between pig manure with cashew almond skin (PM-CS) and cow dung with cashew nut hull (CD-CH) cultures although it was high in order of 127.02 ± 0.40 L /kg VS and 115.01 ± 1.91 L /kg VS ($p = 0.068$), respectively.

In general, the biogas produced from different co-digestion displayed a methane (CH_4) and carbon dioxide (CO_2) contents ranging from 59.1% to 69.2% and 30% to 39.6%, respectively, with regard to substrate (CNW) and co-substrate (inoculum) used (Figure 4). The CH_4 yield was significantly higher in pig manure with cashew nut hull (PM-CH) cultures (130.89 ± 2.38 L/Kg VS) ($p < 0.001$), containing the highest CH_4 content (69.2%), than other cultures (Table 2, Figure 4). The cow dung with cashew almond skin (CD-CS) cultures were the second cultures to release a relatively high CH_4 yield (99.58 ± 1.27 L/Kg VS) with 62.3% CH_4 (Table 2, Figure 4).

Table 1: Physicochemical characteristics of cashew nut wastes.

	Cashew nut hull (CH)	**Cashew almond skin (CS)**	***P* value**
pH	6.44 ± 0.01 [a]	5.86 ± 0.03 [b]	0.0002***
Total solids (%)	93.04 ± 0.06 [a]	89.65 ± 0.08 [b]	0.0002***
Moisture (%)	6.96 ± 0.06 [a]	10.35 ± 0.10 [b]	0.0002***
Volatile solids (%)	92.38 ± 0.18 [a]	86.80 ± 0.28 [b]	0.0002***
Total organic carbon (%)	53.09 ± 0.10 [a]	49.88 ± 0.16 [b]	0.0002***
Total nitrogen (%)	1.67 ± 0.12 [a]	1.32 ± 0.14 [b]	0.0013**
Carbon/Nitrogen ratio	31.79:1 ± 0.83 [a]	37.79:1 ± 1.14 [b]	0.0032**
Low heating value (MJ/Kg)	23.094 ± 0.340 [a]	18.113 ± 0.210 [b]	0.0002***

*** : very highly significant; ** : high significant

Mean values (± standard deviation) followed by the same letter on each line are not significantly different using the Tukey HSD test ($p = 0.05$).

