# Determination of the physiochemical characteristics of hotel food waste and its biogas fuel potential

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**Abstract:** Hotels are the source of large quantities of food waste, which can potentially be used for the generation of biogas for different applications, including agriculture. Thus, the purpose of this study was to investigate the physiochemical characteristics and biogas potential of the food waste generated by hotels in Nairobi City County, Kenya. To achieve this, a composition and physiochemical analysis of the feedstock were undertaken, which involved collecting and analysing a food waste sample of 130 kg, which gives an accuracy the same as that of a 1000 kg sample, according to the literature. In addition, the theoretical biomethane potential of food waste was determined using the Buswell and Carbon Balance equations, and the theoretical results were validated using anaerobic digestion experiments. The analysis showed that the fractions of different FW groups were fruits and vegetables (46%), roots and tubers (17%), meat and fish (14%), grains and cereals (9%), others (8%), bakery (4%), and tea and coffee (2%). The hotel food waste total solids, volatile solids, pH, COD, carbohydrates, and protein contents were determined to be 9.6%, 8.81%, 4.65, 142.3 g L$^{-1}$, 70%, and 13%, respectively. The C, H, O, N, and S compositions of the FW were 48.46%, 9.8%, 30.48%, and 2.2%, respectively. The test results showed that, based on these physiochemical characteristics, the hotel food waste had a theoretical methane yield of 643.07 mL gVS$^{-1}$ and an experimental methane yield of 518.53 ± 9.69 mL gVS$^{-1}$. The experimental yield was almost equal to an average biomethane potential of food waste (i.e., 525.65 $CH_4$ ml gVS$^{-1}$) based on the results of the other similar studies. Therefore, the hotel food waste can be used as an alternative feedstock for biogas generation if it is properly secured by, among other things, promoting onsite segregation of the hotel food waste.

**Keywords:** food waste, hotel, biogas, biomethane potential, Nairobi City County

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## 1 Introduction

Food waste (FW) is defined as any discarded food along the food supply chain (FAO, 2013; Huho et al., 2020). Food wastage is usually blamed on a lack of infrastructure and poor decisions by key stakeholders, such as the government, traders, and consumers (GIZ, 2016; Lipinski et al., 2013; Feedback Global, 2015; FAO, 2019). FW accounts for the largest share of the MSW, and it is regarded as a major global challenge that needs to be properly addressed (Ding et al., 2021). FW contributes to food insecurity apart from negatively impacting the environment through poor sanitation and greenhouse gas (GHG) emissions (EPA, 2015; Chen and Neibling, 2014; Quested et al. 2020; Tomaszewska et al., 2021). Food is wasted at different stages, including during the production,

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processing, packaging, and marketing stages along the supply chain (FAO, 2013; FAO, 2014; Banks et al., 2018; Kilibarda et al., 2019). One of the key sectors that produces large quantities of FW in urban areas is the hotel sector (Banks et al., 2018). This is not a surprise considering that hotels are major consumers of resources, such as food and water (Salama and Abdelsalam, 2021; Were et al., 2018; Kilibarda et al., 2019). According to Tomaszewska et al. (2021), about 5.8% of food is wasted per food service prepared for a customer in the European Union (EU), and it is estimated that restaurants and hotels account for about 12% of the total FW generated. This amount appears to be very small, yet it accumulates in large quantities every day (Kilibarda et al., 2019). In hotels, it is observed that food wastage mostly happens during preparation and production apart from due to spoilage and food leftovers on the plates of consumers (Tomaszewska et al., 2021; Salama and Abdelsalam, 2021; Were et al., 2018; Arsova, 2010).

