

UNIVERSITY OF BAHRAIN

College of Science



Investigating the Waste-to-Energy Potential of Selected Household Organic Waste

A Thesis Submitted in Partial Fulfilment of the Requirements for the
master's degree in Environment and Sustainable Development

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Abstract

Food waste (FW) is a global issue due to the increasing rates of waste generation and the subsequent economic, social, and environmental consequences it presents. The household sector has been identified as a major contributor to food waste across the food supply chain. Anaerobic digestion (AD) is a promising technique that has the potential to provide a sustainable solution for diverting organic food waste from landfills while generating biofuels that can be used as an energy source. This study investigates the potential for waste-to-energy conversion of household organic waste at the University of Bahrain's campus. The research aims to quantify and characterize household food waste (HFW) and evaluate its potential as a feedstock for anaerobic digestion.

The methodology includes a cross-sectional study design involving food waste sampling and analysis, characterization, and anaerobic digestion operation. The waste collection was done using a direct-measurement approach, collecting food waste from the household's doorstep. Characterization of the food waste was based on the total (TS) and volatile solids (VS) analysis as well as the chemical characteristics of the food waste. Anaerobic digestion was performed in a 10 L lab-scale continuous-stirred tank reactor (CSTR) under mesophilic conditions (37 °C), a mixing speed of 100 rpm, and organic loading rates (OLR) varying from 2 to 4 g VS L⁻¹ d⁻¹. The experiments were conducted for fruit and vegetables waste (FVW) and cooked food waste (CFW) to evaluate their digestion performance and determine the methane potential.

The research findings show that the average food waste generation rate was 3.99 ± 0.54 kg/household/week, of which 63.3% was considered avoidable food waste. Analysis of the quantities and compositions has shown a significant increase in household food waste generation rates and the avoidable food waste composition during Ramadan. The collected food waste had a high organic matter with 94.2% and 95.2% VS for FVW and CFW, which makes it suitable as a feedstock for anaerobic digestion. The methane potential was 370.9 and 380.6 mL/g VS at optimal OLRs of 3 and 4 g VS L⁻¹ d⁻¹ for FVW and CFW, respectively. Overall, cooked food waste had a better digestion performance than fruit and vegetable, indicated by the higher efficiency in VS and COD reduction and the process stability parameters such as pH, intermediate alkalinity to partial alkalinity ratio, and ammonium nitrogen.

The study concludes that household food waste has a high potential for anaerobic digestion and the technology can be applied in Bahrain to reduce greenhouse gas emissions, minimize waste disposal, and generate renewable energy. In addition, the research contributes to the limited literature on household food waste management and anaerobic digestion technology in Bahrain and provides the basis for future research.

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List of Abbreviations

AD – Anaerobic Digestion

BA – Bicarbonate Alkalinity

BMP – Biochemical Methane Potential

C/N – Carbon to Nitrogen ratio

CFW – Cooked Food Waste

CH₄ – Methane

CM – Cow Manure

CO₂ – Carbon Dioxide

COD – Chemical Oxygen Demand

CSTR – Continuous Stirred Tank Reactor

FSC – Food Supply Chain

FVW – Fruit and Vegetable Waste

FW – Food Waste

GCC – Gulf Cooperation Council

GHG – Greenhouse Gas

H₂ – Hydrogen

HFW – Household Food Waste

HRT – Hydraulic Retention Time

IA – Intermediate Alkalinity

KW – Kitchen Waste

LCFA – Long Chain Fatty Acids

LFG – Landfill Gas

MSW – Municipal Solid Waste

NH₃ – Ammonia

NH₄⁺-N – Ammonium Nitrogen

OLR – Organic Loading Rate

PA – Partial Alkalinity

RPM – Rotation Per Minute

TA – Total Alkalinity

TS – Total Solids

UASB - Up flow Anaerobic Sludge Blanket

UNEP – United Nations Environment Programme

USD – United States Dollar

VFA – Volatile Fatty Acids

VFW – Vegetable Food Waste

VS – Volatile Solids

VS_r – Volatile Solids Reduction

WCA – Waste Composition Analysis

WtE – Waste to Energy

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Chapter One

Introduction to the Study

- 1.1 Introduction
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- 1.5 Research Significance
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- 1.7 Definition of Terms

1.1 Introduction

The amount of waste generated by households has increased significantly due to rapid population growth, a rise in living standards, and current trends in the economic system of production and consumption (Laurent et al., 2014). Organic waste, particularly food waste (FW), represents a significant portion of the waste produced by households. Food waste is the unnecessary disposal or non-alternative use of food that is still suitable for human consumption (FAO, 2014). In 2019, an estimated 931 million tons of food waste were generated worldwide, with 61% originating from households (Forbes et al., 2021). Bahrain's decision-makers face a critical challenge regarding household waste management and curbing its adverse impacts.

Food waste significantly pressures waste management facilities, both logistically and financially. Bahrain's only site for municipal solid waste disposal, the Askar landfill, is currently reaching its full limit due to incoming household food waste, accounting for 50% of the waste disposed at the landfill (Blanchard et al., 2019). The decomposition of food waste at landfill sites is a major source of greenhouse gas emissions, notably methane, and carbon dioxide pollution, contributing to climate change and causing public health concerns due to air pollution (Papargyropoulou et al., 2014). In 2020, Askar landfill's annual carbon footprint emissions were estimated to be around 371,089 tons of CO₂ equivalence (Coskuner et al., 2020). Given the rapidly increasing population, scarcity of disposal sites, and growing public concerns regarding environmental degradation, developing effective methods for processing household organic waste should be a high priority.

Waste-to-energy (WtE) technologies, such as pyrolysis, gasification, fermentation, and anaerobic digestion (AD), are effective in the reduction and stabilization of household food waste (HFW), while enabling energy recovery and generating value-added products (Fernández-González et al., 2017). Anaerobic digestion is considered a more sustainable approach for treating food waste than traditional disposal methods (Zhang et al., 2020). The process involves the biological breakdown of organic matter through a consortium of microorganisms in the absence of oxygen to produce biogas, a mixture consisting of 60-70% methane (CH_4) and 30-40% carbon dioxide (CO_2) (Xu et al., 2018). Upon removal of CO_2 and other impurities, biomethane is derived from the process and can be utilized for numerous applications as a renewable energy source, offering a sustainable alternative to fossil fuels (Kannah et al., 2020). Moreover, a nutrient-rich digestate is a by-product of AD and can be used as a biofertilizer and soil amendment to help reduce land degradation (O'Connor et al., 2020).

While anaerobic digestion is an established and commonly used technology for treating organic waste, it faces political, economic, and managerial obstacles that must be addressed to be widely implemented in Bahrain (Abbas et al., 2021a). From a technological perspective, AD is a complex process that requires efficient control of factors such as process configuration, operational conditions, and inhibition parameters. Furthermore, the diverse nature of food waste influences process efficiency due to characteristics such as nutrient content, volatile solids, moisture, pH, and particle size (Negri et al., 2020). These factors impact biomethane yield; therefore, it is essential to quantify the potential of applying AD technology for treating food waste in Bahrain.

1.2 Research Problem

Food waste generation in Bahrain is increasing at an alarming rate, posing severe environmental and socioeconomic threats. A large fraction of solid waste disposed at Askar landfill is attributed to food waste from households. Anaerobic digestion technology has the potential to provide a sustainable solution for diverting organic food waste from landfills while generating biofuels that can be used as an energy source. However, this technology has yet to be practically investigated in Bahrain. Technology implementation requires quantification and characterization of food waste to assess its potential. In addition, monitoring of process variables is necessary to ensure process stability and enhance its performance.

1.3 Research Questions

- What are the quantities and compositions of food waste produced by households at the University of Bahrain?
- What are the physicochemical characteristics of household food waste on campus and its potential as a feedstock for anaerobic digestion?
- How does the organic loading rate influence the digestion performance of each type of food waste?

1.4 Research Objectives

The primary aim of this research is to evaluate the feasibility of converting household food waste produced at the University of Bahrain into energy. The research aims to achieve the following objectives:

- To determine the quantities and compositions of the food waste generated from households on campus.

- To analyze the physicochemical characteristics of household food waste produced on campus to assess its potential as a feedstock for anaerobic digestion.
- To evaluate the digestion performance of each type of food waste and determine the optimal organic loading rate.

1.5 Research Significance

Food waste is one of the primary types of waste produced at the University of Bahrain's campuses, and like other waste, it is disposed of in landfills. Implementing effective resource management and waste reduction strategies can contribute to sustainability efforts and raise awareness. Universities are home to individuals with lots of experience and expertise, which enables them to initiate change in their environment easily. Moreover, university campuses are convenient for waste collection and management, as waste is generated in a few centralized locations.

This research provides insight into the quantities and types of food waste produced at the university, primarily from households. It also investigates the application of anaerobic digestion (AD) to convert food waste into biogas. This approach helps the university dispose of waste more effectively and produce clean energy, which reduces greenhouse gas emissions. In addition, implementing anaerobic digestion technology on campus can further reduce the need for waste transportation, thereby reducing fuel consumption and associated emissions. The results of this study could have implications for future research on the technical feasibility of the technology for food waste treatment in Bahrain.

1.6 The Study's Setting

This research focuses on the main campus of the University of Bahrain, located in Sakhir (**Fig.1**) and covering an area of 0.1 square kilometers. The campus contains eight colleges, academic and administrative buildings, research centers, libraries, food courts, and recreational facilities. In addition, a housing zone includes 62 staff housing units and some student apartment buildings. The staff housing consists of two-story houses suitable for up to 7 people. Household waste is collected in large garbage bins provided for each house and then taken to the landfill by municipality trucks. This study focuses solely on organic waste from staff housing.

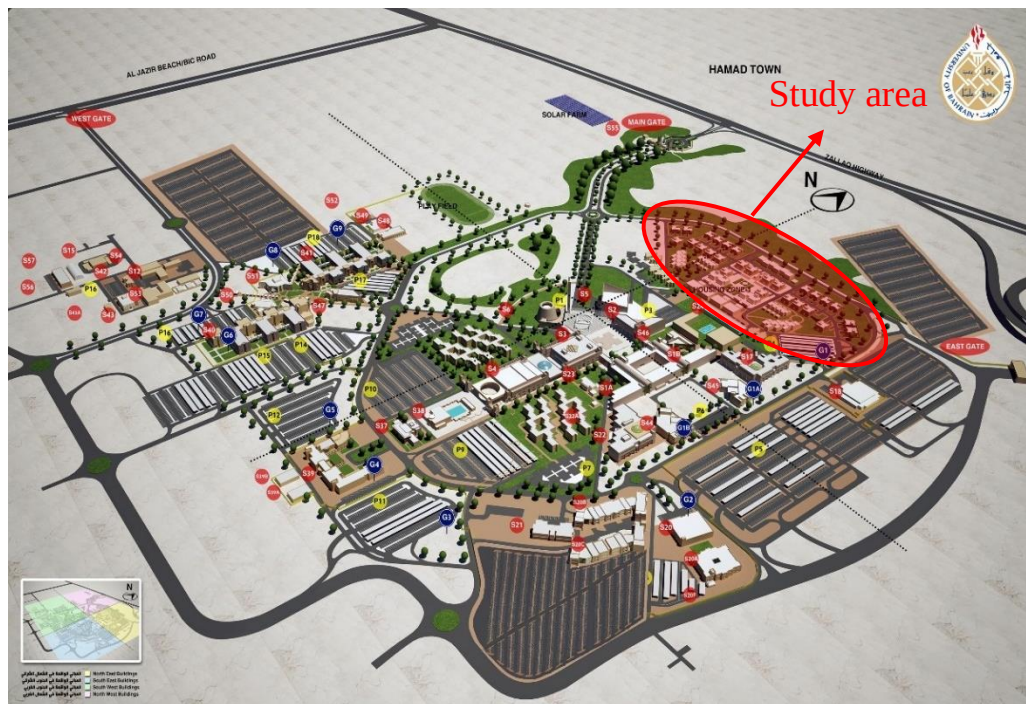


Fig. 1: The University of Bahrain Sakhir campus map and the study area

1.7 Definition of Terms

Anaerobic digestion: Anaerobic digestion (AD) is a biological process in which microorganisms break down organic matter in the absence of oxygen, producing biogas and a nutrient-rich residue called digestate. This process can be used to treat various types of organic waste, such as food waste, animal manure, and wastewater sludge (Xu and Li, 2017)

Avoidable food waste: Avoidable food waste refers to food that humans could have consumed if it had been handled differently, such as through better storage, preparation, or distribution practices (Quested and Jonson, 2009).

Chemical oxygen demand: Chemical oxygen demand (COD) measures the amount of oxygen required to oxidize the organic matter in a sample. This parameter is commonly used in analyzing wastewater and organic waste, as it estimates the sample's organic content and biodegradability (Harnadek et al., 2015).

Food waste: Food waste (FW) refers to any edible food discarded, lost, or uneaten, whether at the household, retail, or industrial level. This can include food that is spoiled or expired and wasted due to overproduction, aesthetic imperfections, or consumer behavior (FAO, 2014).

Hydraulic retention time: Hydraulic retention time (HRT) refers to the time that wastewater or other liquid waste remains in a treatment system, typically measured in days (Gerardi, 2003).

Organic loading rate: Organic loading rate (OLR) refers to the amount of organic matter that is added per unit volume of a treatment system per unit

time ($\text{g VS L}^{-1} \text{ d}^{-1}$), typically measured in terms of volatile solids (VS) or chemical oxygen demand (COD). This parameter is used to evaluate the capacity and performance of anaerobic digestion and other biological treatment processes (Nagao et al., 2012)

Unavoidable food waste: Unavoidable food waste is a byproduct of food preparation and includes the inedible parts of food such as fruit and vegetable peels, bones, shells, and coffee grounds (WRAP, 2009).

Volatile solids reduction: Volatile solids reduction (VS_r) refers to reducing the amount of organic matter in a waste stream through biological or thermal treatment. This can be measured as the percentage of volatile solids that are removed from the waste (Koch et al., 2009)

Volatile solids: Volatile solids refer to the portion of organic matter in a sample that is lost when heated at a specific temperature. This measurement is commonly used in the analysis of organic waste, as it estimates the waste's biodegradable fraction (Nagao et al., 2012).

Waste-to-energy: Waste-to-energy refers to the method of converting waste materials, such as municipal solid waste or biomass, into energy. This can be done through various methods, such as incineration, gasification, or pyrolysis (Sun et al., 2020).

Chapter Two

Theoretical Framework and Literature Review

2.1 Literature Review

2.2 Theoretical Framework

2.3 Research Hypothesis

2.1 Literature Review

Household food waste (HFW) has gained attention recently due to studies showing that large amounts of food waste are produced (Gustavsson et al., 2011). In addition, food waste has been identified as a valuable feedstock for waste-to-energy (WtE) due to its high organic content and biodegradability (Pfaltzgraff et al., 2013). As a result, many researchers in developed countries have attempted to quantify the energy potential of this organic material. However, research on household food waste management in the Middle East region is limited. The literature gap is particularly evident in the GCC countries including Bahrain, where household food waste is a significant challenge due to the high levels of consumption and waste. There is a lack of data on the amount and types of food waste generated in this region. With accurate data, it is easier to develop effective strategies and policies to address the issue of food waste.

This literature review aims to provide an understanding of the current state of food waste management and to identify potential areas for improvement in Bahrain and the GCC region. It provides an overview of household food waste generation status, including a comprehensive analysis of the methods and data collection in household food waste quantification studies. The review also focuses on food waste management in Bahrain and includes an analysis of various waste-to-energy technologies, with an emphasis on anaerobic digestion and its process parameters, as well as the potential for implementation of anaerobic digestion in the country.

2.1.1 Current status of household food waste

In developed countries, consumers are responsible for generating most of the food waste. In the EU, household food waste (HFW) accounts for about 53% of the total food waste generated in the entire food chain, equivalent to 92 kg/capita/year (Stenmarck et al., 2016). Similarly, the consumption stage has been identified as the most significant contributor to food waste in GCC countries. According to Baig et al. (2019a), most food waste generated in Saudi Arabia could be attributed to post-consumption including restaurants, cafeterias, and households. The latest Food Waste Index report by the United Nations Environmental Programme (UNEP) estimated 132 kg/capita/year of HFW in Bahrain; 105 kg/capita/year in Saudi Arabia; and 95 kg/capita/year for Kuwait, Oman, Qatar, and UAE (Forbes et al., 2021). Although these estimates indicate substantial household food waste in Bahrain and other GCC countries, the figures reported are primarily derived from computations utilizing the waste databases of the member nations.