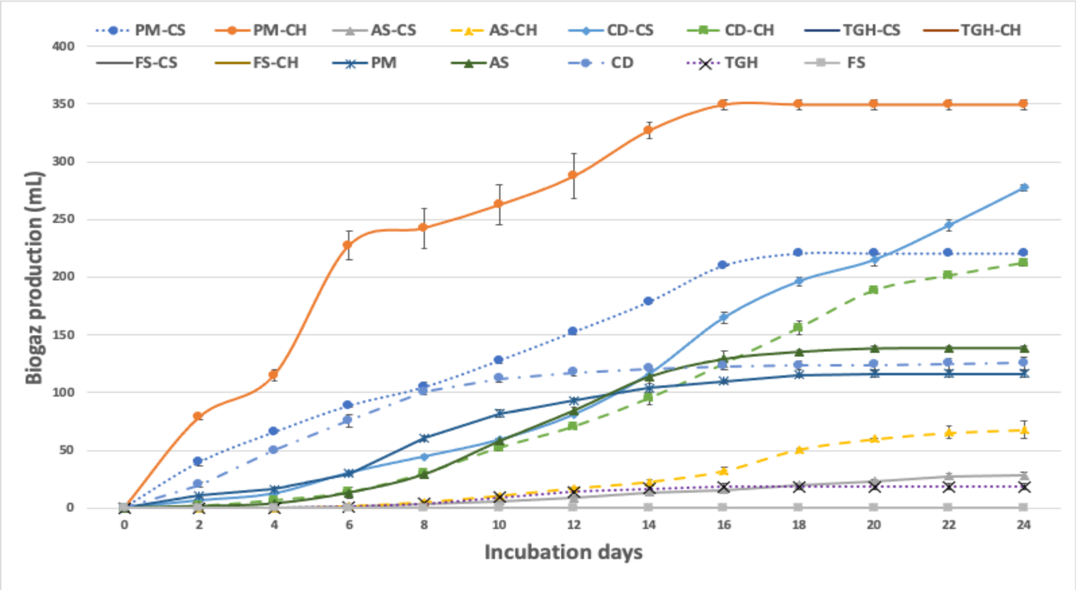

Figure 2: Evolution of biogas production during the anaerobic digestion of cashew nut wastes with regard to inoculum compared to controls (inoculum without waste).

AS: Activated Sludge; **CD**: Cow Dung; **FS**: Fermentation Sludge; **PM**: Pig Manure; **TGH**: Termite Gut Homogenate; **AS-CH**: Activated Sludge with Cashew nut Hull ; **AS-CS**: Activated Sludge with Cashew almond Skin; **CD-CH**: Cow Dung with Cashew nut Hull; **CD-CS**: Cow Dung with Cashew almond Skin; **FS-CH**: Fermentation Sludge with Cashew nut Hull ; **FS-CS**: Fermentation Sludge with Cashew almond Skin; **PM-CH**: Pig Manure with Cashew nut Hull; **PM-CS**: Pig Manure with Cashew almond Skin; **TGH-CH**: Termite Gut Homogenate with Cashew nut Hull; **TGH-CS**: Termite Gut Homogenate with Cashew almond Skin.

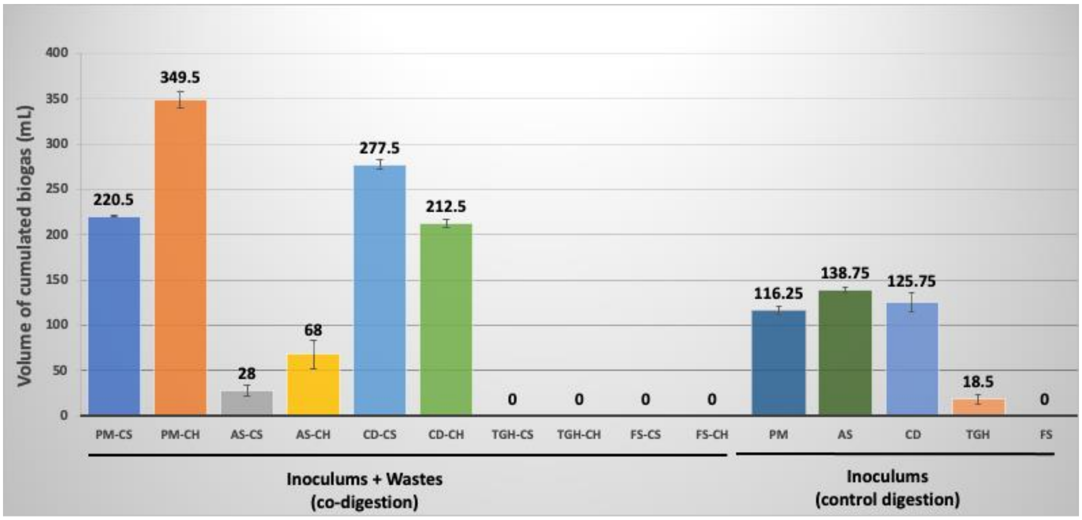

Figure 3: Cumulative biogas during 24 days of incubation in different designs comparative to inoculum controls.

AS: Activated Sludge; **CD**: Cow Dung; **FS**: Fermentation Sludge; **PM**: Pig Manure; **TGH**: Termite Gut Homogenate; **AS-CH**: Activated Sludge with Cashew nut Hull ; **AS-CS**: Activated Sludge with Cashew almond Skin; **CD-CH**: Cow Dung with Cashew nut Hull; **CD-CS**: Cow Dung with Cashew almond Skin; **FS-CH**: Fermentation Sludge with Cashew nut Hull; **FS-CS**: Fermentation Sludge with Cashew almond Skin; **PM-CH**: Pig Manure with Cashew nut Hull; **PM-CS**: Pig Manure with Cashew almond Skin; **TGH-CH**: Termite Gut Homogenate with Cashew nut Hull; TGH-CS: Termite Gut Homogenate with Cashew almond Skin.