Usually, anaerobic digestion (AD) is the most preferred option for treating segregated organic MSW, such as FW, which usually has a moisture content of 45%–50% (ADB, 2020; Arsova, 2010; Zupančič and Grilc, 2012; Thenabadu et al., 2015). Regardless of AD being one of the oldest technologies, it faces the problem of a lack of understanding of the biomethane potential (BMP) of specific types of feedstocks. The economy of methane generation is connected to feedstock in terms of its availability and BMP, among others (Kulichkova et al., 2020; Algapani et al., 2018; Arsova, 2010; Al Seadi et al., 2008). The BMP of a given feedstock is an important factor that relates to the amount of methane that can be generated per kilogram of the feedstock (Al Seadi et al., 2008; Cyril et al., 2018; Li et al., 2013). The physiochemical characteristics of the feedstock help to understand whether the feedstock is suitable for methane generation (Rabii et al., 2019; Kulichkova et al., 2020; Al Seadi et al., 2008; EPA, 2015).

FW generated in different geographical areas may differ in terms of composition as well as physiochemical characteristics, and these variations may have an impact on the methane yield obtained from the FW. In addition, amidst the lack of globally accepted BMP standards, authors have adopted different experimental methods for determining substrate methane yield and theoretical models for predicting the BMP of the substrate, which also complicates efforts to compare the BMP of the substrates generated in different geographical areas. Therefore, the objective of this study was to determine the physiochemical characteristics and BMP of the hotel FW generated in Nairobi City County (NCC), while also comparing the findings of other similar studies undertaken around the globe.

## 2 Materials and methods

### 2.1 Feedstock and inoculum used

The feedstock used for FW composition analysis, FW physiochemical analysis, and BMP in this study was FW collected from hotels in NCC, Kenya. On the other hand, the inoculum used for BMP experiments was obtained from a nearby active reactor, which used cow dung as feedstock. The inoculum was used to introduce the required population of anaerobic digestion microorganisms during the BMP experiments.

### 2.2 Sample size, collection and preparation

***Hotel FW sample for composition analysis:*** Studies done in the United States on waste composition found that waste samples of 100 kg for compositional analysis had an accuracy that was almost equal to that of 1000 kg (Gawaikar and Deshpande, 2006). This study used a sample of 130 kg of FW. An arrangement was made with the operators to provide a certain amount of FW generated by the hotel considering that it was also highly demanded by chicken and pig farmers. The FW comprised both, cooked and uncooked food. The collected FW samples were brought to a waste handling center for composition analysis.

***Hotel FW sample for physiochemical and BMP analysis:*** Fresh hotel FW obtained from a representative sample was collected and stored at 4°C to prevent microbiological decomposition from taking place before the physicochemical analysis was conducted. Before conducting the experiments, the FW samples were brought to room temperature and then mixed with distilled water in preparation for the physicochemical tests and BMP experiments. The mixing was done both manually in a dish and through a home blender to improve the susceptibility of enzymatic hydrolysis by reducing particle size homogeneity.

### 2.3 Experimental setup and procedure

***Hotel FW composition analysis*****:** The grouping of FW was done using a combination of methods adopted by Ventour (2008), FAO (2011), GIZ (2016), and Huho et al. (2020). Using smaller, well-labelled buckets, the collected FW samples were segregated into seven (7) different categories. These were meat and fish, fruits and vegetables, grains and cereals, tea and coffee, roots and tubers, bakery products, and others. The "others" group contained mixed FW that was too difficult to segregate by the researchers.

***Hotel FW Physiochemical analysis:*** The suspended solids (SS), total solids (TS), and volatile solids (VS) were all measured using the standard method (APHA, 2005). The tests were conducted at Kenyatta University's Civil Engineering and Chemistry Laboratories. The determination of the SS for the samples was done through filtration using Whiteman Membrane Filter Paper of 0.45 μm size. After the filtration, the filter paper was dried in a laboratory oven at 103°C–105°C until a constant weight was obtained. The TS of the sample was determined by drying the substrate and inoculum for 12 hours at 103°C–105°C using a laboratory oven. The VS was determined by reheating the samples that were initially dried at 103°C–105°C during TS testing using a muffle furnace (FNC-BX1200 series) at 550°C. The pH was measured using the Sensodirect 150 pH meter (Lovibond, Germany). A UV-Visible Spectrophotometer (YIMA-UV1800) in the Chemistry Laboratory at Kenyatta University was used to determine the nitrate and phosphate contents of the samples. The COD test was conducted at the Kenya Industrial Research and Development Institute (KIRDI) in Nairobi. Protein and carbohydrate tests were done at Analabs in Nairobi. C, H, and N tests were done with an elemental analyzer (ICP) at Lab Works East Africa in Nairobi. The content of O was analyzed using an oxygen analyzer (Perkin Elmer Instruments, USA).