Over the past decade, research in this area has increased, with more comprehensive studies on household food waste published in developed countries with often inconsistent results (Kazsa et al., 2020). Most research in this field has been conducted in Northern and Western Europe particularly in countries such as Denmark (Edjabou et al., 2016), Hungary (Kazsa et al., 2020), Italy (Aureli et al., 2021), Norway (Hanssen et al., 2016), Sweden (Williams et al., 2012; Bernstad and Andersson, 2015) and the UK (Quested et al., 2013; Graham-Rowe et al., 2015). However, there are also some examples of research in this area outside of Europe, such as in the United States (Buzby and Hyman, 2012), China (Zhang et al., 2018), and Canada (Parizeau et al., 2015). **Table 1** summarizes household food waste figures

from previous studies in kilograms per household per week (kg/hh/w) and the methods used. Reported HFW quantities varied from 1.7 to 5.0 kg/hh/week. This variation could be due to the lack of consistency in the methodological approach utilized in these studies.

Comprehensive analysis of HFW in the Middle East, particularly GCC countries, has often been lacking. However, an unpublished report was conducted by WRAP in 2016, comprising a waste composition analysis (WCA) on 100 households to estimate household food waste in Jeddah, Saudi Arabia (Quested et al., 2020). The study reported 5.28 kg/hh/week of food waste, of which 4.16 kg/hh/week was avoidable food waste (78%). Abdelaal et al. (2019) conducted on-site measurements of food waste generated from food outlets and student housing complexes at a university campus in Qatar. The study found that 64 % of food waste generated daily was avoidable. The distinction between avoidable and unavoidable food waste has been employed in most studies. Other regions reported avoidable food waste proportions between 35 and 58.8% (Bernstad and Andersson, 2015; Hanssen et al., 2016). GCC countries' cultural and religious context plays a role in the quantities and compositions of HFW produced (Baig et al., 2019a). According to the latest UNEP report, Bahrain ranks among the top 10 food waste producers (Forbes et al., 2021). However, there is a lack of detailed and reliable data on the quantities and compositions of food waste produced at the household level. Therefore, the adoption of appropriate methods could provide a more accurate account of the extent of household food waste in the country.

Table (1): Summary of household food waste quantification studies

Reference	Country	Sample size	FW (kg/hh/w)	Method
Williams et al. (2012)	Sweden	61	1.7	Kitchen diary. Households measured the weight of FW of seven food categories.
Buzby and Hyman (2012)	USA	-	2.1 /capita	Secondary data: aggregated values for the total food loss in the US were generated using USDA data.
Quested et al. (2013)	UK	-	2.69	Direct measurement through a WCA of household residual waste streams and kitchen diary .
Bernstad and Andersson (2015)	Sweden	486	2.50	Direct measurement. Waste composition analysis of source-separated organics and 50% of residual bins.
Hanssen et al. (2016)	Norway	220	3.76	Direct measurement: waste collected by municipality from each household was weighed and analyzed.
Visschers et al. (2016)	Switzerland	796	5.33 portions	Survey: self-reported amounts of FW as food portions were assessed for 11 food groups.
Zhang et al. (2018)	China	418	-	Survey: self-reported amounts and types of FW along with mathematical models to estimate avoidable FW.
Sosna et al. (2019)	Czech Republic	9	3.56	Direct measurement: waste collected by municipality was sampled separately for each household.
Kazsa et al. (2020)	Hungary	165	3.22	FW diary: measurement of FW using kitchen scales and recording the type of food in a diary.
Quested et al. (2020)	Saudi Arabia	100	5.28	Direct measurement: waste composition analysis of residual household waste combined with observations and informal and semi-standardized interviews .
Ilakovac et al. (2020)	Croatia	115	3.64	FW diary: self-reported amounts of FW over a week of 12 different food categories.
Aureli et al. (2021)	Italy	1142	2.86	Survey: Self-reported quantities of FW with emphasis on the level of waste during the study.

2.1.2 Methods in household food waste studies

The methods adopted in previous studies (**Table 1**) can be categorized into three major categories: (i) mass balances and estimations based on secondary data; (ii) self-reporting methods, including surveys, kitchen diaries, and interviews; and (iii) physical waste surveys (direct measurement) (Quested et al., 2011). For example, one approach described in the food waste literature involves utilizing secondary data from previous FW studies at the household level, in conjunction with consumption or national/regional FW estimates, to derive FW estimates at the household level. In addition, many studies typically use estimates from global, federal, or national databases and combine them with previously published studies from the same or similar regions, along with modeling techniques, to address various research questions (Monier et al., 2010; Buzby and Hyman, 2012). These may include determining the extent of the food waste problem, analyzing the reason behind its occurrence, and determining the calorific household food waste (e.g., Beretta et al., 2013); identifying regional differences in avoidable and unavoidable food waste to target interventions, and conducting scenario modeling for future reductions in avoidable food waste (e.g., De Laurentiis et al., 2018).

Although secondary data allows access to large amounts of data in the absence of primary data and is considered an effective method in terms of cost and time, there is uncertainty due to limitations in the underlying published studies (Buzby and Hyman, 2012). In addition, this method has a limitation because it relies on assumptions and approximations instead of precise measurements, resulting in estimates with increased levels of error. Furthermore, accumulating results from various studies that apply different

data collection and analysis approaches reduces the comparability between food waste quantification studies using this method (Xue et al., 2017).

Self-reporting methods like surveys, food waste diaries, and interviews have been implemented in numerous studies as a suitable and inexpensive method for generating data about food waste quantities (Moller et al., 2014). Surveys are a commonly used method in household quantification studies, providing a cost-effective and efficient way to collect data from a large sample of households (Xue et al., 2017). This approach can be advantageous when there is no direct access to discarded food waste. Measures of food waste typically include absolute or frequency measurements, indicating how often food is wasted (Parizeau et al., 2015; Visschers et al., 2016). An alternative way of measuring food waste is through proportional or relative measures, where survey participants indicate the percentage or proportion of food items brought into the household that is not consumed and went to waste (Graham-Rowe et al., 2015; Secondi et al., 2015).

Surveys have the advantage of collecting demographic information about participants, which allows for investigating correlations between waste generation and factors such as income, age, and family size (Graham-Rowe et al., 2015). For example, Zhang et al. (2018) estimated avoidable household food waste quantities and found a positive correlation between household size and income with the total quantity of avoidable food waste generated. Moreover, it was used to determine the composition of 11 different food groups, along with the assessment of intentions to avoid food waste, attitudes, and behavioral norms in a study by Visschers et al. (2016). However, surveys often require a good sample design and large sample sizes. Moreover, they rely on the assumption that respondents can accurately recall waste events and

assess the amount of food wasted, leading to underreporting of food waste amounts (Aureli et al., 2021).

Food waste is often estimated using diaries where participants report the quantity and category of food they discard over a few days. Food waste diaries differ from surveys in that they document the amount of food waste as it occurs, typically over a more extended period (Quested et al., 2011). Williams et al. (2012) used a food waste diary that involved self-measurement of food waste by the households and a record of the main reasons for wasting food. The study found that packaging was a significant contributor to household food waste, with consumers often discarding food due to concerns about food safety or freshness. The use of diaries offers a significant advantage over surveys in terms of accuracy as FW is recorded at the time of disposal, eliminating the possibility of unintentionally incorrect estimations due to recall. However, Quested et al. (2020) reported a degree of underestimation between 7% and 40% in comparison to waste composition analyses. Using a kitchen diary could increase awareness and alter participants' behavior during the study period. This could lead to a reduction in food waste, which limits the ability to acquire data on the usual quantities wasted, thereby affecting the accuracy of the results (Langley et al., 2010). According to a study by Leverenz et al. (2019), the participant's behavior related to food purchase and waste production improved significantly by using a kitchen diary, leading to more than a 50% reduction in avoidable food waste.

Interviews are a less commonly used method in household food waste composition studies than other self-reporting methods. Interviews provide researchers with the opportunity to gather detailed information about households, including their income, expenditure, and consumption patterns

(Sosna et al., 2019). Glanz et al. (2008) conducted face-to-face interviews supported by a quantitative analysis of expired products found in households. The findings were presented as a total mass of the expired products from households. The high cost of conducting interviews usually dictates a small sample size, which limits the effectiveness of interviews as a method, as a larger sample size may provide more accurate and diverse data (Moller et al., 2014). Interviews tend to be more helpful in understanding households' social and economic dynamics by exploring their values, beliefs, and attitudes toward various issues (Evans, 2011). However, the quality of the data collected through interviews is subject to biases encountered in other self-reporting methods and can be compromised if the interviewer is biased or has preconceived notions about the subject being studied (Moller et al., 2014).

Although self-reported methods may underestimate food waste, they are still helpful in collecting information about the quantities of food waste in households, mainly when frequency measures are employed (Ilakovac et al., 2020). However, these methods are subject to social desirability bias, where people tend to respond or behave in a way that believe is socially desirable rather than giving a true can of events (Xue et al., 2017). A direct comparison between self-reporting methods and national waste composition reports has shown a tenfold discrepancy between both results (Delley and Brunner, 2018). This highlights the need for more objective methods to quantify food waste in households. One way to calculate the amount of food waste objectively and accurately is through direct measurement, also known as a physical waste survey. This involves directly collecting and categorizing various waste fractions and components and measuring their weight, as described by Langley et al. (2010). This method is more reliable and unbiased than methods

like kitchen diaries or questionnaires, which rely on self-reported data and can be time-consuming for participants. In addition, physical waste surveys can be conducted by a third party, making them more objective and accurate (Sahimaa et al., 2015).

Studies based on physical waste surveys can vary significantly based on factors such as the sample size, sampling duration, collection method, and sample type (Sahimaa et al., 2015). The most common process involves the curbside collection of samples from households' residual waste bins on municipal collection days (Quested et al., 2013). This method is not biased and does not alter the behavior of participating households if they were not informed about the study objectives prior to sampling (Lebersorger and Schneider, 2011; Hanssen et al., 2016). In a study conducted by Bernstad and Andersson (2015), a collection scheme that separates organic waste was available in the study area, which further simplified the process by reducing the effort required to separate it from other waste. However, due to the shared waste collection system, Edjabou et al. (2016) encountered a challenge when sampling multi-apartment buildings. Consequently, the waste from each area is treated as a single sample, resulting in one dataset per multi-family dwelling area. Moreover, this method cannot capture discarded food waste through means other than the garbage bin such as kitchen sinks, composting, pet food, etc. (Parizeau et al., 2015). Elimelech et al. (2018) introduced a more comprehensive approach that involved providing households with separate bags or kitchen caddies to dispose of food waste. In this method, individuals were directed to dispose of all their food waste in the caddies to prevent disposal through other means. In addition, it addresses the problems associated with analyzing food waste in multi-family buildings and can be

carried out with a relatively high level of accuracy (Elimelech et al., 2018). This requires minimal effort on the respondents' behalf, although researchers may need to put significant effort into visiting households (Van Herpen et al., 2019). This method was the most suitable for the current study because it captures food waste as it enters the stream, providing accurate measurements. In addition, the effort required for visiting households is minimized due to the distribution of the households on campus (**Fig. 1**).

Some studies have reported sorting samples within a week of the sampling day, but this interval can cause severe difficulties in the sorting process and the accuracy of waste component identification and separation due to sample degradation, particularly in hot weather countries (Parizeau et al., 2015; Hanssen et al., 2016; Edjabou et al., 2016). Collecting samples daily or every two days improves sample accuracy and reduces waste sample size (Lebersorger and Schneider, 2011; Van Herpen et al., 2019). Sorting waste within the same day of collection eliminates uncertainties about the waste items and ensures the physical and chemical properties of the sample are accurate (Elimelech et al., 2018). The method adopted in this study minimizes samples' degradation, given Bahrain's hot weather conditions.

2.1.3 Household food waste management

There is a growing concern among Gulf Cooperation Council (GCC) countries, including the Kingdom of Saudi Arabia, United Arab Emirates, Oman, Kuwait, Qatar, and Bahrain, concerning organic waste management. This is mainly due to the high levels of food consumption and wasteful habits of consumers in the region (Abiad and Meho, 2018). Bahrain is not exempt from these challenges and has been experiencing rapid economic

development, persistent high population growth rates, and changes in consumer lifestyles that have led to an increase in waste generation (Al-Joburi, 2018).

Investigations of the municipal solid waste (MSW) system in Bahrain show the waste collection services' reliability in terms of frequency of collections and coverage of different governorates (Al Ansari, 2012). However, several inadequacies of the current system reduce its overall capability to achieve the standards of a good and efficient waste management system. For example, it is estimated that the recycling rate of domestic waste amounts to only 8%, highlighting the underdevelopment of materials recovery as part of the waste management system in Bahrain (Al Sabbagh et al., 2012). Similarly, resource recovery and recycling in neighboring GCC countries are still at an early stage, with countries like Saudi Arabia, Qatar, and Oman having recycling rates of 10-15%, 10-15%, and 10%, respectively, most of which are carried out by the informal sector (Zafar, 2018).

Regarding disposal options, Bahrain's reliance on Askar municipal as its only waste disposal method creates many environmental and socio-economic impacts (Jassim et al., 2019). This method of waste disposal causes numerous ecological issues, including foul odors and contamination of water, soil, and air, all of which threaten food safety and human health (Cheng and Hu, 2010). Moreover, the uncontrolled disposal of organic food waste results in the release of greenhouse gases and landfill leachate due to its high moisture content and biodegradability (Ji et al., 2017). The organic fraction (mainly FW) comprises 59.6% of domestic waste in Bahrain (Al Sabbagh et al., 2012). Coskuner et al. (2020) estimated methane (CH₄) and carbon dioxide emissions (CO₂) from Askar landfill at 8840 and 24280 Mg/year in 2020. The study

showed that over a period of 32 years, there was a 110-fold increase in carbon footprint from 3375 to 371,089 tons CO_{2, eq} in 2020, which reflects a significant annual growth rate in solid waste generation. With the landfill reaching its full capacity, implementing effective waste reduction strategies is a crucial task, considering the growing population, developmental activities, and economic growth.

2.1.3.1 Reduction and prevention strategies

The primary approach to tackling food waste is reducing its generation, which is challenging even in long-term predictions. Studies have found that the amount and economic value of global food waste will increase in the coming decades (Melikoglu et al., 2013). Although various design interventions are suggested in the literature and available in the market to address the material and non-material factors that drive food waste, their actual or potential impact on food waste levels is not yet fully understood (Hebrok and Boks, 2017).

Household food waste is a complex issue influenced by various behaviors related to planning, shopping, storage, food preparation and consumption, as well as by leftover handling methods (Quested et al., 2013). In addition, multiple factors, such as demographic, socioeconomic, cultural, and contextual factors, can impact food waste (Secondi et al., 2015). Aktas et al. (2018) conducted a study in Qatar and found that several contextual factors, including financial attitudes, planning routines, social relationships, motives, and food surplus, significantly correlate with food waste. The research indicates that changes in eating habits during specific periods, such as Ramadan, and other cultural events, can significantly impact food waste

quantities. Similarly, cultural practices were found to have an impact on food waste habits among the Saudi population according to Baig et al. (2019b). Generosity and hospitality are highly valued and hosts often provide more food than necessary for their guests, even if they have limited resources. This leads to a significant amount of food waste, especially during events like Eid festivals, weddings, and parties, where lavish banquets with large amounts of food varieties are common (Baig et al., 2019a).

Interventions suggested in the literature for reducing food waste in the GCC have mainly focused on increasing awareness to alter consumer behaviors toward reducing food waste in households (Abiad and Meho, 2018; Aktas et al., 2018; Ben Hassen et al., 2020). However, the behaviors that lead to food waste are deeply entrenched in the cultural traditions and daily routines of populations in this region and cannot be easily changed through education or information campaigns alone. Alternative food waste management strategies, such as food bank initiatives, have been increasingly successful in FW source reduction in Saudi Arabia and Bahrain through food redistribution (Baig et al., 2019b). A study by Abbas (2021b) in Bahrain found that the public have shown a willingness to participate in waste management efforts. However, more collaboration is needed from stakeholders, and proactive policies and support from the government are crucial for the continued success of these initiatives. Although food reduction/prevention strategies can potentially reduce household food waste at its source, a fraction of food is inevitably wasted (Parizeau et al., 2015). Therefore, it is necessary to find sustainable methods to recycle or repurpose food waste as raw materials for different processes is another attractive proposal that has received much attention in recent years.

2.1.3.2 Energy recovery from household food waste

Food waste is an underutilized resource with potential to produce energy. As a result, researchers have been exploring technologies to extract valuable fuels from food waste to alleviate the environmental impact of its disposal, reduce the depletion of natural resources, minimize health risks, and maintain ecological balance (Pham et al., 2015). Waste-to-Energy (WtE) technologies have been developed for exploiting the energy content of food waste and recovering it in the form of heat, electricity, or fuel (Fernández-González et al., 2017). These methods have the potential to divert waste from landfills and replace fossil fuels because they are environmentally sustainable and renewable. WtE technologies (**Fig. 2**) can be broadly classified into thermochemical technologies (such as incineration, pyrolysis, and gasification) and biochemical technologies (such as composting, anaerobic digestion, fermentation, and landfill gas capture) (Ma and Liu, 2019). A study by Al Sabbagh (2019) evaluated the impact of waste-to-energy (WtE) technologies on climate change mitigation in Bahrain using a multicriteria (MCA) analysis based on environmental, economic, and social dimensions. The results indicated that utilizing these technologies can aid in achieving renewable energy targets, reducing carbon dioxide emissions, and minimizing the land area required for landfills in Bahrain.