Table 2: Biogas and CH_4 yields, and pH variation before and after pH adjustment at 7.0.

Batch cultures	Biogas yield (L/Kg VS)	CH_4 yield (L/Kg VS)	Final pH	Initial pH
PM-CH	189.16 ± 3.44 [a]	130.90 ± 2.38 [a]	5.8	5.3
CD-CS	159.85 ± 2.03 [b]	99.58 ± 1.27 [b]	6.4	6.5
PM-CS	127.02 ± 0.40[c]	82.56 ± 0.26 [c]	5.7	5.4
CD-CH	115.01 ± 1.91 [c]	67.97 ± 1.13 [d]	6.9	6.9
AS-CH	36.80 ± 6.12 [d]	ND	7.1	7.3
AS-CS	16.13 ± 2.45 [e]	ND	7.1	6.9

Mean values (± standard deviation) followed by the same letter in each column are not significantly different using the Tukey HSD test (p = 0.05). **AS-CH**: Activated Sludge with Cashew nut Hull; **AS-CS**: Activated Sludge with Cashew almond Skin; **CD-CH**: Cow Dung with Cashew nut Hull; **CD-CS**: Cow Dung with Cashew almond Skin; **PM-CH**: Pig Manure with Cashew nut Hull; **PM-CS**: Pig Manure with Cashew almond Skin. **ND**: Not determined