***Hotel FW Theoretical BMP:*** The study used the Buswell equation to predict the composition of the biogas recovered from the substrate (Equation 1) (Achinas and Everink, 2016; Kumar, 2015; Li et al., 2013; Orangun et al., 2021; Świechowski et al., 2022) and applied the Carbon Balance (Equation 2) to calculate the substrate $CH_4$ yield in mL $gVS^{-1}$, where it was assumed that the degradation rate of the VS was at 75%.

$$C_nH_aO_bN_c + (n - \frac{a}{4} - \frac{b}{2} + \frac{3c}{4})H_2O \rightarrow \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8}\right)CH_4 + \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4} + \frac{3c}{8}\right)CO_2 + cNH_3 \quad (1)$$

$$TMP(\frac{mLCH_4}{gvs}) = \frac{22.4 \times 1000 \times (\frac{n}{2} + \frac{a}{8} - \frac{b}{4} - \frac{3c}{8})}{12n + a + 16b + 14c} \quad (2)$$

Where, *TMP* is the theoretical methane potential, *n*, *a*, *b* and *c* stand for molar percentage share of the specific elements of the VS of the substrate.

***Experimental BMP:*** The reactors used in this experiment were degassed using $N_2$ at Chemigas Limited in Nairobi to flush out $O_2$ from the reactors. This was done to create a suitable environment for AD. The pressure-hold-vacuum method for purging $O_2$ was used. The method involved pressurizing the reactor with $N_2$ and allowing it to mix and dilute the $O_2$ as much as possible. The diluted mixture was then released, and the process was repeated until the vessel was adequately purged. Then the mixed substrate was measured to proportion (150 mL and 50 mL for the substrate and blank reactors, respectively), and it was then transferred into six empty 500 mL reactors whose sizes could easily fit into the laboratory oven used in this study.

The reactors were classified as the substrate and the blanks, which were in triplicate (Figure 1). The substrate reactors contained the substrate, inoculum, and water, whereas the blank was filled with inoculum and distilled water only. The inoculum was introduced into the substrate reactors to supply the required population of microorganisms. The reactors were placed into an oven (DHG-9030A Series Drying Oven model), ensuring that the appropriate mesophilic temperatures were maintained at 35°C±0.50°C for a period of 21 days to allow for anaerobic digestion.

Figure 1 reactors of 500ml used for BMP experimentation

The batch test method was used during BMP experimentation. This method involves feeding a reactor at the start, and the feedstock is allowed to undergo all degradation stages before another feedstock is fed. During this period, the biogas yield for all the reactors was recorded daily to assess the BMP of the substrate. The accumulated biogas was calculated based on the pressure increase in the reactor headspace. The sampled gas was obtained from the accumulation of the produced gas in the headspace of the reactor. The sampled gas in 20-mL syringes was later transferred to 10-ml gas vials, which were later taken for composition analysis at the International Research and Livestock Institute (IRLI).

***Experimental biogas composition analysis:*** The methane and carbon dioxide gas measurements were done using both the portable OT-600 biogas analyzer (Henan Zhonghan, China) and the GC-SRI gas chromatography machine (model 8610C, USA) at the IRLI facility. This GC-SRI had both the Flame Ionization Detector (FID) and the Electron Capture Device (ECD). The carrier gas used was nitrogen, with oven temperatures in the range of 65°C–700°C.

### 2.4 Statistical analyses

The collected quantitative data was analyzed using statistical packages excel and R Package for biogas research. The results were expressed as mean outcomes and standard deviations. The t-tests were undertaken using SPSS (IBM, USA), and statistical significance was considered at $p< 0.05$.