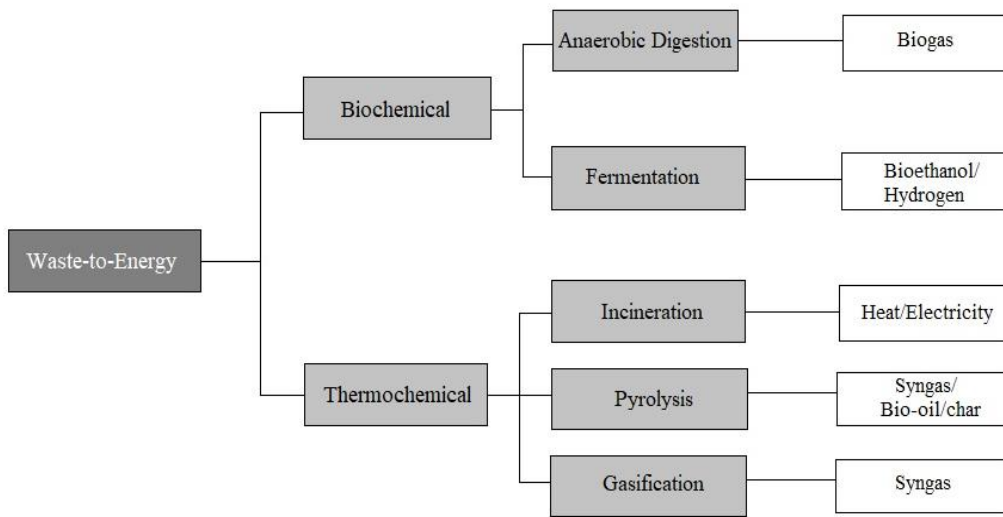


Fig. 2: Summary of waste-to-energy technologies

Thermochemical technologies have emerged as a promising method for converting food waste into energy. Incineration is a well-established technique that has been used for numerous years, which involves burning waste materials to transform them into energy and heat (Melikoglu, 2020). The energy generated by the combustion process can be used to operate steam turbines for electricity generation or to warm process streams in industrial heat exchangers. When used to dispose of solid waste, it can reduce the volume of waste by 80-85% (Pham et al., 2015). Incineration had the highest potential for generating electricity in Bahrain, estimated at around 1120 MWh/day (Al Sabbagh, 2019). However, food waste combustion has been found to have lower efficiency in terms of energy recovery and is associated with toxic air emissions such as particulate matter (PM_{2.5}), nitrogen oxides (NO_x), sulfur oxides (SO_x), volatile organic compounds (VOCs) and heavy metals (Zhang et al., 2020). These emissions contribute to numerous human health issues such as respiratory diseases, cardiovascular problems, neurological disorders, and can potentially lead to cancer.

Food waste can be used as a feedstock for gasification and pyrolysis due to its high energy content. These processes are considered cleaner than incineration and have gained interest as their products are recyclable and have many industrial applications (Igalavithana et al., 2020). Gasification of food waste can result in the production of combustible gas mixture consisting primarily of hydrogen with lower greenhouse gas emissions (Wang et al., 2020). The resulting gas can be used as fuel for gas engines and gas turbines or burned directly. Moreover, the product gas can be utilized as a feedstock (syngas) to produce chemicals such as methanol (Sridhar et al., 2021). Pyrolysis is a process that transforms food waste into bio-oil, biochar, and syngas. This process is carried out in an oxygen-free environment and at temperatures ranging from around 400 °C to 1000 °C (Yang et al., 2019). Elkhailifa et al. (2019) investigated the pyrolysis of five types of FW in the context of Qatar and achieved a maximum biochar yield 41.8% using optimized food waste blends. The study suggested that the produced biochar can be utilized in carbon sequestration when applied as soil amendment and can also serve as a precursor for higher value-added products, such as adsorbents. Both gasification and pyrolysis processes present a great opportunity for food waste thermal treatment, with the specific goal of power generation (O'Connor et al., 2020). However, when it comes to reducing greenhouse gas emissions, thermochemical conversion of food waste may not be the optimal choice (Melikoglu, 2020). Moreover, these technologies demand a significant amount of energy for drying biomass with high water content, such as food waste, and for separating the generated gases (Chen et al., 2020).

Biomass biochemical conversion technologies involve the use of bacteria and other microorganisms to break down biomass into biofuel. These processes are carried out at low temperatures and are characterized by a high selectivity of the generated products (Chen and Wang, 2017). However, they are characterized by high process complexity and usually necessitate unique pre-treatment methods for individual substrates to ensure effective microbial growth and optimize product yield (Pandey, 2015). Anaerobic digestion and fermentation are common biochemical technologies used to convert waste. Landfill gas (LFG) capture is another method that utilizes biochemical reactions to produce landfill gas from waste materials within a landfill gas system (Behera et al., 2010). LFG has been quantified in Bahrain and its capture using LFG-to-energy technologies has the potential to generate 57.4 GWh of electricity and achieve massive carbon footprint reductions (Coskuner et al., 2020).

Fermentation of food waste to create value-added products is a recently popular area of research. This process can produce a wide variety of bio-products by carefully selecting the appropriate microorganism and type of food waste (Melikoglu, 2020). It is frequently employed to transform sugar into bioethanol following biomass pretreatment and hydrolysis procedures. For instance, 58 g/L of bioethanol was produced from food waste, but it was necessary to dispose of approximately 30-40% of solid residue left over after the fermentation process (Kiran and Liu, 2015). Recently, Ma et al. (2017) introduced an innovative method for bioethanol production from food waste by using hydrolytic enzymes that are produced in situ. The new approach resulted in a greater concentration of bioethanol (71.8 g/L) and a substantial reduction in the total volume of food waste by approximately 90%.

Biohydrogen is another type of bioenergy that can be produced through dark fermentation by using food waste as a feedstock. Hydrogen is widely considered a clean and promising fuel source for the future. It can be used as compressed gas and has a high energy yield of 142.35 kJ/g (Kiran et al., 2014). Antonopoulou et al. (2020) found that adding cellulolytic enzymes to dried household food waste resulted in a maximum biohydrogen yield of 210.44 L/kg total solid.

Anaerobic digestion (AD) is a highly viable method for addressing issues such as waste management and climate change. Anaerobic digestion is a process that breaks down organic waste materials into biogas and digestate through a series of biological reactions (O'Connor et al., 2020). Food waste is an ideal substrate for anaerobic digesters due to its high biodegradability and methane yield. Moreover, nutrient-rich digestate is generated that can be utilized as a fertilizer or a soil amendment (Qi et al., 2018). Sowunmi et al. (2016) investigated the biomethane potential (BMP) of food waste among 8 other biomasses in the UAE. The highest methane yield was achieved from the digestion of food waste (517.36 mL CH₄/g VS). In addition, the estimated total biomethane potential could contribute to 6% of domestic energy requirements. Similarly, anaerobic digestion was found to be the most suitable WtE technology in Saudi Arabia, with an energy generation capacity of 86,000 kWh and a gross benefit of \$1.5 billion annually from direct savings and revenue (Baig et al., 2019b). In Bahrain, Abbas (2020) estimated that AD technology can reduce landfill methane emissions by 535,251 tons of CO₂ equivalent annually by diverting biodegradable waste away from the landfill. However, no studies have been found in the literature regarding the practical application of the AD technology in Bahrain to test its feasibility in food waste

treatment. Therefore, this study evaluates the potential of food waste treatment through anaerobic digestion in a local context.

2.1.4 Anaerobic Digestion

The anaerobic digestion (AD) process involves the breakdown of organic material in the absence of oxygen, resulting in biogas production (Banks et al., 2008). Biogas is a renewable gas that consists primarily of methane (55–65%) and carbon dioxide (30–45%) and trace amounts of hydrogen sulfide, ammonia, hydrogen, and oxygen (Chen et al., 2008). Anaerobic digestion is a complex biochemical reaction (**Fig. 3**) that includes four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis facilitated by a distinctive group of microorganisms (Zhang et al., 2014). These microorganism groups are classified into two domains: bacteria (which include hydrolyzers, acidogens, and acetogens) and archaea (which include methanogens).

Hydrolysis is the rate-limiting step in anaerobic digestion. It involves breaking down complex organic compounds, such as carbohydrates, lipids, and proteins, into simpler, soluble molecules, such as glucose, amino acids, and fatty acids. This process is facilitated by enzymes produced by hydrolytic bacteria (Leung and Wang, 2016). Hydrolytic bacteria, which play a crucial role in breaking down complex organic matter, can be found across various phyla including Chloroflexi, Thermotogae, Firmicutes, Bacteroidetes, Proteobacteria, and Spirochaetes. Among these, Firmicutes and Bacteroidetes are the most dominant in anaerobic digestion. The abundance of hydrolytic bacteria in AD is influenced by factors such as the type of inoculum, operating temperature, cell retention time (CRT), and substrate characteristics (Nguyen et al., 2019). Notably, hydrolytic bacteria

possess a unique feature in that they produce a specialized multienzyme complex called cellulosome, which allows them to secrete various hydrolases like glucanases, hemicellulases, chitinases, and lihanases. These enzymes facilitate the breakdown of diverse complex organic wastes (Menzel et al., 2020).

During acidogenesis, fermentative bacteria with acidogenic properties transform soluble molecules into end products such as volatile fatty acids (VFAs), alcohol, and gases like carbon dioxide (CO_2), hydrogen (H_2), and ammonia (NH_3). Common VFAs include acetic acid, propionic acid, and butyric acid (Chen and Wang, 2017). In the process, acetate, CO_2 , and H_2 serve as direct resources for methanogens during methanogenesis, while other complex organic acids are subsequently converted to acetic acid and H_2 by acetogenic bacteria in acetogenesis. Acidogenic bacteria can be found across various phyla, including Firmicutes, Bacteroidetes, Proteobacteria, and Actinobacteria (Wang et al., 2018). Several abiotic factors, such as digester design, temperature, cell retention time (CRT), and substrate characteristics, influence the population of acidogenic bacteria. Among these factors, substrate composition and concentration play the most significant role (Menzel et al., 2020).

In the next stage, acetogenic microbes further break down the volatile fatty acids (VFAs) into acetic acid, H_2 , and CO_2 . These compounds serve as direct substrates for methanogenic microbes. In this phase, organic acids like propionic, butyric, and pentatonic acid are metabolized by acetogenic microbes to form acetic acid and H_2 . Some of these acetogens belong to the genus *Syntrophomonas*, which are syntrophic fatty-acid oxidizing microbes such as *Syntrophobacter wolinii* and *Syntrophomonas wolfei*

(Schnurer, 2016). Interestingly, the production of H_2 during this process inhibits acetogenic metabolism. To favor the conversion of VFAs to acetate, the hydrogen partial pressure must be kept very low under thermodynamically favorable conditions. The activity of hydrogenotrophic methanogens is crucial for maintaining this low hydrogen partial pressure in anaerobic digestion. Failure to maintain this balance can lead to VFA accumulation in the system, affecting overall AD performance. Notably, the success of acetogenesis significantly impacts biogas production efficiency, as approximately 70% of methane is produced through acetate reduction (Wang et al., 2018).

Methanogenesis, also known as biomethanation, is a form of anaerobic respiration where carbon serves as the terminal electron acceptor, resulting in the production of methane. This process involves a complex interplay between methanogens (microbes capable of producing methane) and enzymes. They thrive in anaerobic environments and play a crucial role in the global carbon cycle (Li et al., 2018a). In the anaerobic digestion (AD) process, methanogens are vital for biogas production. Researchers have identified 65 methanogenic species, classifying them into five orders including Methanobacteriales, Methanococcales, Methanomicrobiales, Methanosarcinales, and Methanopyrales. These species exhibit extreme sensitivity to oxygen and are considered slow-growing microbes due to their reliance on a limited range of organic compounds for carbon and energy sources (Nguyen et al., 2019). Based on their substrate utilization, methanogens can be categorized into three groups: Methylotrophic methanogens that utilize methyl and other one-carbon compounds; hydrogenotrophic methanogens that rely on CO_2 and H_2 ; and acetolactic

methanogens that use acetate as their substrate. Among these archaea, acetolactic methanogens are primarily responsible for the majority of methane production in anaerobic environments. This pathway utilizes acetate oxidizing rod (AOR) enzyme, which oxidizes acetate to produce H_2 and CO_2 , which is then used by the thermophilic methanobacterium enzyme to produce methane (Schruner, 2016).

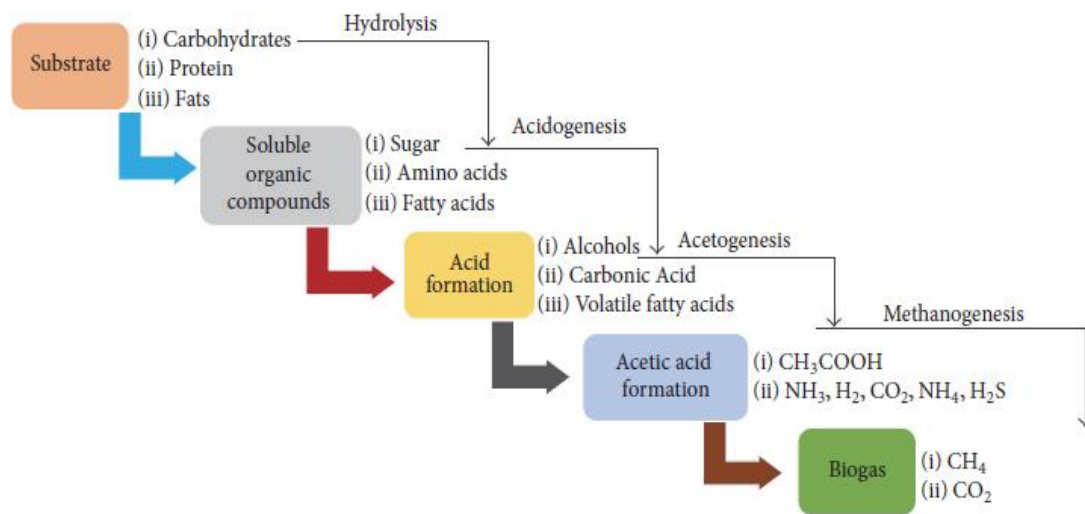


Fig. 3 Anaerobic digestion process (Paritosh et al., 2017)

2.1.4.1 Feedstock characteristics

The physical and chemical properties of the waste, including moisture, volatile solid and nutrient contents, particle size, and biodegradability are crucial in designing and operating anaerobic digesters, as they influence biogas production and process stability (Kiran et al., 2014). **Table 2** shows the properties of food waste reported in previous studies in different regions. Food waste has a significant amount of organic material, containing around 85-98% volatile solids, which suggests that it has a great potential for biological treatment (Li et al., 2018b). The moisture content of food waste

usually lies between 50 and 80% (Kannah et al., 2020). However, most food waste has acidic pH levels (ranging from 3.65 to 5.87), which can deplete the digester alkalinity and ultimately have a negative impact on the anaerobic digestion process (Li et al., 2018b). The pH levels significantly impact both methane production and methane content in biogas. During the start-up phase, the pH tends to decrease, accompanied by the production of volatile fatty acids (VFAs), which hinder the growth of methanogens. Methanobacterium, which utilizes carbon dioxide and hydrogen to generate methane, is particularly inhibited at very low pH levels (Li et al., 2020). Researchers have found that alkalinity pre-treatment enhances methanogenesis during anaerobic digestion, highlighting the crucial role of pH in the anaerobic digestion process (Wang and Li, 2016). Additionally, Zhang et al. (2010) reported that sludge pretreated with a pH of 10 exhibited a significantly higher percentage of active Archaea compared to the control group.

