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Investigation of the Effect of Percentage Carbohydrate Composition on Carbon/Nitrogen Stability on Biogas Yield from Selected Kitchen Biodegradable Wastes

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Abstract

This study investigated the effect of varying percentage carbohydrate composition on carbon/nitrogen (C/N) stability and subsequent biogas yield from selected kitchen biodegradable wastes. The objective was to optimize the anaerobic digestion process for maximum energy recovery by identifying the ideal C/N ratio. Experiments were conducted in 10 litres batch plastic digesters under mesophilic conditions range of 35-37 ^{0}C, utilizing different mixtures of kitchen wastes to achieve specific C/N ratios (<30, >30, and 20⩽C/N⩽30). Feedstocks were characterized for their percentage composition of carbohydrates. The volume of daily biogas production and methane concentration were measured over a defined hydraulic retention time (HRT) of 45 days. Digester stability was monitored by tracking pH of the slurry throughout the HRT. The results obtained showed that biogas yield was significantly affected by the carbohydrate content and the C/N ratio, with the optimal range typically found with C/N ratio 20⩽C/N⩽30. The ratios outside this range resulted in lower yields due to nutrient imbalance or inhibition. The findings emphasize the critical importance of feedstock characterization and blending to achieve an optimal C/N ratio for efficient and stable biogas production from kitchen waste. This research provides valuable insights for waste management and renewable energy applications, highlighting a practical approach to maximizing energy potential from a readily available organic waste source.

Keywords: Anaerobic digestion; Kitchen waste; Carbon–nitrogen ratio; Carbohydrate composition; Biogas yield

1. Introduction

Nigeria must confront a serious national energy problem, lessen its heavy reliance on environmentally harmful fossil fuels, and achieve sustainable economic development, all of which make the adoption of renewable energy urgent [1–5]. Inadequate infrastructure and ongoing power outages, which cost the economy over $28 billion a year, highlight the urgent need for a reliable, diverse energy mix [6–10]. Social and economic activities are greatly hampered by the fact that over 40% of Nigerians do not have access to electricity, with significantly lower rates in rural areas [11–14]. Oil and gas dominate Nigeria's energy industry, rendering the country susceptible to fluctuations in the price of oil globally and a major contributor to greenhouse gas emissions and environmental pollution [15–17]. In order to make up for grid instability, individuals and businesses frequently utilize costly and polluting diesel and gasoline generators, which raises operating costs and has an adverse effect on public health [18, 19]. The nation has enormous, underutilized renewable resources that might close the supply-demand gap, such as strong solar irradiation (averaging 5.5 kWh/m^2/day), huge hydropower potential, and substantial biomass resources [5, 13, 20, 21]. Transitioning to renewables is vital for Nigeria to accomplish its national and international climate action targets, such as those contained in the Paris Agreement and the Nigerian Energy Transition Plan [22-24]. A viable and sustainable route to increased energy security, job creation, and general national development is provided by utilizing these resources through decentralized solutions like solar household systems and mini-grids [25–29]. Additionally, by producing biogas from organic waste that is high in carbohydrates, Nigeria's energy dilemma can be resolved sustainably by using a clean, decentralized, renewable energy source. This approach helps diversify Nigeria's energy mix and lessen dependency on conventional fossil fuels by using anaerobic digestion to turn plentiful agricultural wastes and food waste into methane-rich biogas.

Many food wastes, such as grains, fruit waste, and vegetables, are primarily composed of carbohydrates, which are typically the organic molecules that break down the fastest during anaerobic digestion (AD) [30]. The production of hydrogen and biogas is frequently directly associated with the substrate's carbohydrate content [31]. If not adequately buffered or balanced, a high carbohydrate content may affect the generation of volatile fatty acids (VFAs), which could result in a pH drop and process instability [32]. Anaerobic digestion (AD) is a naturally occurring microbial process in which bacteria in enclosed tanks (digesters) break down organic waste (such as food scraps and manure) without oxygen to produce nutrient-rich digestate (biofertilizer) and sustainable energy (biogas, methane, and CO_2) [33-37]. This multi-stage process, which includes hydrolysis, acidogenesis, acetogenesis, and methanogenesis, reduces waste and smells while transforming complicated materials into fertilizer and useable energy. a blend of carbon dioxide and methane (50–75%) that is used as fuel for cars, electricity, or heat [38-43]. The AD processes are important for turning organic waste (food scraps, manure, and sewage) into useful resources, producing nutrient-rich digestate (fertilizer) and renewable energy (biogas for heat, electricity, and fuel), reducing landfill waste, lowering methane emissions, enhancing soil health, and promoting a circular economy by closing nutrient loops in wastewater treatment and agriculture [44-49].