## 3 Results and discussion

### 3.1 FW composition

The analysis showed that the fractions of different FW groups were fruits and vegetables (46%), roots and tubers (17%), meat and fish (14%), grains and cereals (9%), others (8%), bakery (4%), and tea and coffee (2%). Generally, the food consumption pattern of the NCC indicates that there is a high consumption of vegetables at 92% (Olielo, 2013). These results also showed that FW generated varies around the globe, which is in line with Banks et al. (2018) study findings. However, different methods were used for FW categorization, thus making it difficult to compare global FW compositions. Study findings also showed that the fruits and vegetables FW component accounted for the largest share, regardless of differences in the generation rate and methods of categorization or grouping adopted by different researchers. For comparative analysis, the findings of this study were compared with those of Bräutigam et al. (2014), Huho et al. (2020), GIZ (2016), Ventour

(2008), Paritosh et al. (2017), Yamada et al. (2017), Lasaridi et al. (2019), Lampert (2017), Ogunmoroti et al. (2022), and Caldeira et al. (2020) (Table 1).

**Table 1 A comparison of FW composition and other authors findings**

| FW groups | NCC hotel FW composition (%) | Other authors FW composition findings (%) |
|---|---|---|
| Fruits and vegetables | 46 | 38.6 ±6.02 |
| Meat and fish | 14 | 10.4±3.53 |
| Roots and tubers | 17 | 16.8 ±7.59 |
| Grains and cereals | 9 | 20.9 ±6.29 |
| Tea and coffee | 2 | - |
| Bakery | 4 | 13.78 ±8.67 |
| Others | 8 | - |

### 3.2 Hotel FW physiochemical characteristics

The analysis showed that the FW pH, COD, carbohydrates, and proteins were 4.65, 142.3 g $L^{-1}$, 70%, and 13%, respectively. The C, H, O, N, and S compositions of the FW were 48.46%, 9.8%, 30.48%, and 2.2%, respectively. The C:N ratio was calculated to be 21.8. The test for these physiochemical properties was very important in this study, as the collected data was used to predict the BMP of the FW (Algapani et al., 2018; Banks et al., 2018; Filer et al., 2019). The calculated theoretical yield obtained later was compared with the experimental BMP of the substrate. The physiochemical characteristics of the Hotel FW in NCC were also compared with the findings of Onyeaka et al. (2022), Browne et al. (2013), Li et al. (2013), Orangun et al. (2021), Browne and Murphy (2013), Al-Wahaibi et al. (2020), and Izaharuddin et al. (2018) (Table 2).

**Table 2 A comparison of FW physiochemical characteristics**

| Parameters | NCC hotel FW physiochemical characteristics | Average findings of other authors. | Unit |
|---|---|---|---|
| pH | 4.65 | 5.77±0.84 | |
| Carbohyd. | 70 | 44.78±24.15 | % |
| Proteins | 13 | 15.5±5.40 | % |
| Nitrogen | 2.2 | 2.95±0.91 | % |
| Carbon | 48.46 | 50.5±5.08 | % |
| Hydrogen | 9.8 | 7.24±0.59 | % |
| Oxygen | 30.48 | 35.58±5.17 | % |
| C:N Ratio | 21.8 | 16.19±3.26 | |

### 3.3 Theoretical BMP of the hotel FW

The biochemical and elemental composition of the substrate are used to predict the methane potential of the feedstock, which can provide preliminary results before conducting the experiments (Banks et al., 2018; EPA, 2015; Filer et al., 2019; Li et al., 2013). In this case, several models that for determining theoretical yields have been used around the globe (Cyril et al., 2018). The Buswell equation for calculating the theoretical biogas composition was adopted for this study. The carbon balance was applied to determine the recoverable methane from the substrate in mL $gVS^{-1}$. It was assumed that the degradation rate of the VS of the hotel FW substrate used was 75%. The results showed that the FW substrate had a theoretical BMP of 643.07 mL $gVS^{-1}$ and a biogas composition of 65% $CH_4$ and 35% $CO_2$. Table 3 shows the physiochemical characteristics of the substrate and inoculum used.