The characteristics of similar food waste types can vary significantly due to several factors such as its origin, processing, handling, cultural background, and weather conditions (Meng et al., 2015). Various substrates have varying contents of carbohydrates, proteins, and lipids, which are the primary micro molecules for acetogenic bacteria metabolism (Li et al., 2019). Substrates with high protein content have higher methane potential (683 mL/g VS) compared to carbohydrates (427 mL/g VS) (Li et al., 2013). The protein content in the substrate plays a crucial role in methane production. Additionally, when proteins are in a soluble state, they contribute to more biological reactions within the system. The degradation of proteins results in the formation of NH_4 (ammonium), which raises the pH value in the system and enhances volatile fatty acid (VFA) production (Li et al., 2018b). Anaerobic digestion of lipid-

rich food waste has a high potential for methane production, but it may be subject to inhibition caused by long-chain fatty acid (LCFA) intermediates. LCFAs are known to negatively impact microbial activity within anaerobic consortia. Specifically, they hinder the growth and function of methanogens, leading to reduced methane production. Therefore, upgrading the process to enhance methanogenesis and relieve inhibition is necessary (Wu et al., 2015). The addition of calcium (Ca^{2+}) has been explored as a means to alleviate LCFA inhibition. However, its effectiveness depends on the inoculum-to-substrate ratio. Furthermore, chemicals like calcium chloride (CaCl_2) and sodium hydroxide (NaOH) can be used to enhance LCFAs' solubility, thereby reducing their impact (Ma et al., 2016). Food waste with high lipid content and a balanced nutrient composition from households and restaurants has the potential to achieve high methane yields (Xu et al., 2018). Meanwhile, fruit and vegetable residues with high lignocellulosic and low lipid contents have lower methane potentials.

The C/N ratio is a significant factor in anaerobic digestion, with a range of 20-30 being reported as an optimal ratio for enhancing methane yields (Blasius et al., 2020). Low C/N ratios can lead to inhibition due to excess nitrogen, as well as a faster conversion to ammonium than methanogens can assimilate, which can cause toxicity. On the other hand, high C/N ratios can cause the accumulation of organic acids in the reactor, leading to a decrease in pH that inhibits the activity of methanogenic archaea, resulting in reduced methane production (Wang et al., 2012). No analysis of food waste characteristics has been found in Bahrain. Therefore, it is important to identify these characteristics, as they may vary based on the geographical context of the food waste produced.

Table (2): Summary of food waste characteristics from different studies

Feedstock	Characteristics				CH ₄ (ml/g VS)	Country	Reference
	TS (%)	VS (%)	pH	C/N			
FW	23.7	91.4	4.7	-	700	UK	Banks et al. (2012)
	32.2	85.4	-	18.8	442	Sweden	Bernstad et al. (2013)
	16.7	91.2	5.63	11.5	400	China	Meng et al. (2015)
	31	96.7	-	-	517	UAE	Sowunmi et al. (2016)
FVW	23.1	90	4.2	24.5	581	China	Zhang et al. (2013)
	7.94	84.9	5.28	17.2	600	China	Wang et al. (2014)
	24	93	-	-	425	Denmark	Naroznova et al. (2016)
KW	26.3	86.3	4.7	20.3	683	China	Li et al. (2013)
LW	25.7	91	4.4	17.9	643	China	Zhang et al. (2013)
	32.5	85.9	-	14.5	-	Qatar	Abdelaal et al. (2019)
	9.1	93.6	4.3		600	Brazil	Perin et al. (2020)
	12.8	95.2	4.73	29.1	348	Brazil	Blasius et al. (2020)
Oily FW	7.62	94.6	3.65	-	440	Japan	Wu et al. (2015)
Synthetic FW	17.1	98.7	5.87	14.9	427.4	China	Li et al. (2018)

*KW - kitchen waste, FVW - fruit and vegetable waste, LW - leftover waste

2.1.4.2 Process configuration

Seeding

The extended start-up period required for microbial activity to form is a drawback of anaerobic digestion (Lins et al., 2012). Seeding with a suitable inoculum is a solution that can accelerate the start-up period by providing the necessary microbial population for the new substrate (Paritosh et al., 2017). Cow manure, anaerobic sludge, and biogas slurry are commonly used as seeding materials for biogas production due to the microorganisms they contain that assist in the process. Cow manure (CM) is considered a major reservoir of methanogens and can be used both as an inoculum and co-substrate for food waste digestion (Zhai et al., 2015). A study by Dhamodharan et al. (2015) revealed that the activity of CM as an inoculum for anaerobic digestion of FW was the highest when compared to other livestock manure. The study found that the volatile fatty acids concentration was the lowest in the anaerobic reactor inoculated with cow manure, the highest methane production was achieved with cow manure as inoculum (227 ml/g VS removed) and the volatile solids reduction was the highest at 54.58%.

Organic loading rate (OLR) and Hydraulic retention time (HRT)

Organic loading rate (OLR) is a measure of the amount of organic matter (often measured as volatile solids) that are fed to an anaerobic digester per unit volume and time. While increasing the OLR can increase the amount of biogas produced, it can also disrupt the balance and efficiency of the digestion process (Mao et al., 2015). Wang et al. (2014) found that the biogas production increased with the increasing OLR from 1.0 to 3.0 g VS L⁻¹ d⁻¹. The average biogas production at these OLRs reached 0.80, 1.36 and 1.95 L L⁻¹ d⁻¹,

respectively. Optimum OLR values ranging between 3 and 5 g VS L⁻¹ d⁻¹ achieved a maximum methane yield and volatile solids reduction of 500 mL/g VS and 89.4% in a study by Li et al. (2015), with process failure occurring at an OLR of 6 g VS L⁻¹ d⁻¹. Operating an extremely high organic loading rate leads to higher hydrolysis/acidogenesis bacterial activity than methanogenesis activity, increasing volatile fatty acids production and leading to irreversible acidification. This lowers the pH of the digester, inhibits the hydrolysis process, and restricts the methanogenesis bacteria from fully converting VFA to methane (Scano et al., 2014).

Hydraulic retention time (HRT) is the duration that the substrate spends in the digester. It affects the performance of anaerobic digestion by controlling the residence time of the microorganisms and the degree of substrate degradation (Banks et al., 2012). Achieving an efficient HRT is influenced by substrate composition and OLR. Shortening the HRT results in the accumulation of volatile fatty acids (VFAs), while extending it beyond the optimal length leads to inadequate utilization of digester components (Guo et al., 2014). A longer HRT was recommended by Liu et al. (2018) particularly during the initial stage of anaerobic digestion, as it provides sufficient activated microorganisms in the system and allows for higher rates of biogas production.

Temperature

Temperature is a key factor in anaerobic digestion that affects process stability and has a significant impact on biogas production. AD systems can be categorized into two main groups: mesophilic, which operate at temperatures between 35-37°C, and thermophilic, which operate at higher

temperatures ranging from 55-70°C (Zhang et al., 2014). A study conducted by Banks et al. (2008) showed better volatile solids destruction and biogas yield under thermophilic conditions (70% and 0.67 m³/kg VS) compared to mesophilic conditions (67% and 0.63 m³/kg VS). However, the process exhibited more stability under mesophilic conditions, while the thermophilic digester showed instability due to high volatile fatty acids concentrations which required a reduced loading rates to be applied. Similarly, Guo et al. (2014) indicated that mesophilic AD systems are more stable and have a richer population of anaerobic bacteria when compared to thermophilic systems. In this study, biogas yields of 887 and 815 mL/g VS were achieved at an OLR of 1.5 g VS L⁻¹ d⁻¹ under thermophilic and mesophilic temperatures respectively. However, when the OLR was increased to 2 g VS L⁻¹ d⁻¹, the biogas yield of the thermophilic digester decreased to 675 mL/g VS, while the mesophilic digester has a biogas yield of 732 mL/g VS. While thermophilic AD systems usually result in faster reaction rates and overall higher productivity, rapid hydrolysis can lead to acidification by accumulating fatty acids, which inhibits biogas production. In addition, they are more susceptible to environmental changes and have a higher energy demand (Mao et al., 2015). Mesophilic AD can achieve comparable biogas yields while exhibiting better performance (Leung and Wang, 2016).

Reactor design

Efficient methane production is highly dependent on the process configuration. Anaerobic digesters can be constructed as single-phase or two-phase reactors to produce biogas, depending on the type of substrate and economic and technical considerations (Kiran et al., 2014). Commercial scale anaerobic digestion systems have often employed single-phase anaerobic

digestion, which uses a single reactor for all the reactions (hydrolysis, acidogenesis, acetogenesis, and methanogenesis). This system type is less prone to technical failures and is favored due to its lower cost, simple setup configurations, and easier operation (Xu et al., 2018).

A single-phase reactor can operate in either batch or continuous mode. In batch mode, the reactor is filled with substrates at the start and then completely emptied after a certain amount of time has passed. Li et al. (2013) evaluated the Biochemical Methane Potential (BMP) of kitchen waste (KW) in 1 L batch reactors at substrate to inoculum (S/I) ratios of 1.5 and 3.0 and obtained methane yields of 725 and 683 mL/g VS respectively. Similarly, Blasius et al. (2020) conducted BMP tests for household food waste at a S/I of 1.0 and achieved an optimum methane yield of 869 mL/g VS.

In contrast to batch systems, continuous anaerobic digestion systems provide samples continuously, resulting in constant biogas production (Leung and Wang, 2016). Continuous AD systems demonstrated a more stable and efficient performance, yielding 1.27 L more biogas per day than the batch feeding system according to Park et al. (2018). Two types of continuous reactors that are frequently used are continuous stirred tank reactors (CSTR) and up-flow anaerobic sludge blanket (UASB). Up-flow anaerobic sludge blanket reactors (UASBs) are a type of reactor that uses anaerobic sludge as a medium for microorganisms to digest the substrate. The substrate flows upward through the reactor, and the microorganisms attached to the anaerobic sludge digest the substrate. UASBs are efficient in terms of biogas production, substrate utilization, and low space requirements. However, they require a long start-up time and are sensitive to the variations in the substrate quality (Kiran et al., 2014). The continuous stirred tank reactor (CSTR) system is the

earliest developed high-rate anaerobic reactor, in which microorganisms are suspended in the digester by means of intermittent or continuous mixing. Complete mixing provides good contact between the substrate and the sludge with minimal mass transfer resistance, leading to effective conversion of organic matter to methane (Zhang et al., 2019). However, these systems usually operate at low OLR and longer HRT, which may cause organic overload and a decrease in buffer capacity, leading to a reduction in biogas production (Li et al., 2018a).

In a two-phase reactor, the effluent from the acidification reactor provides substrate, primarily volatile fatty acids (VFAs), for the methanogenesis reactor. Volatile fatty acids are rapidly consumed by methanogenic bacteria when pumped into the reactor, without accumulating or inhibiting the reaction (Li et al., 2020). According to Wang et al. (2014), a two-phase digestion of kitchen waste (KW) and vegetable waste (VFW) demonstrated higher treatment capacity and better buffering ability for a high organic loading rate (OLR) of up to $5.0 \text{ g VS L}^{-1} \text{ d}^{-1}$, as compared to the low OLR of $3.5 \text{ g VS L}^{-1} \text{ d}^{-1}$ for a single-phase system. In another study conducted by Wu et al. (2015) for the treatment of lipid rich waste, the single-stage system achieved a greater amount of lipid degradation and transformation of long chain fatty acids. In this study, the first phase of the two-phase system exhibited pH values lower than 4.0, which resulted in reduced hydrolysis. Upgrading the process through recycling the effluent of the second phase increased the pH in the first phase to above 5.0 and improved the hydrolysis and acidogenesis by 16.2% and 40.3%. Despite the favorable process performance and improved biomethane yield compared to single-phase CSTR systems, two-phase systems are known for their complex design and

operation, as well as their high energy intensity and capital investment (Ward et al., 2008).

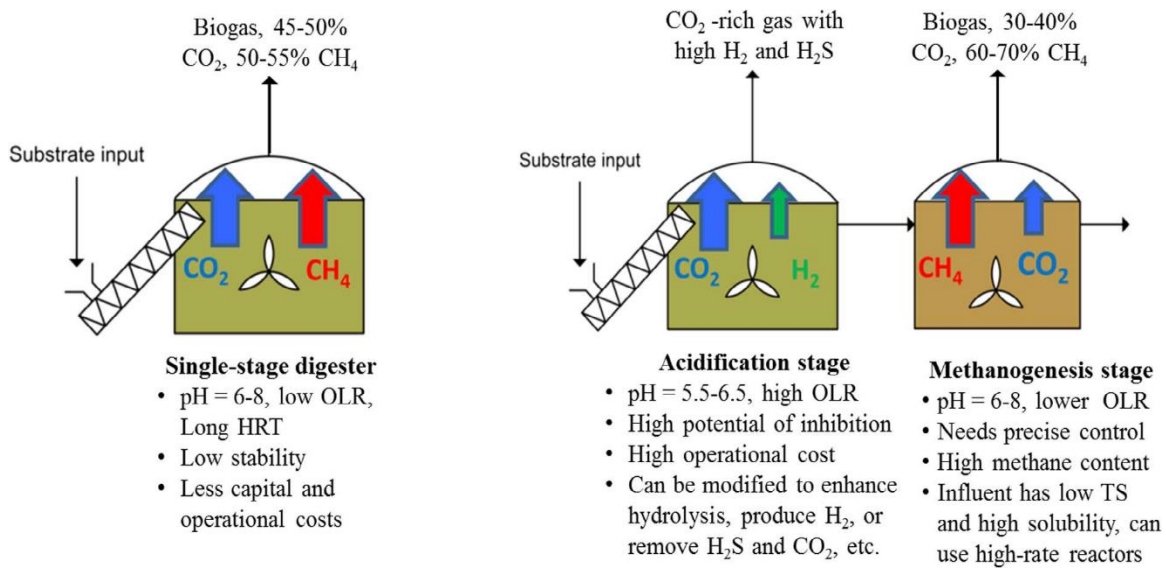


Fig. 4: Comparison between one-stage and two-stage AD systems (Xu et al., 2018)

Mixing

Mixing plays a critical role in anaerobic digestion, as it impacts the distribution of microbial communities and the creation of a uniform substrate, eliminating layering and ensuring that solid substrates are suspended for degradation (Ward et al., 2008). Moreover, mixing helps to evenly distribute heat throughout the digester, aids in the transfer of gas from the inoculum, and prevents foaming and temperature gradients in the digesters (Lindmark et al., 2014). In a study by Wang et al. (2016), the mechanical mixing during food waste anaerobic digestion was evaluated in a 30 L digester with four different propeller speeds (20, 60, 100, 140 rpm). The research found that the optimal propeller speed for anaerobic digestion was 100 rpm. A slower propeller speed (20 rpm) hindered mass transfer and resulted in AD failure, while a higher propeller speed (140 rpm) led to system instability and greater energy loss.

Similarly, Zhai et al. (2018) conducted a study which suggested that the most effective mixing intensity for methane production was 100 rpm. These results indicate that there may be a threshold for mixing intensity, beyond which methane production is hindered.

Digesters can be mixed continuously or semi-continuously. Continuous mixing results in more methane production due to better substrate, heat, and microorganism mixing, but consumes more energy. Semi-continuous mixing, on the other hand, requires less energy but may result in lower methane production (Lindmark et al., 2014; Zhang et al., 2019). Zhang et al. (2019) conducted a study to improve the energy efficiency of mechanical mixing in FW anaerobic digestion. The researchers found that semi-continuous mixing is a better strategy than continuous mixing for producing high-efficiency and energy-saving biogas, with an optimal mixing time of 2 min/h at an organic loading rate of $2.4 \text{ g VS L}^{-1} \text{ d}^{-1}$.

Process parameters

Process monitoring and control are common approaches used to enhance the stability and effectiveness of anaerobic digestion. Many research studies have investigated process indicators, such as gas production, pH, VFA, alkalinity, and ammonia, which can accurately indicate the operational conditions of anaerobic digestion (Li et al., 2018b). The pH of the digester is a critical parameter that affects microbial activity and biogas production. The optimal pH range for anaerobic digestion is between 6.5 and 7.5, which provides the ideal conditions for the growth of methanogenic bacteria (Li et al., 2019). Wang et al. (2014) observed better methane yields and volatile solids removal rate at average pH values of 7.07 and 7.28 for single-phase and two-phase AD

systems. In addition, higher organic loading rates (OLR) were associated with a decline in the pH values inside the digester (Zhang et al., 2013; Wang et al., 2014). Generally, the pH value decreases during the start-up process due to volatile fatty acids (VFA) accumulation, which inhibits the growth of methanogens. Li et al. (2018a) reported a decline in pH during the first three days of digestion corresponding to a high VFA concentration of 4017 mg/L. However, the pH value increased afterwards with the consumption of accumulated VFAs which gradually decreased in concentration.

Martín-González et al. (2013) found that in order to maintain stable reactor performance, concentrations of volatile fatty acids (VFA) and total alkalinity (TA) should be kept within the ranges of 2500-3500 mg/L and 13,000-15,000 mg/L, respectively. Alkalinity plays a crucial role in anaerobic digestion as a buffer against rapid pH changes. The buffering capacity is proportional to the concentration of bicarbonate and is a reliable measurement of digester imbalance (Ward et al., 2008). Alkalinity can also be measured using the IA/PA ratio (also known as Ripley's ratio), which can serve as an indicator for monitoring a digester. Partial alkalinity (PA) refers to the alkalinity titrated to pH 5.75, while intermediate alkalinity (IA) is titrated to pH 4.3 (Ripley et al., 1986; Anderson and Yang, 1992). An IA/PA ratio below 0.3 indicated a stable performance in mesophilic anaerobic digestion (Banks et al., 2012). According to Li et al. (2014), a combination of the total VFA concentration, VFA/TA, and the ratio of bicarbonate to total alkalinity (BA/TA) can provide a quick and effective early warning of process instability. Li et al. (2014) also reported that the thresholds for VFA/TA and BA/TA are 0.35 and 0.8, respectively. High concentrations of volatile fatty acids can decrease the buffer capacity and pH level, which in turn negatively

affects the hydrolysis and acidogenesis processes. Meng et al. (2015) reported that high volatile fatty acids concentrations of 6483.3–6496.2 mg/L were measured at higher organic loading rates, which led to low pH values and partially inhibited the digester.