A steady carbon-to-nitrogen (C/N) ratio is essential to the sustainable energy source provided by anaerobic digestion (AD) of biodegradable kitchen trash [50-52]. For balanced microbial development and maximal methane production, an ideal C/N ratio Typically between 20 and 30:1 is essential [53-55]. To avoid process inhibition and guarantee steady biogas generation, a stable C/N ratio must be maintained [50]. Co-digestion, which combines various waste streams such as high-carbohydrate waste with a nitrogen-rich source like manure is frequently used to do this [56-67]. The carbohydrate, protein, and lipid content of kitchen waste varies greatly, which has an immediate impact on the C/N ratio and process stability. If not adequately balanced, a high carbohydrate content in food waste might cause rapid acidification (the formation of volatile fatty acids) due to quick breakdown, which could interfere with digestion [67-71]. Lower methane production or even digester failure might result from either nitrogen insufficiency or ammonia inhibition brought on by uncontrolled C/N ratios [72-75]. Nitrogen deficit, which restricts microbial protein synthesis and lowers biogas generation, is indicated by a high C/N ratio. A low C/N ratio causes nitrogen to be consumed quickly and ammonia (NH_3) to build up. This raises pH and can be harmful to methanogenic bacteria. In order to determine the best mixing ratios for improved performance, this study attempts to methodically examine how changing the % carbohydrate composition of particular kitchen wastes affects the stability of the C/N ratio and the total biogas generation.

2. Materials and Methods

2.1 Materials

The following materials were used.

2.1.1 Substrates

The substrates, which include specific kitchen biodegradable wastes including vegetable peels, fruit pulp, rice debris, and remnants of residual starch like fufu and eba, were gathered from nearby eateries.

2.1.2 Inoculum

The inoculum used was a cow dung slurry collected from abattoir.

2.1.3 Digesters

A laboratory-scale anaerobic digesters (e.g., 10 litre plastic bottles) with airtight seals was used.

2.1.4 Gas Collection System

The water displacement method setup using graduated gas cylinders and water troughs, or automated gas flow meters as recommended by [24, 27] was used.

2.1.5 Analytical Equipment

The following analytical equipment were used.

i. Elemental analyzer (e.g., LECO Truspec CHN) for total carbon and nitrogen content,
ii. pH meter.
iii. Thermometer,
iv. Weighing scale, and
v. Gas chromatograph (GC) for biogas composition analysis (methane percentage).

2.2 Methods

The following methods were adopted.

2.2.1 Waste Characterization and Preparation:

i. Collect and categorize kitchen wastes into carbohydrate-rich and nitrogen rich groups,
ii. Shred or blend the wastes to a uniform size (e.g., 1-5 mm) to facilitate digestion,
iii. Determine the C/N ratio of each waste type using standard methods (e.g., APHA standards, elemental analyzer).

2.2.2 Experimental Design and Feedstock Mixing:

i. To obtain particular total C/N ratios, design several feedstock combinations with different beginning carbohydrate percentages (e.g., 15:1, 20:1, 25:1, 30:1, 35:1),
ii. Determine the mass of each waste component needed to reach the target C/N ratio using formulas based on their individual carbon and nitrogen concentrations, and
iii. Create slurries for each variation in the C/N ratio by combining the calculated waste mass with the proper amount of water and inoculum (e.g., 60:20:20%) to achieve a desired total solids concentration (e.g., 7–15% for wet digestion).

2.2.3 Anaerobic Digestion Setup and Operation:

Airtight sealing was ensured by charging the prepared slurry into the laboratory-scale digesters. Initial anaerobic conditions were established by purging the experimental 10-liter plastic digester with nitrogen gas. As recommended by [63], the batch AD plastic digester was run in an ideal controlled mesophilic temperature range of 35–37°C. Knowing full well that a pH range of 6.8–7.2 will favor an optimal biogas yield, the slurry's pH was routinely monitored to assure process stability. Figure 1 depicts the experimental setup as suggested by [20, 24].