On the other hand, the findings of other authors around the globe showed a FW theoretical methane yield of 556.82±98 mL $gVS^{-1}$. Apart from the variations in theoretical methane yields reported by different authors, it was observed that they used different theoretical models. However, Buswell equation was the model adopted by most of the authors. Table 4 shows theoretical yields of FW as reported by different authors.

**Table 3 Physiochemical characteristics of hotel FW and inoculum used**

| Parameters | Substrate (FW) | Inoculum | Unit |
|---|---|---|---|
| SS | 4.54 | 1.6 | % |
| TS | 60.75 | 5.3 | % |
| VS | 57.7 | 4.5 | % |
| VS:TS | 0.92 | 0.84 | |
| pH | 4.65 | 6.38 | |
| COD | 142.3 | 76.5 | g/L |
| Carbohydrate | 70 | ND | % |
| Proteins | 13 | ND | % |
| Nitrogen | 2.2 | ND | % |
| Carbon | 48.46 | ND | % |
| Hydrogen | 9.8 | ND | % |
| Oxygen | 30.48 | ND | % |

**Table 4 Theoretical models used by different authors and the reported methane yields of FW**

| Theoretical $CH_4$ yield (mL $gVS^{-1}$) of FW by other authors | Theoretical models used | Authors |
|---|---|---|
| 700.15 | Modified gompertz model | (Xue et al., 2019) |
| 725 | Buswell equation | (Li et al., 2013) |
| 455.15 | Calculated from COD concentration. | (Cyril et al., 2018) |
| 506.6 | Buswell equation | (Orangun et al., 2021) |
| 494 | - | (Ding et al., 2021) |
| 460 | Buswell equation | (Świechowski et al., 2022) |

### 3.4 Experimental BMP of the hotel FW- cumulative yield and generation rate

The standardized cumulative biogas volume (cvBg) was determined to be 845.39±8.37 mL $gVS^{-1}$. The biogas composition test was conducted using a GC at ILRI in Nairobi (Kenya). The results showed that the compositions of the biogas were 61.33%±0.78% CH4 and 23%±1.73% $CO_2$. Using the measured cvBg and the biogas composition results, the standardized methane volume ($cvCH_4$) was determined to be 518.53± 9.693 mL $CH_4$ $gVS^{-1}$. Figure 2 shows the cvBg and $cvCH_4$ during the experimentation.