The biodegradation of protein or nitrogen-rich substrates generates ammonia, which exists in the form of ammonium ($\text{NH}_4^+\text{-N}$) and free ammonia (NH_3). Ammonia affects microbial growth and plays a crucial role in the C/N ratio, which impacts the performance of the digestion process. High ammonia concentrations can increase pH and ammonia ions, which can hinder the anaerobic process. Zhang et al. (2013) reported that ammonia concentrations ranging from 568-735 mg/L neutralized the acidic materials in the digester, which reduced acidification. According to Wu et al. (2015), the inhibitory concentration of total ammonia nitrogen on methanogenic activities was 3800 mg/L for unacclimated inoculums that have not yet adapted to reactor conditions. The ideal ranges of these factors depend on the type of organic waste and the specific conditions of each process. Therefore, it is essential to monitor process parameters to determine the optimal ranges related to the stability of anaerobic digestion under various operating conditions.

2.2 Theoretical Framework

The research problem addressed is the lack of sustainable waste management practices in Bahrain, which has led to the accumulation of large quantities of food waste in landfills. Anaerobic digestion can convert food waste into renewable energy while reducing its environmental impact. However, accurate data about the quantities and types of food waste generated is necessary to quantify its energy potential. Therefore, this study's theoretical framework (**Fig. 5**) draws upon relevant existing theories and ideas related to household food waste measurement and anaerobic digestion to address the research problem in the specific context of this study.

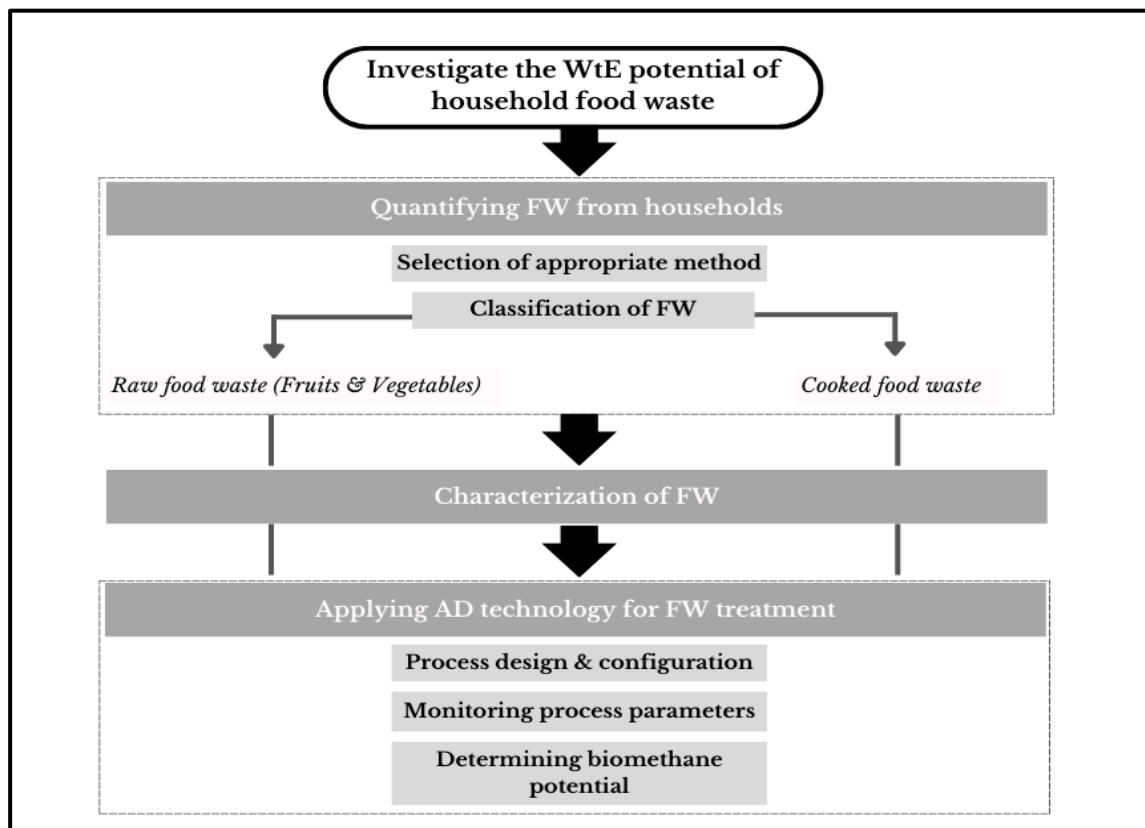


Fig. 5: Theoretical framework and organization of the study

2.2.1 Household food waste quantification

Although there have been an increasing number of studies on household food waste, many of the findings are not comparable due to the different methodological approaches used by researchers. Questionnaire-based surveys, food waste diaries, and physical waste surveys were the most frequently used methods in previous studies. Based on the analysis of these methods, physical waste surveys are considered the most reliable and unbiased method for quantifying food waste in households (Lebersorger and Schneider, 2011). In most of the reviewed studies, a household waste composition analysis was conducted, in which the proportion of food waste was determined from the residual household waste through curbside collection or from waste collection centers (Parizeau et al., 2015; Hanssen et al., 2016; Edjabou et al., 2016). A few studies collected food waste separately using caddies or containers provided to households and collected at regular intervals (Elimelech et al., 2018; Van Herpen et al., 2019). The later approach was adopted to determine the quantities and composition of household food waste at the university campus, due to its accuracy when applied at a small scale.

In addition to the basic methodology, differences in the considerations applied by the researchers have been found in terms of classification of avoidable and unavoidable waste, categorization of different types of food, and consideration of different housing types and seasons (Sahimaa et al., 2015). The distinction between avoidable and unavoidable food waste has been found in most studies. The most common definition is the one by WRAP (2009) (**refer to section 1.7**). The literature review highlights the cultural and religious context of GCC countries as a factor that can play a role in the

quantities and compositions of household food waste produced (Abiad and Meho, 2018; Aktas et al., 2018; Baig et al., 2019a). This suggests that household food waste quantities and the composition of avoidable food waste might vary during cultural and religious events such as Ramadan. Therefore, this study will consider the cultural and religious context of Bahrain in the analysis of household food waste. This will include an examination of the quantities and compositions of food wasted during Ramadan.

2.2.2 Characterization of food waste

The physical and chemical characteristics of food waste play a major role in anaerobic digestion. These include particle size, moisture content, total and volatile solids content, pH, and biodegradability (Kiran et al., 2014). Volatile solids are the organic matter in a sample that is lost upon heating at a certain temperature (Nagao et al., 2012). The biodegradability of a material can be measured by the percentage of volatile solids that are reduced during anaerobic digestion and its biomethane potential (Zhang et al., 2014). The biomethane potential is the amount of gas produced per unit of volatile solids in the feedstock after it has been subjected to anaerobic digestion at a certain temperature for a specific period (Zhang et al., 2007). The variation in food waste characteristics between studies conducted in different regions indicates that geographical and cultural factors have an influence on the composition of micro molecules such as carbohydrates, proteins, and lipids (Meng et al., 2015). The composition of micro molecules in the substrates affects the anaerobic digestion process and therefore the methane potential. Therefore, the characteristics of household food waste in this study will be analyzed to determine its potential for anaerobic digestion.

2.2.3 Anaerobic digestion of food waste

Anaerobic digestion involves a chain of complex biochemical reactions through which organic matter is converted into biogas (Wang et al., 2012). Due to the diverse nature of the feedstock characteristics, process optimization is often required to avoid process inhibition and improve biomethane production. Process configuration, including organic loading rate (OLR), hydraulic retention time (HRT), and temperature, are critical factors that affect the performance of anaerobic digestion (Zhang et al., 2014). Anaerobic digestion systems were found to exhibit better stability and richness of anaerobic bacteria under mesophilic conditions with temperature ranging between 35 and 37°C (Guo et al., 2014). Organic loading rate, which is the amount of volatile solids fed per unit volume of the digester per day, has been identified as a key factor in biogas production (Nagao et al., 2012). An optimal OLR range between 2 and 5 g VS L⁻¹ d⁻¹ has been found in most studies (Wang et al., 2014; Li et al., 2015; Liu et al., 2018). Although, AD of fruit and vegetables waste is optimized at OLRs from 1 to 3 g VS L⁻¹ d⁻¹ due to rapid hydrolysis occurring at higher loading rates, which inhibits the process (Scano et al., 2014; Ji et al., 2017). Hydraulic retention time (HRT), which is a function of organic loading rate, refers to the average amount of time that the inoculum and substrate are held in the reactor (Guo et al., 2014). An HRT of around 40 days has been recommended in most studies to allow degradation of the substrates (Zhang et al., 2013; Li et al., 2018b). A higher HRT (80 – 95 days) during the start-up process is desirable, as it allows acclimatization of microorganisms (Banks et al., 2012; Liu et al., 2018). Therefore, the OLR will be varied in this study to determine the optimal conditions for the substrates used.

2.3 Research Hypotheses

The following hypothesis was tested in this study:

- The cultural and religious context has an influence on the quantities and composition of food waste produced by households at the university campus.

Null hypothesis: H_0 : The quantities of household food waste do not change during Ramadan.

Alternative hypothesis: H_1 : The quantities of household food waste are higher during Ramadan.

Chapter Three

Methods and Procedures

3.1 Research Methodology

3.2 Study Design and Sampling

3.3 Material and Methods

3.1 Research Methodology

This study used a quantitative approach to evaluate the viability of converting food waste generated by households at the University of Bahrain into energy through anaerobic digestion. The study was designed to collect data on the quantity and composition of household food waste and to analyze the potential for anaerobic digestion. The research methodology consisted of two phases: the first phase was a quantitative study involving the collection and analysis of household food waste data, and the second phase was an experimental study involving the analysis of the potential of the collected food waste for anaerobic digestion.

The first phase of this study involved using on-site direct measurements for the collection and analysis of household food waste data in the University of Bahrain. This approach was chosen due to the lack of existing data on food waste from the generating sources. Direct measurements yield more accurate and objective results than self-reporting methods such as surveys, food waste diaries, and interviews. Moreover, it offers greater control over potential interferences that may arise due to the study's geographic location (Van Herpen et al., 2019). However, direct characterization is a resource-intensive and time-consuming method, which limited the sample size used in this study. The “Daily Family Waste Collection” model proposed by Elimelech et al. (2018) was adopted in this study and adapted to fit the specific context (**Fig. 6**).

The research design was a longitudinal study, whereby household FW quantities and composition were observed over time (Kothari and Garg, 2019). The sampling frame for this study was households located in the

university accommodation area. A random sampling method was applied for sample selection. The sample size was determined based on the number of households that agreed to participate in the study.

The second phase involved the analysis of the potential for anaerobic digestion of household food waste in the University of Bahrain. An experimental method was implemented to measure the potential for producing biogas from food waste. This method allows for control over the research environment and manipulation of variables to observe how they impacted other variables. The study monitored the biogas composition for two types of food waste fed into the digester at different organic loading rates. Additionally, the stability of the process was monitored through certain parameters which are explained in the following sections.

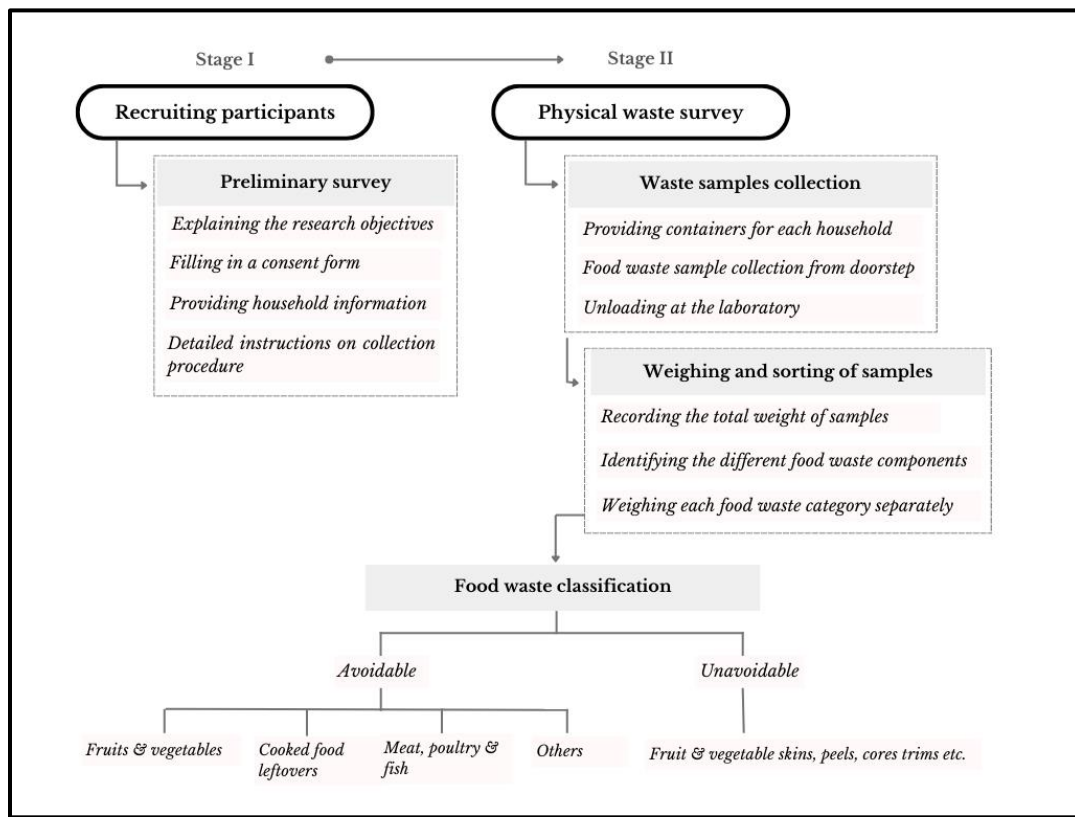


Fig. 6: A detailed flowchart of the methodology (adapted from Elimelech et al. 2018)

3.2 Study Design and Sampling

3.2.1 Recruitment of participants

To recruit participants for this study, permission was obtained from the deanship of graduate studies at the University of Bahrain. A consent form (Appendix A) providing information about the study's purpose was then sent to academic staff members residing in the university accommodation through emails and printouts. The selection of households was based on voluntary participation. Interested participants were asked to provide some information about their household characteristics and food waste routines to assess the extent of resources required for the study. The acquired information was promised to be kept confidential, and participants had the option to withdraw their participation at any point during the study.

Out of 62 houses, 15 volunteered for the study and were given specific guidelines on disposal routines and food waste collection. Only 7 out of these 15 potential participants agreed to participate, with 3 showing no interest and 4 being unavailable during the study period. Two households dropped out during the trial, leaving a final sample of 5 households (23 individuals), accounting for 8% of all houses in the study area.

There is no established method for food waste characterization, and household waste composition studies have different sample sizes. When dealing with a population with a known mean and standard deviation, a sample size above 30 is considered optimal for obtaining normally distributed sample means and standard errors (Adelodun et al., 2021). Similar studies reported sample sizes ranging from 9 to 1474 households based on several levels of stratification including the sampling location, housing types, size of

the property and seasons (Sahimaa et al., 2015). In addition, most of these studies were conducted on a national or regional scale. The current study focuses solely on the food waste produced by households at the university campus, which is made up of a single housing type. This ensures homogeneity in terms of the geographical distribution of the samples. This study merely aims to quantify the extent of food waste generated by households on campus. Identifying correlations between food waste quantities and socio-demographic characteristics is not feasible in this context since residents inside the campus are of similar income level and mostly non-Bahraini residents. Moreover, other considerations such financial resources and experience in conducting direct measurements by the researcher limit the sample size. Therefore, it can be concluded that collection of 120 samples from five households over two months provides a reasonable approximation of the food waste generated by households on campus.