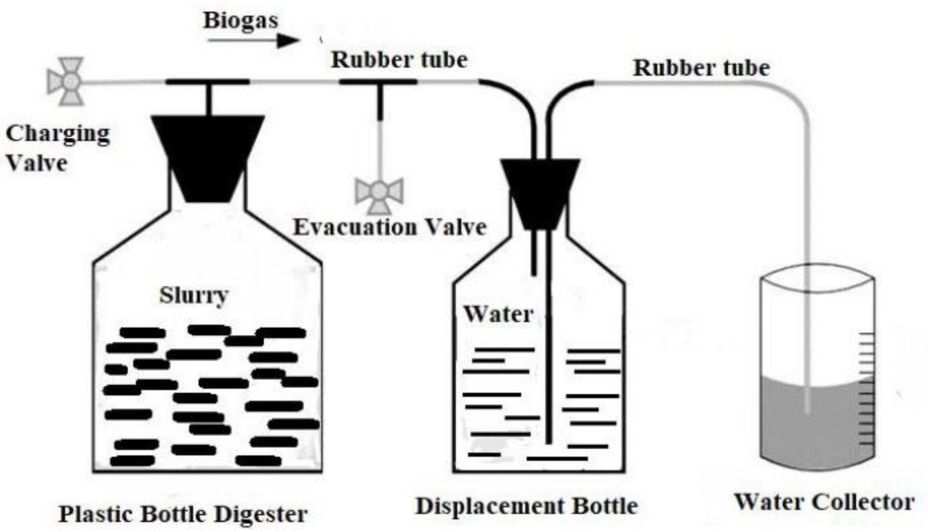

Figure 1. Experimental setup [24]

3. Results and Discussion

Figure 2 displays the results of the kitchen waste's percentage carbohydrate composition. Although a larger percentage of carbs in kitchen waste results in a quicker initial biogas generation rate, an excessively high concentration can impede the process and cause rapid acidification. Maximum and sustained biogas yields require an ideal balance with other components (proteins and lipids). During the initial phases (hydrolysis and acidogenesis), bacteria readily and swiftly break down carbohydrates, creating volatile fatty acids (VFAs) [51, 52]. As a result, gas production starts more quickly. The digester's pH may drop to levels that hinder the methane-producing archaea (methanogens) due to an accumulation of VFAs brought on by an extremely high carbohydrate load [71]. The ultimate methane production is decreased by this instability. When carbs are matched with the right ratios of proteins and lipids, usually by co-digestion, the best biogas is produced [20, 24, 27]. All of the microbial populations engaged in the anaerobic digestion process benefit from this balance, which aids in maintaining a steady pH and C/N ratio [50].