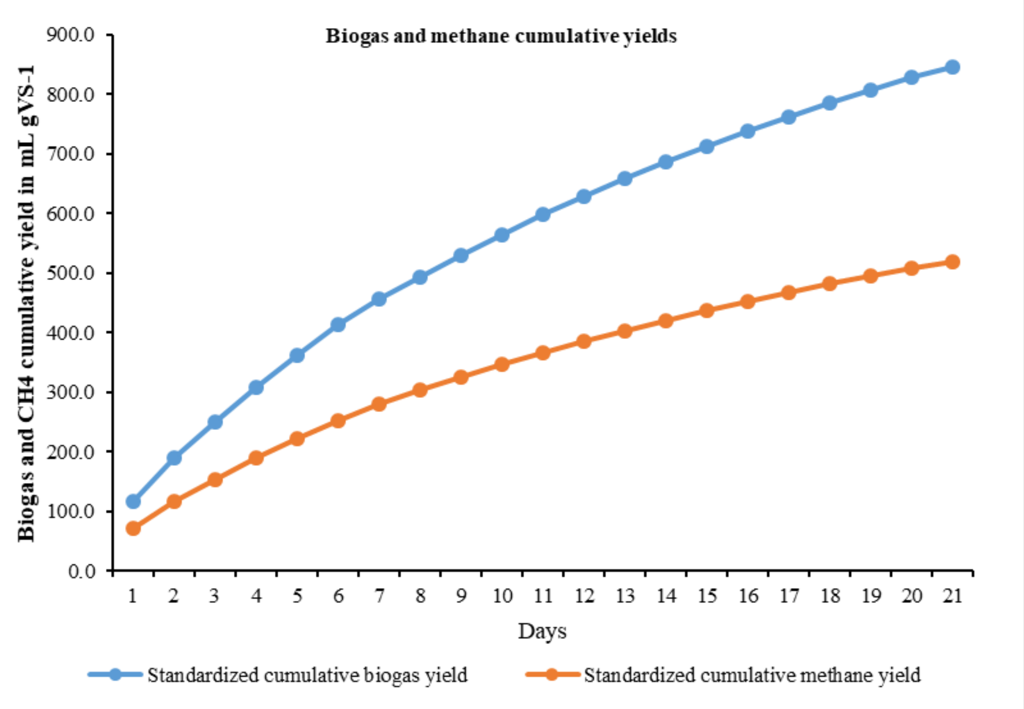

Figure 2 Biogas and $CH_4$ cumulative yield

The generation rate of the methane was calculated using the Online Biogas App (OBA). The tool is written in R, which can be used directly in the R environment. This tool helps to improve the efficiency of biogas research and the accuracy of BMP measurements and predictions by providing access to standardized algorithms for data processing and stoichiometric calculations (Hafner et al. 2018). Figure 3 shows the biogas and methane generation rates during the 21 days of incubation.

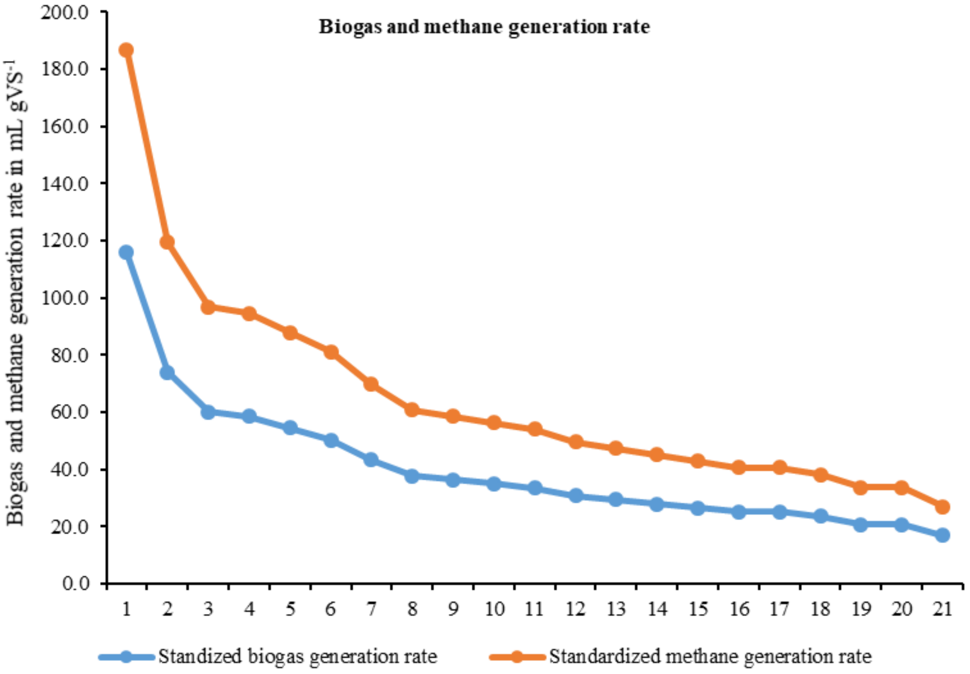

Figure 3 Methane generation rate

### 3.5 Comparison of experimental BMP yield of FW with other study findings

The study analysed the physiochemical characteristics of the FW as reported by Onyeaka et al. (2022), Browne et al. (2013), Li et al. (2013), Orangun et al. (2021), Browne and Murphy (2013), Al-Wahaibi et al. (2020), and Izaharuddin et al. (2018) (Table 5). Of these parameters, protein composition was of great concern because, if in higher concentration, it has the potential to suppress the methane formation process and cause considerable ammonia toxicity during AD (Kulichkova et al., 2020; Rabii et al., 2019; Arsova, 2010). However, most of the authors did not have complete data related to FW physiochemical characteristics.