3.2.2 Food waste sampling procedure

3.2.2.1 Sampling duration

The study was conducted over a period of two months between March and May 2022. To obtain a representative sample with a 90% confidence interval and 10% margin of error, the minimum number of sampling days required was calculated using **Eq. (1)** (Gallardo et al., 2016).

$$n_0 = \left(\frac{t.s}{e.X'} \right)^2 \quad (1)$$

Where n_0 is the minimum number of sampling days, X is the mean waste generation, S is the standard deviation, t is the percentile which depends on the confidence level, and e is the acceptable error level for the mean. The t

value was 1.28 for a confidence level of 90% ($\alpha = 0.1$), and the acceptable level of error was fixed as 10%. A pilot study was carried out over a week, where a mean of 2.92 kg and standard deviation of 0.686 kg of FW per day were produced. The resulting sample size was a minimum of 9 sampling days. The month of Ramadan was considered in this study (1st of April). Therefore, data collection was conducted during normal days (period 1) and during Ramadan (period 2) to observe the difference in food waste quantities between both periods. For this reason, the collection was done over eight weeks, four weeks in March (n=12 days) for normal days and four weeks in April (n=12 days) for Ramadan. The sampling period did not include public holidays.

3.2.2.2 Food waste collection procedure

Participants were instructed to store their waste in plastic bags and place the containers outside their homes during the morning hours of every collection day. The samples were collected every two days from the household's doorstep except on weekends. Sorting samples that have been produced for more than two days could impact the accuracy of waste component classification and separation, especially in hot areas (Lebersorger and Schneider, 2011). By collecting samples from households' doorsteps with minimal exposure to weather conditions, potential seasonal effects were minimized, as suggested by Elimelech et al. (2018). The collection from all households was done in one round, except on cases where containers were not placed outside. In such cases, the participants were informed and requested to place their containers outside to be collected on the same day.

3.2.2.3 Sorting and classification procedure

Households were provided with two coded kitchen containers and garbage bags for disposing of their food waste. To conduct the experiments, it was necessary to separate fruit and vegetable waste from other types of waste. Therefore, one container was designated for fruit and vegetable waste, while the other was for the remaining food waste. Participants were instructed to discard whole or partly consumed fruits and vegetables, and cooked food leftovers in small bags to be measured separately. The samples were sorted in the lab shortly after collection to remove any non-biodegradable or indigestible materials such as bones and shells as they were not included in the analysis.

In this study, food waste was mainly classified as either raw (e.g., fruits, vegetables) or cooked (e.g., cooked rice, pasta etc.) (Monier et al., 2010). The food waste analysis primarily used two categories to define the type of food waste: avoidable and unavoidable. Unavoidable food waste refers to waste generated during food preparation or consumption that cannot be consumed by humans, such as bones, eggshells, tea bags, fruit and vegetable skins, peels, trims, and cores. Avoidable food waste refers to food that is fit for human consumption that was discarded by households (WRAP, 2009). This fraction of the food waste was grouped into cooked food leftovers; fruits and vegetables; meat, poultry, and fish; and others. The category of leftovers consisted of cooked food items like pasta, potatoes, rice, and mixed vegetables. The fruit and vegetables category included all types of fresh or raw fruits and vegetables in different stages of consumption. Any other food items were categorized as "others". Each food waste category was then weighed to determine their quantities and compositions.

3.2.2.4 Statistical analysis

The statistical analyses were performed using Minitab software version 19.1 with a significance level of $p < 0.05$ and a confidence interval of 95%. Independent samples T-tests were performed to identify significant differences in food waste quantities during Ramadan and between avoidable and unavoidable FW generation rates.

3.3 Material and Methods

3.3.1 Inoculum and substrates

Mesophilic anaerobic sludge from an 8 L working volume lab-scale anaerobic digester (with cow manure as the substrate) at the university renewable energy labs was used as the seeding inoculum to start-up the experiments. The digester had been stably running for more than 3 months at an organic loading rate (OLR) of $3 \text{ g VS L}^{-1} \text{ d}^{-1}$, and the hydraulic retention time (HRT) was 40 days. The inoculum was pre-incubated in both digesters at $36^\circ\text{C} \pm 1$ for a week to ensure the depletion of any residual organic matter. The inoculum was prepared using fresh cow manure that was collected from a cattle farm in Hamala and stored at 4°C . The cow manure was diluted and homogenized with tap water (CM 1:1 water) and 200 g of the mixture was fed to the digesters 3 times a week over a period of two weeks to ensure stable biogas production prior to starting the FW digestion experiments. The characteristics of both fresh and diluted cow manure are reported in **table 3**.

Table (3): Characteristics of cow manure used as inoculum

Characteristics	pH	TS (%)	VS (%)
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Fresh cow manure	6.41	19.88	87.79
Diluted cow manure	6.94	12.43	86.30

Large samples were drawn from food waste collected and classified as either fruit and vegetables waste (FVW), or cooked food waste (CFW) to serve as substrates for the anaerobic digestion experiments. To enhance the efficiency of anaerobic digestion (AD), it is important to carry out physical pretreatments like grinding, as the particle size of solid materials can significantly affect the rate of hydrolysis and acidification (Zhang et al., 2014). In this study, the samples were diluted with distilled water in equal amounts and homogenized in a blender to reduce their particle size. Afterwards, they were stored in separate labelled containers at 4°C until smaller samples were taken for total and volatile solids analysis and for use in lab-scale experiments.

3.3.2 Experimental design and operation

The experiments were conducted in two lab-scale 10 L continuous stirred tank reactors (CSTR); one for fruit and vegetable waste and the other for cooked food waste. A schematic diagram of the experimental set up is shown in **Fig. 7**. The reactor openings were filled with air-tight seals and the oxygen level was monitored daily to ensure anaerobic conditions.

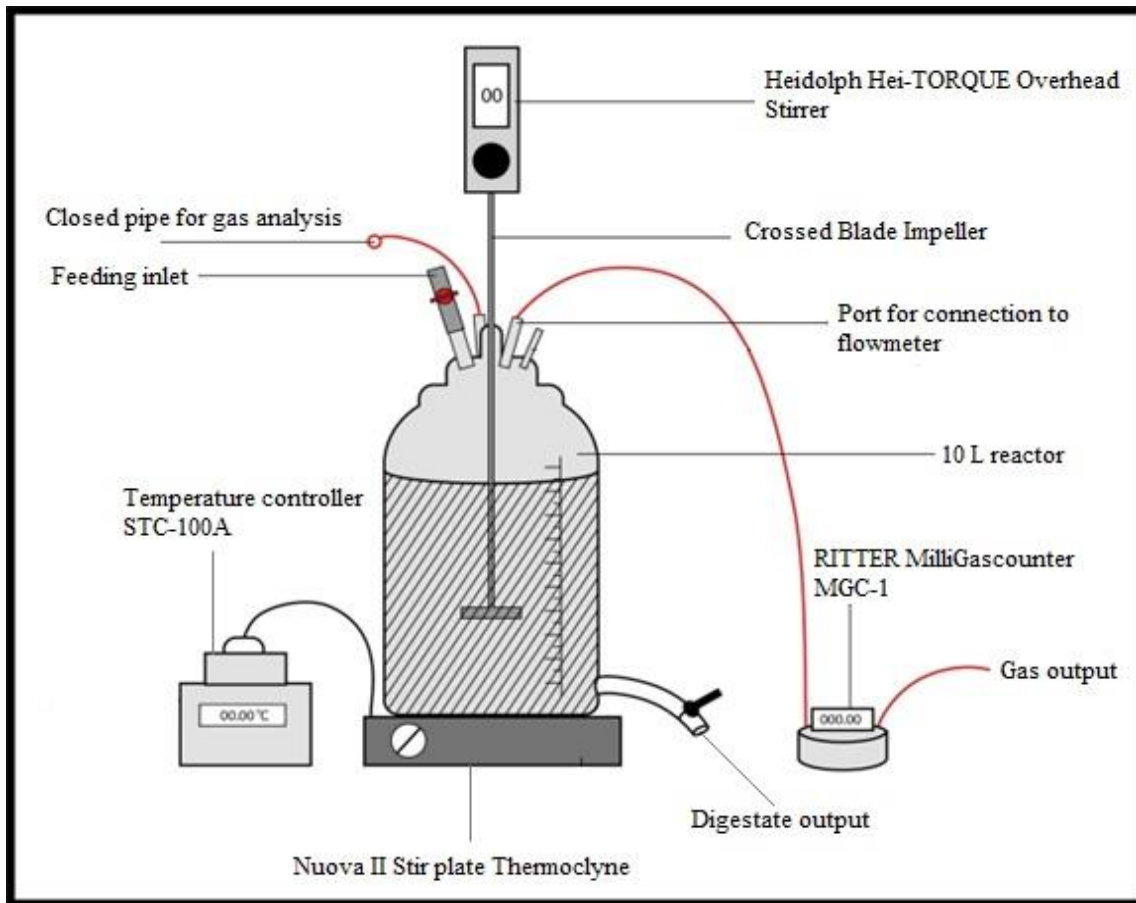


Fig. 7: A schematic of the anaerobic digestion system

Both reactors were fed daily with substrates for five days a week. The working volume of each reactor was maintained at 8 L by adding and removing the same amount of substrate and digestate respectively, while 2 L of the reactor was kept as a headspace volume. The reactors were operated under three different organic loading rates of 2,3, and 4 g VS L⁻¹ d⁻¹. The organic loading rates were calculated using **Eq. (2)**, where M is the mass of the substrate (g/day), TS is the total solid percentage of substrate (%), VS is the volatile solid percentage of substrate (%TS), and V is the working volume of the reactor (L). Each OLR was maintained for a period of two weeks, which allows for the adaptation of microorganisms to the AD system (Wang et al., 2014). Anaerobic digestion of food waste is usually carried out at low organic

rates (2 to 5 VS L⁻¹ d⁻¹) due to the high organic matter, protein, and lipid contents of FW, which could lead to process inhibition through enhanced levels of ammonia, hydrogen sulfide (H₂S) or long-chain fatty acids (LCA) (Li et al., 2015).

$$OLR = \frac{M \cdot TS \cdot VS}{V} \quad (2)$$

The hydraulic retention time (HRT) varied depending on the OLRs and VS added to the reactor. HRT was calculated using **Eq. (3)** as follows:

$$HRT = \frac{V}{Q} \quad (3)$$

Where V is the working volume of the reactor and Q is the influent flowrate in time (Mao et al., 2015). A longer HRT is usually recommended particularly during the initial stage of anaerobic digestion, as it provides sufficient activated microorganisms in the system and allows for higher rates of biogas production (Liu et al., 2018).

3.3.3 Analytical methods

3.3.3.1 Total and volatile solids analysis

Total and volatile solids analysis was conducted twice a week according to standard methods 2540D and E (Greenberg et al., 1992). To determine the total solids, samples (25 mL) of the digestate were taken and transferred into a dried silica dish of known weight and then placed in a water bath until all the liquid has evaporated. The sample was then dried in an oven at 103-105 °C for an hour and then cooled in a desiccator before weighing. The TS % was then calculated according to **Eq. (4)**, where the weight of sample dried at 105

°C is the difference between the weight of the dish with dried residue and the weight of the empty dish. The samples from each reactor were duplicated for consistency in data and all measurements were done using a precision scale of an accuracy of $\pm 0.005\text{g}$. For volatile solids analysis, the dried sample is ignited at 550°C in a muffled furnace for 15-20 mins and the loss of volatile matter is represented by the difference in weight. The VS % represented as a percentage of the total solids is calculated using **Eq. (5)**, where the weight of sample ignited at 550°C is the difference between the weight of the dish with ignited residue and the weight of the empty dish.

$$TS \% = \frac{\text{Weight of sample after } 105^\circ\text{C}}{\text{Weight of digestate}} \times 100 \quad (4)$$

$$VS \% = 100 - \left(\frac{\text{Weight of sample after } 550^\circ\text{C}}{\text{Weight of sample after } 105^\circ\text{C}} \right) \times 100 \quad (5)$$

Volatile solids reduction (VS_r) refers to the percentage of VS entering the digester that is consumed by bacteria, which is estimated by **Eq. (6)** (Koch et al., 2009).

$$VS_r (\%) = 1 - \frac{VS_{\text{digestate}} \cdot (1 - VS_{\text{feed}})}{VS_{\text{feed}} \cdot (1 - VS_{\text{digestate}})} \quad (6)$$

3.3.3.2 Biochemical methane potential (BMP)

Daily measurement of the biogas composition was conducted for both digesters. Methane (CH_4 , %), carbon dioxide (CO_2 , %), oxygen (O_2 , %), and hydrogen sulfide (H_2S , ppm) concentrations were analyzed using a GFM406 gas analyzer (Gas Data, UK). The CH_4 and CO_2 concentrations were measured via infrared sensors with a reference channel, while an optional LEL expansion and electrochemical cells were used to measure O_2 and H_2S .

For the measurement of biogas production, a RITTER biogas counter was attached to the reactor to measure the daily volume of biogas produced. However, the biogas counter was not functioning properly due to lack of maintenance and required software which was not available at the university. Therefore, the theoretical biomethane potential (BMP) was calculated instead. The described method is used to easily determine the amount of methane produced by a particular substance based on its COD characterization. However, the method assumes that all organic material will be degraded, so an adjustment is necessary to account for the actual biodegradability of the substance (Nielfa et al., 2015). Methane potential is expressed as mL of CH₄ per unit of organic material added (VS) at standard temperature and pressure. The maximum methane potential (BMP_{th}) can be calculated using **Eq. (7)** based on the amount of material and COD concentration of the test, assuming that this equation is applicable to any substance or product. The theoretical value of methane at laboratory conditions is provided by this equation:

$$BMP_{th} = \frac{n_{CH_4}RT}{pVS_{added}} \quad (7)$$

where BMP_{th} is the theoretical production (mL CH₄/g VS) at laboratory conditions, R is the gas constant ($R = 0.082$ atm L/mol K), T is the temperature of the reactor (310 K), p is the atmospheric pressure (1 atm), VS_{added} (g) are the volatile solids of the substrate and n_{CH_4} is the amount of molecular methane (mol) determined from **Eq. (8)**

$$n_{CH_4} = \frac{COD}{64(g/mol)} \quad (8)$$

During the experiments, the biodegradability of the substrates was obtained through analysis of the COD content of the reactor effluent. The COD reduction (COD_r) can be calculated using **Eq. (9)** based on the initial and final COD concentrations (COD_0 and COD_f) (Nielfa et al., 2015). The BMP_{th} can be adjusted by multiplying it with the COD_r .

$$COD_r = \left(\frac{COD_0 - COD_f}{COD_0} \right) \times 100 \quad (9)$$

Further adjustment to the BMP_{th} was made using **Eq. (10)**, where it is multiplied by the percentage of volatile solid reduction (VS_r), assuming a linear relationship with biomethane production (Wu et al., 2016). Where BMP_{exp} is the adjusted value based on experimental results.

$$BMP_{exp} = BMP_{th} \times VS_r \quad (10)$$

The energy potential for food waste produced by the households on campus was calculated using **Eq. (11)** (Blanchard et al., 2020).

$$EP = BMP_{exp} \times M_{fw} \times VS_{\%} \times E_{CH_4} \quad (11)$$

Where EP is the energy potential (MJ), M_{fw} is the total mass of food waste, and E_{CH_4} is the energy content of methane, which was taken as 36 MJ/m³ (Banks, 2009).

3.3.3.3 Process monitoring

Digestate samples were taken from the reactor once a week to determine the process stability parameters including pH, intermediate alkalinity (IA), partial alkalinity (PA), chemical oxygen demand (COD) and ammonia-nitrogen (NH_4^+ -N). The pH value was determined using a basic pH meter

(Sper Scientific, US) at the digester temperature (37 °C). The meter probe was plunged into a well-mixed sample using a magnetic stirrer, and the pH value was recorded. The ideal pH range for the growth of microorganisms in anaerobic digesters is reported to be around 6.8–7.2 (Ward et al., 2008).

The IA/PA ratio (Ripley's ratio) is a useful indicator of process stability and the relative buffering capacities of bicarbonates and volatile acids in anaerobic digestion. The ratio was determined using a two-step titration procedure. A 50 mL sample was titrated with a 0.5 M hydrochloric acid (HCl) solution to an endpoint of pH 5.75 then further titration is carried out until the pH reaches 4.3. The volume of HCl required to reduce the sample pH to 5.75 is a measure of partial alkalinity (PA) and is noted down as volume A. The amount of acid needed to reduce the pH from 5.75 to 4.3 is volume B, which is a measure of the intermediate alkalinity (IA). The IA/PA ratio was calculated by dividing volume B by volume A. A value of 0.3 is the ideal ratio for a well operating anaerobic digester (Ripley et al., 1986).