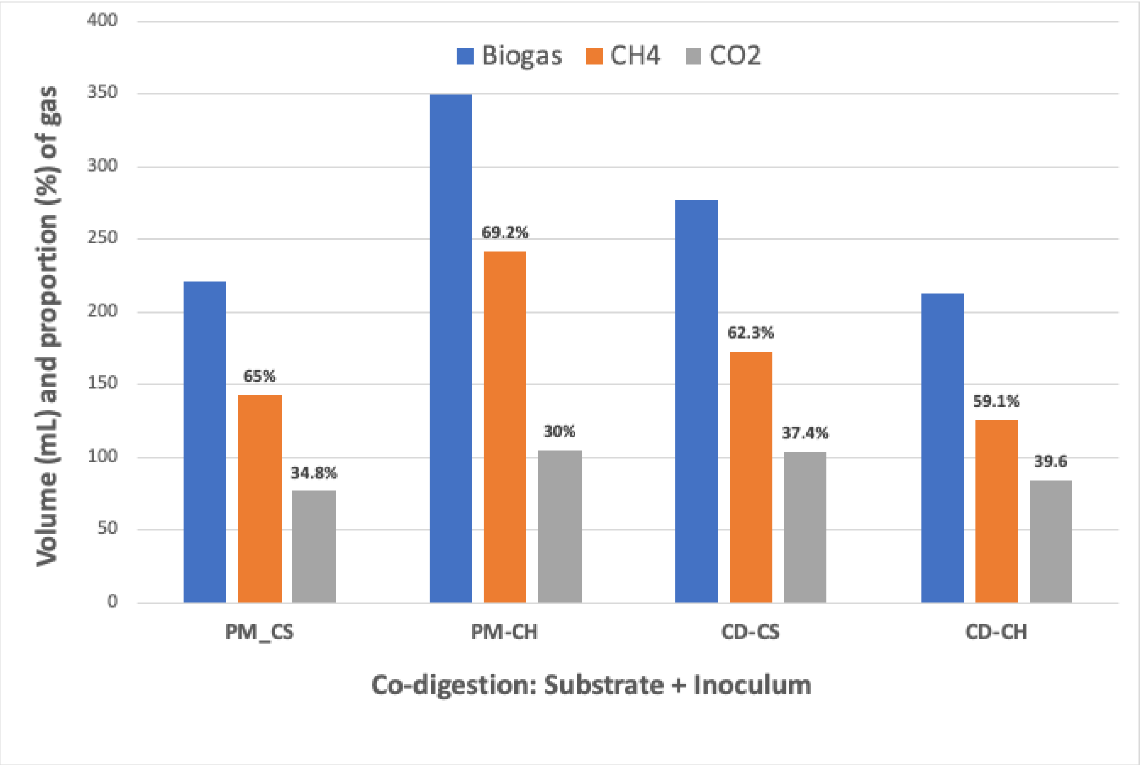

Figure 4: Methane (CH_4) and carbon dioxide (CO_2) content in the biogas produced at the end of co-digestion process.
CD-CH: Cow Dung with Cashew nut Hull; **CD-CS**: Cow Dung with Cashew almond Skin; **PM-CH**: Pig Manure with Cashew nut Hull; **PM-CS**: Pig Manure with Cashew almond Skin.

DISCUSSION

Acidic pH of cashew nut hull (CH) and cashew almond skin (CS) (5.86 and 6.44, respectively), as observed in this study, was this result was reported by Nikiema et al. (2020, 2021). These latter found a pH 4.29 and 6.41 for fresh and 8 years-aged cashew nut shells, respectively. The pH values of aged cashew nut hulls are similar and close to neutral pH in both studies (6.41 and 6.44). Cashew nut hulls contain some unsaturated phenolic compounds more and less important, such as anacardic acid, 2-methyl cardol, cardanol and cardol (Das et al., 2004; Patel et al., 2006). Sharma et al. (2020) reported that cashew almond skin (Testa) consists of primary phenolic acids as syringic, gallic and p-couramic acids. All these compounds could drop pH to acidic levels in these residues. These chemical compounds are not suitable for methanogenesis. Previous studies used diverse pretreatments (biological, chemical, enzymatical, physical, silage and thermal) for breaking chemicals and lignocellulosic materials from cashew bagasse and shell (Leitão et al., 2011; Nikiema et al., 2021). However, the results of biogas yield were not satisfactory so far.

The high contents in total solids (TS), volatile solids (VS) and total organic carbon (TOC) can positively affect the parameters of anaerobic digestion. Indeed, the viscosity of the content in the biodigester, fluid dynamics and solid sedimentation which can affect the rates of mass transfer within biodigesters (El Asri et al., 2020). This organic fraction is one of the main factors influencing the performance and stability of digesters and the biogas production (Wu et al., 2009). Interestingly, this study updated the values of TS, VS, TOC, total nitrogen and C/N ratio, which are poorly known in cashew nut skin (Testa). It is known that the amount of carbon available in a substrate defines also the amount of CH_4 and CO_2 that can be produced during biodigestion (El Asri et al., 2020). But the low nitrogen content in cashew nut waste samples could compromise the good working of biodigesters. Indeed, the nitrogen is needed for forming new cell biomass and stabilizing pH value in biodigesters (Fricke et al., 2007; Li et al., 2011). Consequently, the C/N ratio can exceed the threshold requested (20-30) for a best performance of anaerobic digestion ranges between 20-30 (Fricke et al., 2007), as revealed by this study (31-37) and that of Nikiema et al. (2020). Thus, it is necessary to supplementing nitrogen-enrichment feedstock like animal manures to adjust the C/N ratio for co-digestion leading to a better production of biogas (Zeshan et al., 2012).