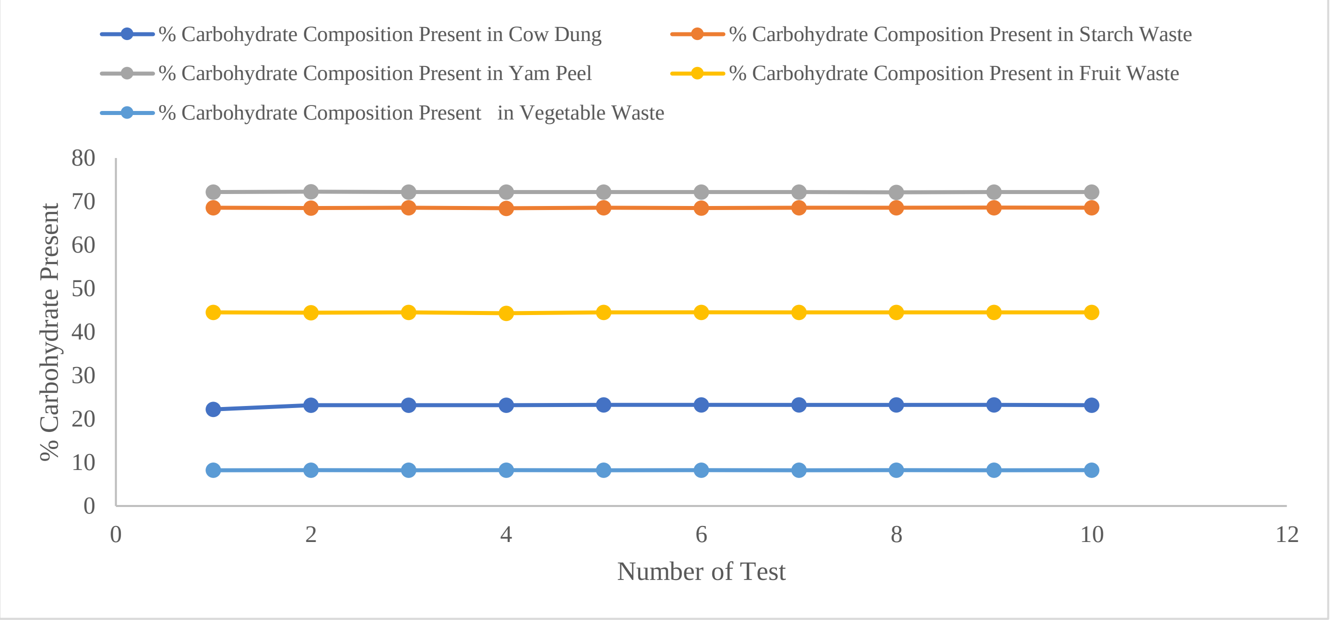

Figure 2. Percentage Composition of Carbohydrate Present in Selected Kitchen Waste and Inoculum

Three samples with varying carbon/nitrogen ratios (C/N) were prepared using the % carbohydrate data. The groups of samples were as follows:

Sample A: Slurry with C/N ratio > 30

Sample B: Slurry with C/N ratio < 30

Sample C: Slurry with C/N ratio $20 \leq C/N \leq 30$

Biogas yield is greatly influenced by the carbon-to-nitrogen (C/N) ratio of kitchen waste; a slurry with a C/N ratio of $20 \leq C/N \leq 30$ yields the most biogas. Additionally, for balanced microbial activity, too low a ratio results in ammonia buildup, which inhibits methanogens and lowers methane production, while too high a ratio produces nitrogen deficiency and low yield [50]. Co-digesting carbon-rich (like paper) and nitrogen-rich (like food scraps) waste helps establish a balanced C/N, which maximizes biogas output by ensuring enough carbon for energy and nitrogen for microbial protein [24].