**Table 5 Physiochemical characteristics of the FW used by different authors**

| Parameter | Composition in percentage (%) at 95% confidence level |
|---|---|
| Carbon | 50.5±5.08 |
| Hydrogen | 7.24±0.59 |
| Nitrogen | 2.95±0.91 |
| Oxygen | 35.58±5.17 |
| C/N Ratio | 16.19±3.26 |
| pH | 5.77±0.84 |
| Proteins | 15.5±5.40 |
| Carbohydrates | 44.78±24.15 |

Apart from the variations in the physiochemical characteristics of the FW used by the authors, different methods were adopted for the BMP experiments (Table 6). One important parameter was the AD temperature, which has the potential to affect yields (Algapani et al. 2018). In this study, the temperature was maintained at 35°C±0.50°C throughout the AD process using a laboratory oven, whereas other authors used 37°C, 36°C, and 38°C. Continuous Stirred Reactors (CSR) and AMPTS were used in one study, while the rest of the authors did not use similar equipment. The number of days for incubation differed from one author to the next, where BMP experiments were done for 22 and 65 days, respectively. Other studies involved degassing the reactors before undertaking the experiments; others did not do the same. It was further observed that other studies accounted for the methane produced from the inoculum while others did not. In addition, in other studies, some important parameters were not properly explained, making it difficult to compare the results.

**Table 6 FW experimental methane yields as reported by different authors**

| Authors | Methods Used | Experimental CH4 ml $gVS^{-1}$) |
|---|---|---|
| (Bartel, 2013) | 32 days incubation; 38˚C AD Temperature; Blanks used. | 590 |
| (Browne et al., 2013) | 5 L & 0.5 L digesters used; Inoculum used; 37˚C AD Temperature; Continuous Stirred Reactors (CSR) used; 5 L reactors used; Automatic Methane Potential Test System (AMPTS) also used; and Experiments in duplicate. | 508 |
| (Li et al., 2013) | 1L reactors used; 37˚C AD Temperature used; Experiments triplicated; Blanks used; 30 days of incubation; Inoculum used. | 683 |
| ( Browne et al., 2021) | Inoculum used; Done at AD Temperature of 36˚C±1˚C; Reactors degassed using nitrogen gas; 500ml reactors used; Liquid displacement method; 65 days of incubation. | 506.60 |
| (Browne and Murphy, 2013) | 5 L & 0.5 L digesters used; Inoculum used; 37˚C AD Temperature; Continuous Stirred Reactors (CSR) used; 5 L reactors used; Automatic Methane Potential Test System (AMPTS) also used; and Experiments in duplicate. | 498.00 |
|  | Average methane yield | 557.12±69.83 CH4 ml $gVS^{-1}$) |

The experimental results of this study were compared with findings from other similar studies done by different authors. In this study, the methane yield at 518.5 $CH_4$ mL $gVS^{-1}$ was observed to be lower when compared with the average BMP of the FW based on the findings from other studies. The calculated average BMP from the reviewed reports was determined to be 557.12±69.83 $CH_4$ mL $gVS^{-1}$.

## 4 Conclusion

The study was done to investigate hotel FW physiochemical characteristics and BMP. An analysis of the FW composition showed that vegetable and fruit types of FW accounted for the largest share. The theoretical yield of this study was found to be higher than the average yield of the reviewed studies done by other authors. However, it was observed that most of the authors did not have complete data related to the physiochemical characteristics of the FW they used. The experiment yield of the NCC hotel FW was determined to be slightly lower than the average yield of the reviewed studies, but the authors used different BMP methods, and some experimental parameters were not properly explained. This made it difficult to ascertain the causes of the variations in results reported by different authors.

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