The COD and $\text{NH}_4^+\text{-N}$ were analyzed using a DR-3900 spectrophotometer (HACH, USA). Liquid samples were centrifuged for 10 minutes at 5000 rpm and the supernatant was then filtered through a 45- μm filter before the analysis. For the COD analysis, 2.0 mL of the filtered sample were added to COD digest vials (LCK514, HACH) containing 90% sulfuric acid, mercury sulfate, and potassium dichromate. The sample was then digested for 2 hours at 148 °C and allowed to cool before analysis. For analysis of COD in food waste, dry amounts of food waste were diluted with de-ionized water and blended to create a “pulp-like” suspension, then 10 mL of the suspension was further diluted to 0.3 g/L and 2.5 mL of diluted suspension

were pipetted in triplicates into the COD digest vials (Harnadek et al., 2015). For the NH_4^+ -N analysis, 0.2 mL of the filtered sample were added to an LCK303 vials containing sodium hydroxide and allowed to react for 15 mins before analysis in the spectrophotometer.



Fig. 8: Titration set-up for measuring IA/PA ratio.

Chapter Four

Results, Discussion, Conclusion and Recommendations

4.1 Results

4.2 Discussion

4.3 Conclusion and Recommendations

4.1 Results

4.1.1 Food waste quantities and composition

During the study, a total of 120 samples of food waste were collected from 5 households with 23 members. The samples weighed a total of 159.6 kg. **Table 4** shows the weighted average quantities of food waste generated by households. The average amount of food waste generated by the sampled households was 3.99 ± 0.54 kg/household/week, which corresponds to 0.87 ± 0.12 kg per/capita/week. Avoidable food waste accounted for 63.3% of total food waste, with an average rate of avoidable food waste generated per household per week of 2.52 ± 0.61 kg (0.55 ± 0.13 kg/capita/week). The difference between the rates of avoidable and unavoidable food waste generation was statistically significant (t-test = 4.14, p-value = 0.002).

Table (4): Weekly average generation rate of food waste from households

Food waste category	Total (kg/week)	Per household (kg/week)	Per capita (kg/week)
Total food waste	19.94 ± 2.70	3.99 ± 0.54	0.87 ± 0.12
Avoidable food waste	12.62 ± 3.05	2.52 ± 0.61	0.55 ± 0.13
Unavoidable food waste	7.32 ± 1.96	1.46 ± 0.39	0.32 ± 0.09

Figure 9 shows the compositions of different food waste categories from the total food waste. Overall, the majority of food waste came from fruits and vegetables (61.6% of total food waste) followed by cooked food waste (28.3% of total food waste). Food items such as bread, pastry products, and eggs were

classified as "others" due to their minimal proportions. Fruit and vegetable peels, trims, rinds, and cores were the main components of unavoidable food waste and constituted 36.7% of the total food waste. These were included in the fruit and vegetables category for the total food waste (**Fig. 9**). **Figure 10** shows the composition of the food categories from the total avoidable food waste. The weight of individual items in each category could not be measured due to their mixed state. The “cooked food leftovers” category was found to be dominant, accounting for 44.7% (45.1 kg) of the avoidable food waste stream. This category consisted mainly of food items such as rice, pasta, potatoes, and mixed vegetables that prior to disposal were fit for consumption. The second most prominent category was the “fruit and vegetables” category, which constituted 38.6% of the total avoidable food waste.

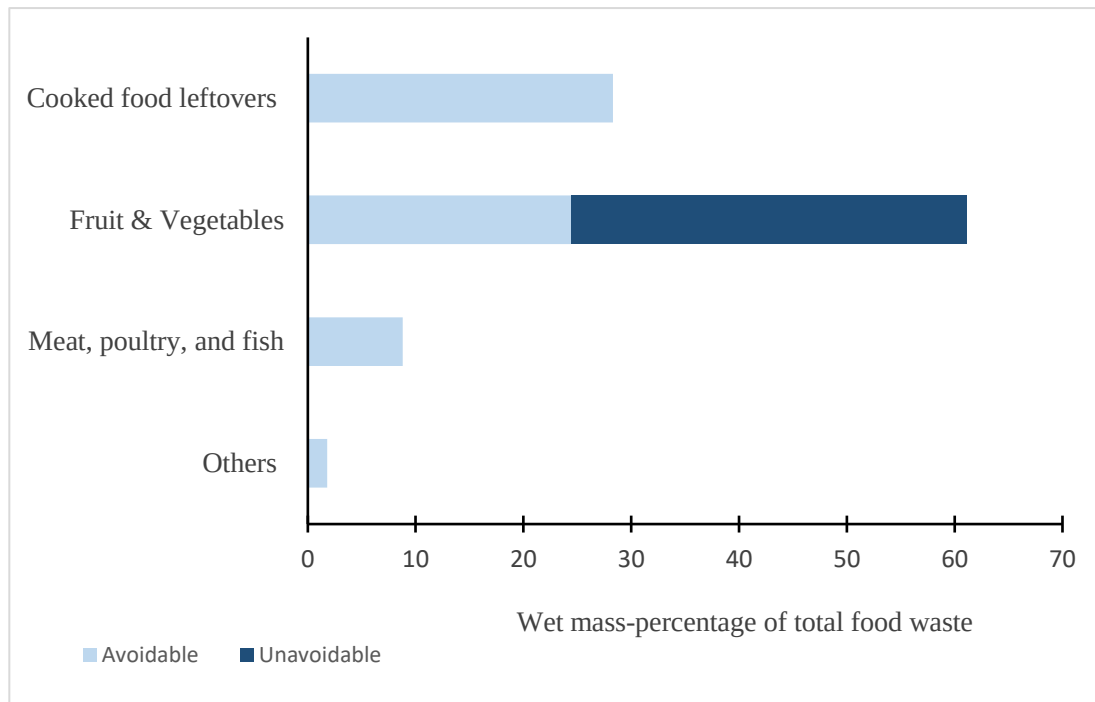


Fig. 9: Percentage of different food categories from the total food waste

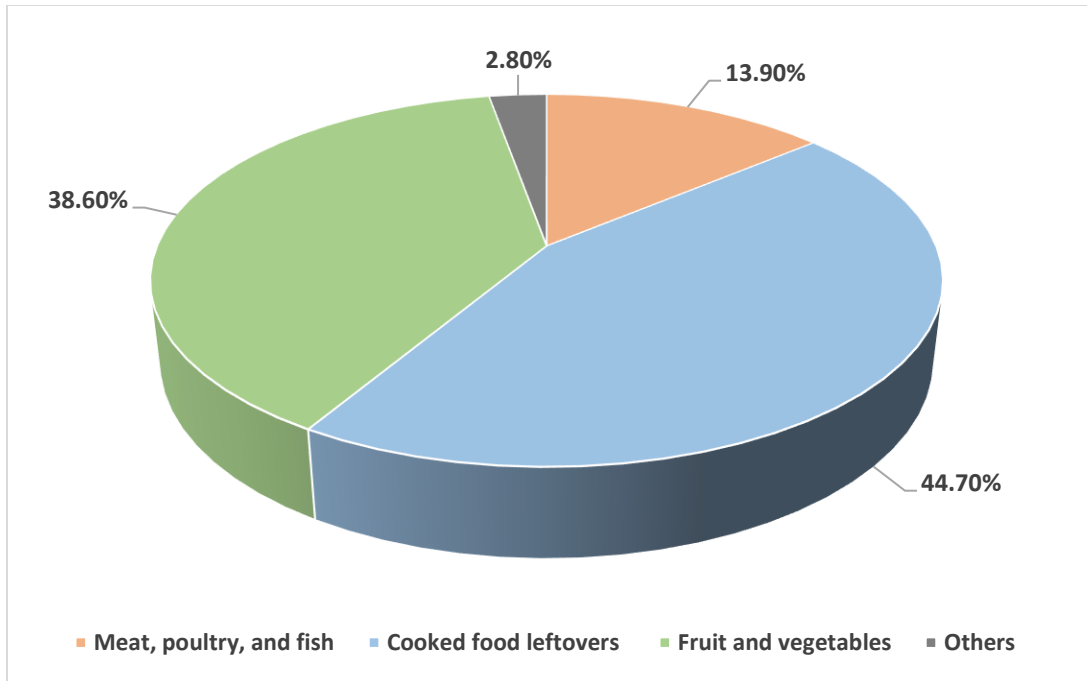


Fig. 10: Avoidable food waste composition

Food waste generated during Ramadan accounted for 54.9% (87.6 kg) of the total quantity. **Table 5** provides a comparison between the food waste generation rate during normal days and Ramadan. The highest amount of food waste produced during Ramadan was 4.81 kg/household/week (1.05 kg/capita/week), while the lowest was 3.87 kg per household per week (0.84 kg per person). The average amount of food waste produced per household per week during Ramadan was 4.38 ± 0.49 kg (0.95 ± 0.11 kg per person), which was significantly higher than on normal days ($p\text{-value} \leq 0.05$). The avoidable food waste produced weekly for each household varied between normal days (2.19 ± 0.45 kg/household/week) and the month of Ramadan (2.86 ± 0.60 kg/household/week), with statistically significant differences ($p\text{-value} \leq 0.05$). However, there was no significant difference observed in the mean weight of unavoidable food waste during both normal days and Ramadan. The mean weight of unavoidable food waste during normal days

was 1.41 ± 0.58 kg/household/week, while during Ramadan it was 1.52 ± 0.13 kg/household/week ($p \geq 0.05$).

Table (5): Average weight of food waste generated during normal days and Ramadan

Category	Period	Mean weight. (kg/household/week)	Significance
Total food waste	Normal days	3.99 ± 0.54	0.022*
	Ramadan	4.38 ± 0.49	
Avoidable food waste	Normal days	2.19 ± 0.45	0.034*
	Ramadan	2.86 ± 0.60	
Unavoidable food waste	Normal days	1.41 ± 0.58	0.632
	Ramadan	1.52 ± 0.13	

* t-test was used for analysis of the significance with p-value < 0.05

4.1.2 Characterization of food waste

Table 6 presents the results of the analysis of two types of waste, fruit and vegetables waste (FVW), and cooked food waste (CFW). The analysis was conducted in duplicates for weekly samples of food waste collected from the households on campus. The total solids (TS) and volatile solids (VS) were calculated on a wet weight basis percentage. The results indicate a high percentage of volatile solids for both types of food waste, with an average VS content of 94.2% and 95.7 % for FVW and CFW, respectively. Statistical analysis of the VS% showed significant differences between both types of food waste (t-test= 3.41, p-value = 0.005) with cooked food waste having a

higher VS%. Both types of waste had high moisture content, with values of 76.1% and 75.5% for FVW and CFW, respectively. The pH values of food waste were slightly acidic; for FVW it was 5.81, and for CFW, it was 5.37. Moreover, COD content of FVW (304.2 g/L) was higher than CFW (254.5 g/L). Fruit and vegetables waste had a higher ammonium nitrogen concentration ($\text{NH}_4^+\text{-N}$) than cooked food waste.

Table (6): Characteristics of food waste used in this study

Parameter	Fruits & vegetables waste	Cooked food waste
Total Solids % (w.b.)	23.9 ± 1.73	24.5 ± 1.26
Volatile Solids % (w.b.)	94.3 ± 0.90	95.7 ± 0.93
Moisture content (%)	76.1 ± 1.73	75.5 ± 1.26
pH	5.81 ± 0.01	5.37 ± 0.03
COD (g/L)	304.2 ± 5.86	254.5 ± 4.25
$\text{NH}_4^+\text{-N}$ (mg/L)	265.0 ± 11.90	73.6 ± 3.57

4.1.3 Anaerobic digestion performance

4.1.3.1 Methane composition

The daily measured methane and carbon dioxide concentrations of biogas produced from both digesters at varying organic loading rates (OLR) for both feedstocks are shown in **figures 11** and **12**. Both digesters showed an increase in methane composition with increasing OLR. However, there was a significant decrease in methane content for the fruit and vegetable waste digester (**Fig. 11**) upon increasing the OLR to $4 \text{ g VS L}^{-1} \text{ d}^{-1}$, where it reached a minimum of 42.7% on day 36. The fruit and vegetable waste digester

showed stable methane composition between day 15 and day 26 at an OLR of 3 g VS L⁻¹ d⁻¹, where a maximum methane content of 63.5% was achieved (**Fig. 11**). The concentration of methane for the cooked food waste digester, on the other hand, steadily increased until it reached its peak at 64.6% when the OLR was 4 g VS L⁻¹ d⁻¹ (**Fig. 12**). The highest methane concentrations for the cooked food waste digester at OLRs of 2 and 3 g VS/L were 55.9% and 60.8%, respectively. Overall, the average methane content over 42 days in the CFW digester (58.4%) was higher than that of the FVW (55.15%). The difference in methane composition between both digesters was found to be statistically significant (t-test = 2.37, p-value = 0.022). The carbon dioxide concentration for both digesters remained steady at an average of 35.9% and 34.1% for FVW and CFW, respectively. However, the carbon dioxide concentration for the fruit and vegetable waste digester started to rise when fed at an OLR of 4 g VS/L, with an average value of 38% (**Fig. 11**).

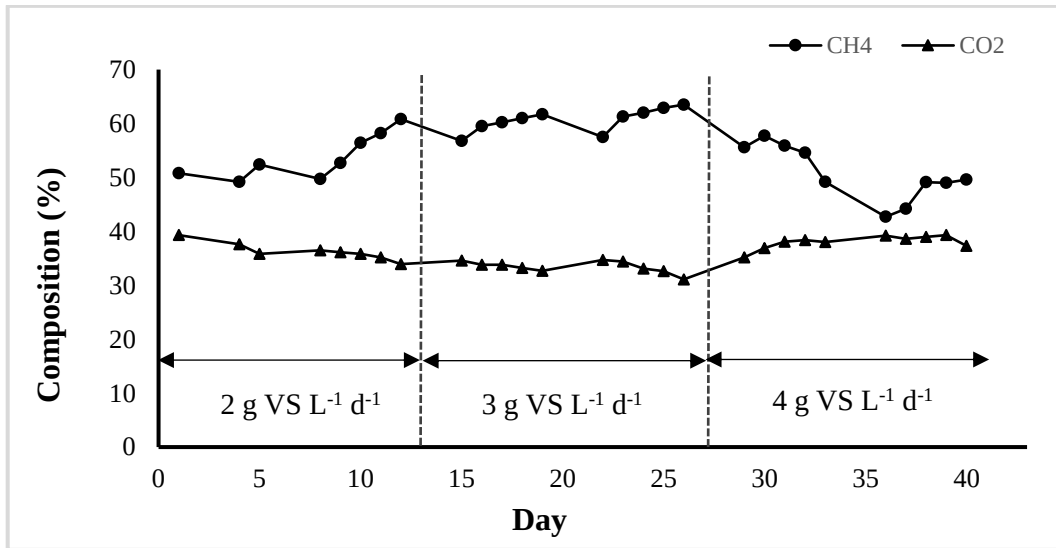


Fig. 11: Daily methane composition of biogas produced from fruit and vegetable waste (FVW)

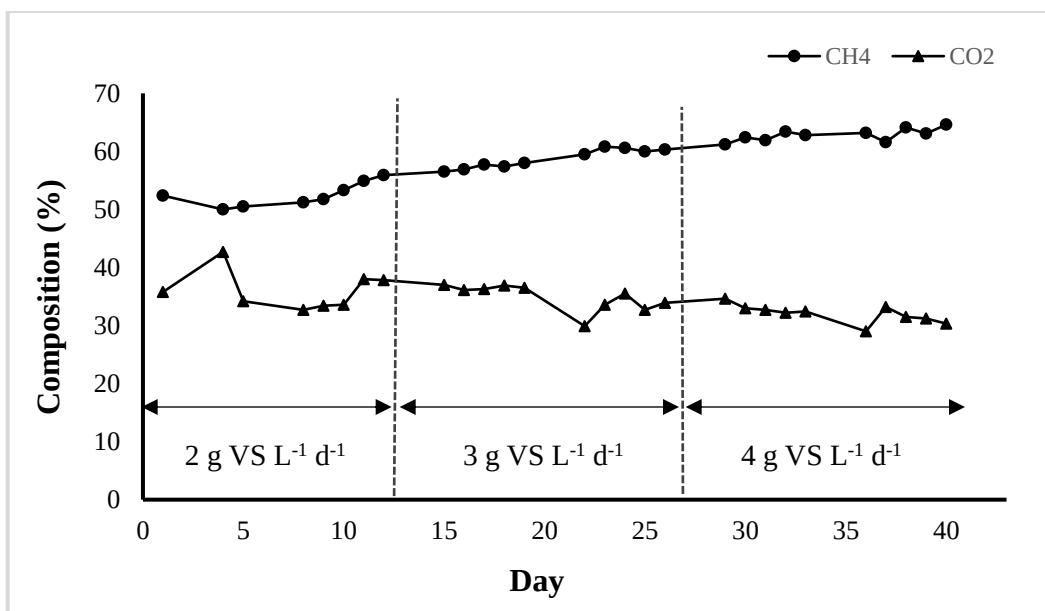


Fig. 12: Daily methane composition of biogas produced from cooked food waste (CFW)

4.1.3.2 Volatile solids reduction

The biodegradability of the food waste was measured by the level of reduction or degradation of volatile solids (VS_r). The amount of volatile solids inside the digester was measured three times a week and graphed to show the percentage reduction of the feedstocks over time under varying loading rates (**Fig. 13** and **14**). The percentage VS_r for both digesters gradually increased over time at increasing organic loading rates. However, a sharp decline in the degradation of volatile solids was observed for the fruit and vegetable waste digester (**Fig. 13**) at an OLR of 4 g VS L⁻¹ d⁻¹. For the digestion of fruit and vegetable waste at OLRs 2 to 4 g VS L⁻¹ d⁻¹, average VS_r of 68%, 80.6% and 70.3% were achieved, respectively. The maximum volatile solids reduction for fruit and vegetable waste was 85.4% at an OLR of 3 g VS L⁻¹ d⁻¹ (**Fig. 13**). The cooked food waste demonstrated a better performance in terms of volatile solids reduction, with average values of 72.6%, 83.1%, and 88.5% for OLRs 2 to 4 g VS L⁻¹ d⁻¹, respectively. A maximum volatile solids reduction of

89.2% was achieved for cooked food waste was at an OLR of 4 g VS L⁻¹ d⁻¹ and it remained stable afterwards (**Fig. 14**). Throughout the experiment duration, CFW had significantly higher average volatile solids reduction (82.2%) than FVW (73.4%) (T-test = 2.47, p-value = 0.024).