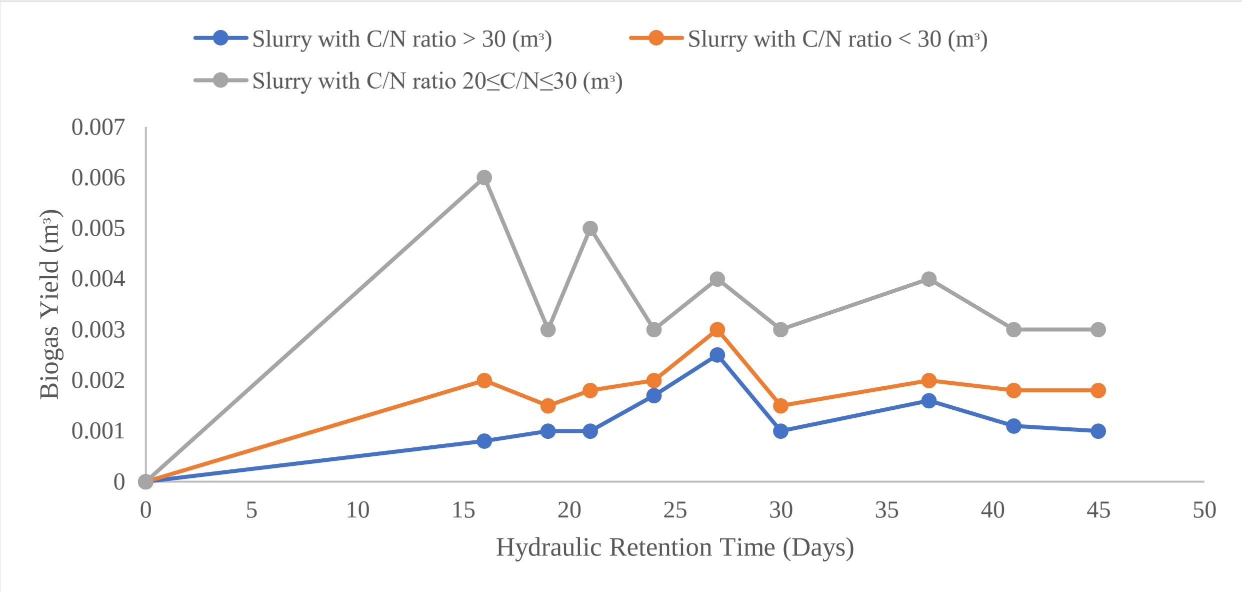

Figure 3. Evaluation of the Effect of Variation of C/N Ratio on Biogas Yield

The pH outcomes of different C/N ratio variations are displayed in Figure 4. A greater pH value within neutrality is found in the slurry with a C/N ratio of 20≤C/N≤30. Kitchen waste's pH has a big impact on the amount of biogas produced; a neutral pH range (about 6.5–7.5) usually encourages the best microbial activity and maximum methane production, while extremely acidic (low pH) or alkaline (high pH) conditions inhibit the methanogens, resulting in lower biogas yields, less degradation, and possibly process failure [76]. Since kitchen waste frequently begins acidic, pH regulation, or buffering, is essential to balance the bacteria that produce methane and acid and guaranteeing effective energy recovery.

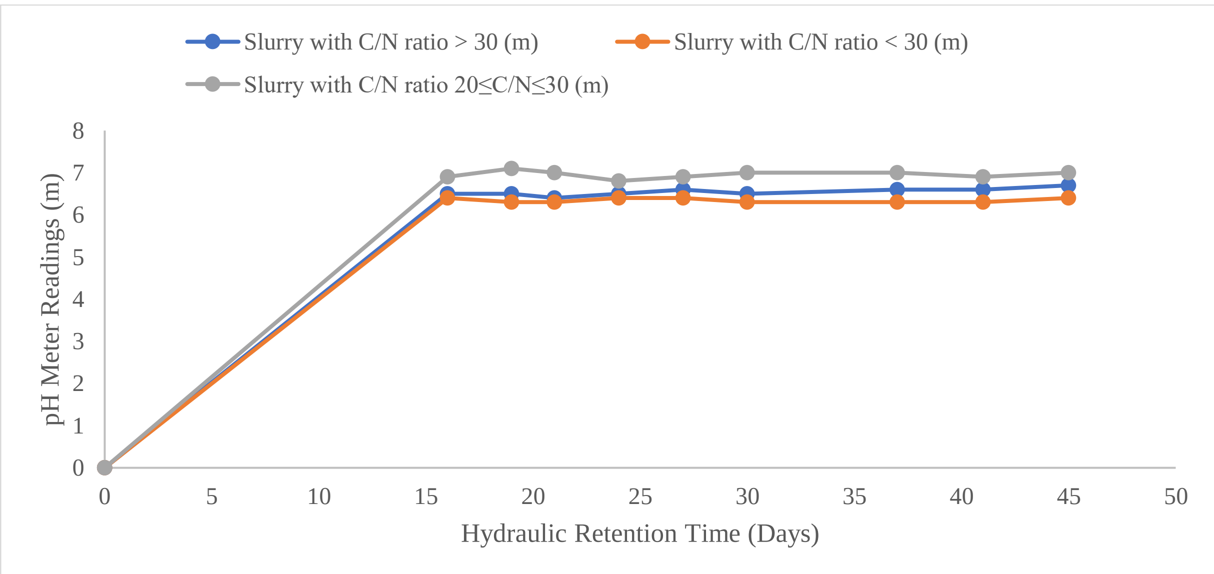

Figure 4. Evaluation of the Effect of Ph

Conclusion

The study found that the stability of the carbon/nitrogen (C/N) ratio and the ensuing biogas yield are strongly influenced by the percentage composition of carbohydrates. When the C/N ratio was kept within an ideal range, usually between 20 and 30, the largest and most consistent biogas generation took place. Nitrogen constraint for microbial growth resulted from feedstocks with an overly high carbohydrate content (and hence a high C/N ratio), slowing down the digestion process and lowering the total biogas yield. Methanogens were inhibited by the unstable circumstance's accumulation caused by acid-forming bacteria's quick consumption of available nitrogen. On the other hand, wastes with high protein/nitrogen ratios (low C/N ratio) and very little carbohydrate content caused ammonia buildup and rapid protein breakdown. This reduced the generation and stability of biogas by raising the digester's pH to inhibitory levels, which are harmful to methanogenic bacteria. Process stability (constant pH) and maximum methane yield were guaranteed by maintaining a balanced carbohydrate-to-nitrogen composition, which is frequently accomplished through co-digestion of several waste kinds.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship and publication of this article.

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