The cashew nut hulls and cashew almond skin presented high lower heating values (LHV) of 23.094 and 18.113 MJ/Kg, respectively. The cashew nut shells LHV is close to that reported by Tagutchou and Naquin (2012) (21 MJ/Kg). As for cashew almond skin, also named cashew nut husk or Testa (Zafeer and Bhat, 2023), a similar finding was reported by Gadelha et al. (2019) (17.36 MJ/Kg). Therefore, we can deduce that the LHV of cashew nut wastes (CNW) are higher comparatively to the standard LHV of dry wood (17 MJ/Kg) (Rogaume, 2009). That denotes the potent capacity of CNW for a good combustion as demonstrated by Gadelha et al. (2019) using briquettes. That explains why existing artisanal and semi-industrial transforming units usually burn these wastes to recover energy needed during the different cashew nut processes.

As for the biogas production, despite the acidic pH and slight high C/N ratio of cashew nut waste, the greatest production, yield and proportion of biogas and methane were obtained by the co-digestion with pig manure (PM) and cow dung (CD). Indeed, despite the simple treatment of the experiments, the respective yields were highly important (115.01-189.16 L biogas/Kg VS; 67.97-130.89 L CH_4 /Kg VS) compared to previous data of Nikiema et al., (2020, 2021) (16.55-40.04 L biogas/Kg VS and 28.76-77.40 L CH_4/Kg VS). Many studies showed the biogas production potential of agricultural, industrial, slaughterhouse, municipal wastes by anaerobic co-digestion or direct digestion (Kpata-Konan et al., 2011; Nikiema et al., 2015; Traoré et al., 2016; Sumardiono et al., 2022).

Among inoculums/co-substrats, pig manure (PM) was found to be the best inoculum to degrade cashew nut hulls (CH) and produce the highest yields of biogas and methane with the lowest CO_2 amount. This finding is probably the first interesting result for biogas production by co-digestion of cashew nut hull with pig manure. This finding is followed by the inoculum cow dung (CD) facilitating the best yields of biogas and methane in co-digestion with cashew almond skin (CS). These inoculums could have some specific and interesting fermentative bacteria that enhance the biodegradation of cashew nut waste and produce more volatile fatty acids conducting to the low pH (5.8 and 6.4) observed at the end of the digestion process (Table 2). The adjustment of pH to 7.0 at the beginning of experiment would have allowed a better activity of bacterial consortium to metabolize and production biogas during the first 16 days of incubation. Indeed, Prabha et al. (2011) and Rajeswari et al. (2011) isolated several bacterial strains from cashew nut shell liquid (CNSL) contaminated soils. Among these strains, *Pseudomonas pseudoalcaligenes* and *Pseudomanas* sp. were able to degrade CNSL phenolic compounds and production methane. Thus, using pig manure and cow dung, as inoculums, could provide potent phenol degrading bacteria for releasing metabolites to active methanogens at neutral pH in culture during the first 16 days of incubation. So, it would be better to monitor and adjust the pH during the first 16 days of incubation in future experiments and to determine the composition of methanogenic and fermentative communities.

Conclusion

The potential of cashew nut wastes by co-digestion with animal manure showed satisfactory biogas and methane productions and yields. Pig manure was the best inoculum for increasing biogas and methane production with cashew nut hulls, whereas cow dung provided high biogas and methane yields with cashew almond skin. It would be necessary to experiment these co-digestion essays in pilot-scale by determining the ratio of inoculum and substrate conducting to a suitable C/N ratio on the one hand. Then, the monitoring and/or adjustment of certain parameters (pH, ammonium and volatile fatty acid), and the analysis of digestate composition would be expected on the other hand for agricultural applications.

COMPETING INTERESTS

The authors declare that they have no competing interests.

AUTHORS' CONTRIBUTIONS

JBS, DD, AST and VN wrote and validated the research project; JBS was the principal investigator of the project; JBS, MN and NB designed experimental setups; JBS, MN and NB sampled et collected wastes and inoculums; JBS and NB performed most of the experiments; EM generated lower heating values of samples; DD and ASO supervised activities and contributed to manuscript improvement; JSB wrote the draft of the manuscript, treated and analyzed data; all authors read, wrote and approved the final manuscript.

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