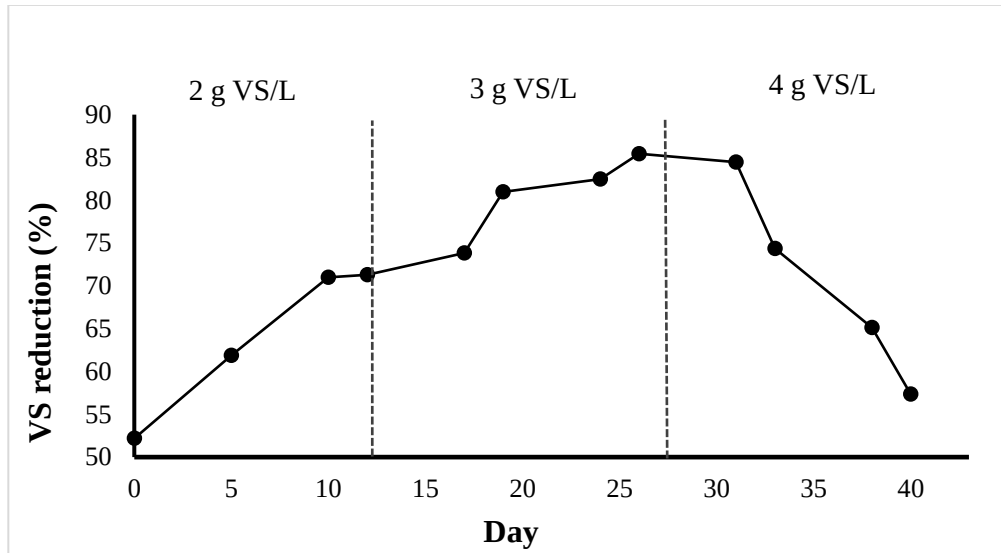


Fig. 13: Reduction of volatile solids over time under varying loading rates for FVW

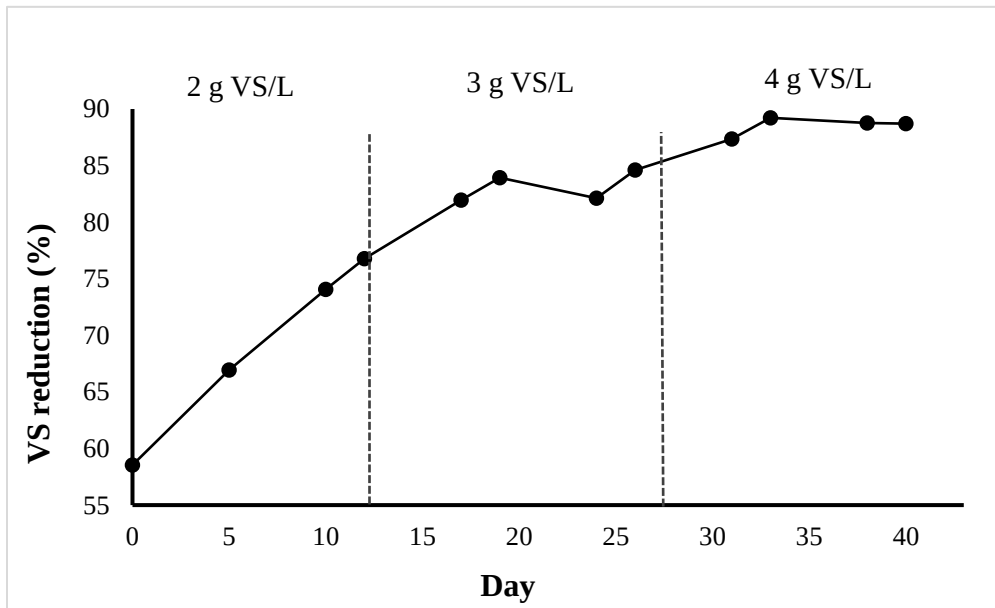


Fig. 14: Reduction of volatile solids over time under varying loading rates for CFW

4.1.3.3 COD reduction

The chemical oxygen demand (COD) content inside the digester indicates the extent to which organic matter in food waste is converted into biogas and mineralized. The COD of the effluent from both digesters was measured to determine the COD reduction efficiency. **Table 7** shows the COD reduction efficiencies of both digesters, which was calculated based on the COD concentration in the digester influents and effluents. The results indicate a decrease in the COD reduction with increase in organic loading rate above 3 g VS L⁻¹ d⁻¹ for the fruit and vegetable waste digester. A maximum reduction of 85.4% was achieved at an organic loading rate of 3 g VS L⁻¹ d⁻¹ with a final concentration of 2.57 g/L in the fruit and vegetable waste digester. On the other hand, the COD reduction efficiency of cooked food waste increased with increasing the loading rate and reached a maximum of 92.9% at an OLR of 4 g VS L⁻¹ d⁻¹.

Table (7): COD reduction efficiency of both digesters

Substrate	OLR (g VS L ⁻¹ d ⁻¹)	COD _{influent}	COD _{effluent}	COD _{reduction}
FVW	2	21.60 g/L	5.05 g/L	76.6%
	3	32.20 g/L	4.70 g/L	85.4%
	4	42.56 g/L	9.17 g/L	78.4%
CFW	2	17.31 g/L	5.64 g/L	67.4%
	3	25.95 g/L	4.04 g/L	84.4%
	4	35.63 g/L	2.53 g/L	92.9%

*COD_{reduction} % is calculated as (COD_{influent} – COD_{effluent})/COD_{influent} x 100

4.1.3.4 Biomethane potential

The digestion performances of the fruit and vegetable waste and cooked food waste substrates under varying organic loading rates were compared (**Table 8**). The maximum methane potential was calculated (using **Eq. 7**) based on the COD of the substrates. Since this value assumes that all organic matter is degraded, experimental values of VS and COD reduction obtained from analysis of the reactor effluent were used to adjust this value. Another underlying assumption of the used, is that the biogas produced has 60% methane content. Since the methane composition was measured in this study, these values were used to further improve the accuracy of the estimation. Biogas production is estimated in L per unit volume of the digester per day from methane potential, methane content and the volatile solids added to the digester.

In the fruit and vegetable waste digester, biogas production increased as the organic loading rate (OLR) increased from 2 to 4 g VS L⁻¹ d⁻¹. The methane production at these OLRs was calculated as 0.93, 1.84 and 1.93 L L⁻¹ d⁻¹, respectively. The methane potential increased from 250 to 370.9 mL/g VS upon changing the OLR from 2.0 to 3.0 g VS L⁻¹ d⁻¹. However, at an OLR of 4.0 g VS L⁻¹ d⁻¹, the methane potential decreased to 246 mL/g VS. On the other hand, the biogas production from CFW was 0.7, 1.49, and 2.42 L L⁻¹ d⁻¹ at OLRs 2.0 to 4.0 VS L⁻¹ d⁻¹. Correspondingly, the methane potential was 184.2, 294.6, and 380.6 mL/g VS, respectively. The energy potential of methane was calculated for 62 households on campus based on the yearly generation rate of both types of food waste and their highest methane potential value (**table 9**). The specific energy potential was 13.35 and 13.7 MJ/kg VS for FVW and CFW, respectively.

Table (8): Comparison of FVW and CFW anaerobic digestion performance

	Organic Loading Rate for FVW / CFW (g VS L ⁻¹ d ⁻¹)		
	2.0	3.0	4.0
Operation conditions			
Duration (days)	12/12	14/14	14/14
Volume of feed (mL)	71/68	106/102	142/136
Total VS added (g/day)	16 / 16	24 / 24	32 / 32
HRT (days)	112 / 117	75 / 78	56 / 58
Effluent Characteristics			
pH	6.8 / 6.6	7.1 / 6.9	6.4 / 6.9
IA/PA	0.5 / 0.69	0.33 / 0.36	0.59 / 0.32
NH ₄ ⁺ -N (mg/L)	16.6 / 23.7	15.4 / 11.0	40.1 / 4.1
Digester performance			
VS reduction (%)	68.1 / 72.6	80.7 / 83.1	70.3 / 88.5
COD reduction (%)	76.5 / 67.5	85.4 / 84.4	78.4 / 92.9
Methane (CH ₄) content (%)	53.7 / 52.5	60.6 / 58.7	50.7 / 62.8
Maximum methane potential (mL/g VS)	536.2 / 429.6	532.8 / 429.5	528.3 / 442.2
Experimental methane potential (mL/g VS)	250.0 / 184.2	370.9 / 294.6	246.0 / 380.6
Biogas production (L L ⁻¹ d ⁻¹)	0.93 / 0.70	1.84 / 1.49	1.93 / 2.42

*Values of pH, IA/PA, NH₄⁺-N, VS_r, and CH₄ (%) are based on averages in each duration

Table (9): Energy potential for both types of food waste generated by households.

Waste Type	Fruit and Vegetable Waste	Cooked Food Waste
Waste Generation Rate (kg/year)	11,445.2	3,610.88
Methane Potential (mL/g VS)	370.9	380.6
VS%	94.2%	95.7%
Volume of Methane (m ³ /year)	2737.2	1,315.2
Energy Potential (MJ)	98,539	47,347
Specific energy potential (MJ/kg VS)	13.35	13.7

4.1.4 Process stability parameters

Figures 15 to 17 show the variation of process parameters (pH, IA/PA, and NH₄⁺-N respectively) for monitoring process stability in both digesters. Measurements of the parameters were conducted on the digester effluents at the end of each week. As shown in **figure 15**, at organic loading rates (OLRs) of 2 and 3 g VS L⁻¹ d⁻¹, the pH of the fruit and vegetable waste digester was maintained at around 6.9, although the mean pH of the influent was 5.87. However, when the OLR increased to 4 g VS L⁻¹ d⁻¹, the pH of the digester decreased and eventually dropped to below 6.3. Correspondingly, the IA/PA in the FVW digester gradually decreased from 0.54 to 0.32 at OLRs of 2 and 3 g VS L⁻¹ d⁻¹ and then increased to 0.65 upon increasing the organic loading rate (**Fig. 16**).

For the cooked food waste digester, the pH initially dropped from an initial value of 6.8 to 6.4 in the first 5 days (**Fig. 15**), corresponding to an IA/PA of 0.72 (**Fig. 16**). Subsequently, the pH gradually increased and

stabilized at around 6.9 for organic loading rates 3 and 4 g VS L⁻¹ d⁻¹. The IA/PA ratio during this period of stable pH was maintained at around 0.32. The concentration of NH₄⁺-N in the fruit and vegetable waste digester was between 13.2 and 15.2 mg/L during the first two loading rate stages but then increased to 43.1 mg/L at the final loading rate of 4 g VS L⁻¹ d⁻¹ (**Fig. 17**). For CFW, the NH₄⁺-N concentration was highest (25.3 mg/L) at organic loading rate of 2 g VS L⁻¹ d⁻¹ but then gradually decreased with increasing the organic loading rate until it reached a final concentration of 3.9 mg/L (**Fig. 17**).

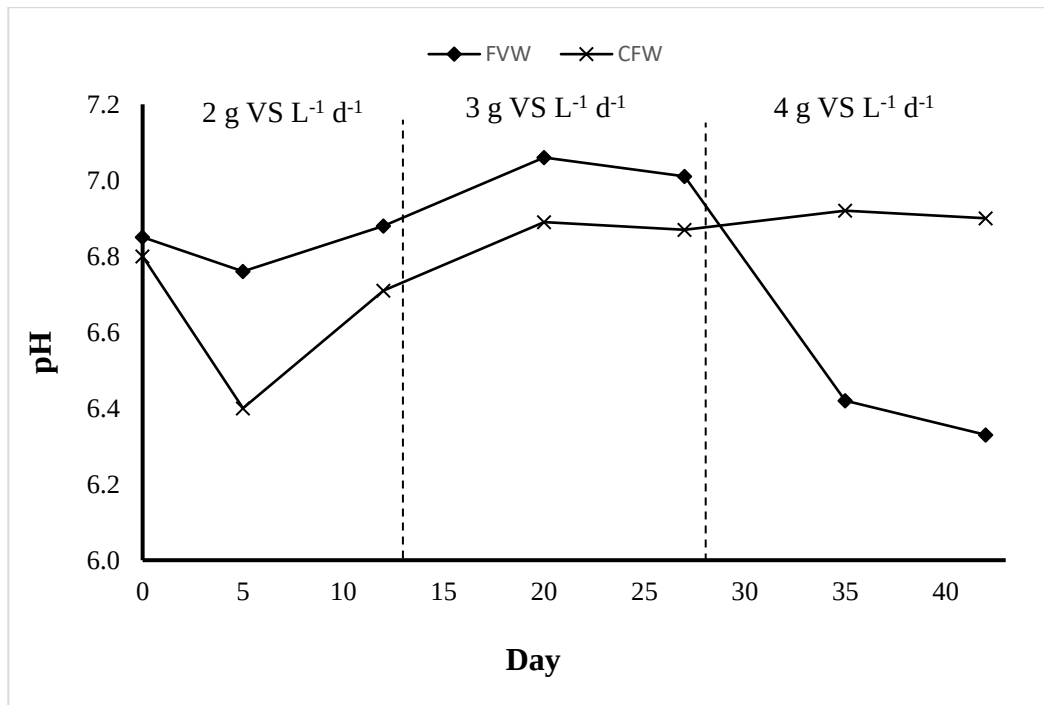


Fig. 15: Variation of pH in both digesters at different organic loading rates

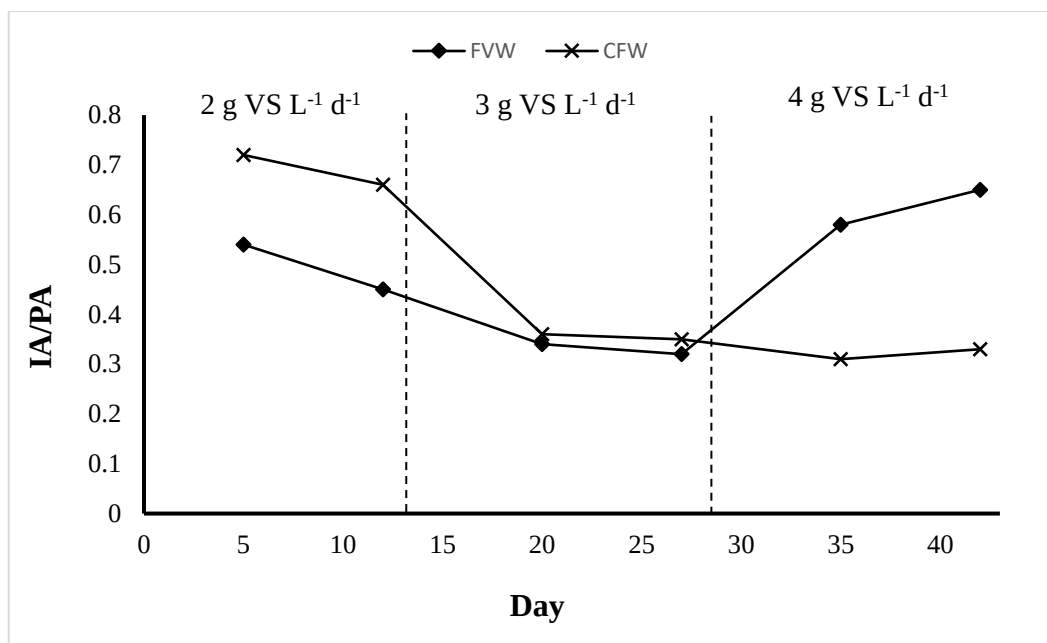


Fig. 16: Variation of IA/PA in both digesters at different organic loading rates

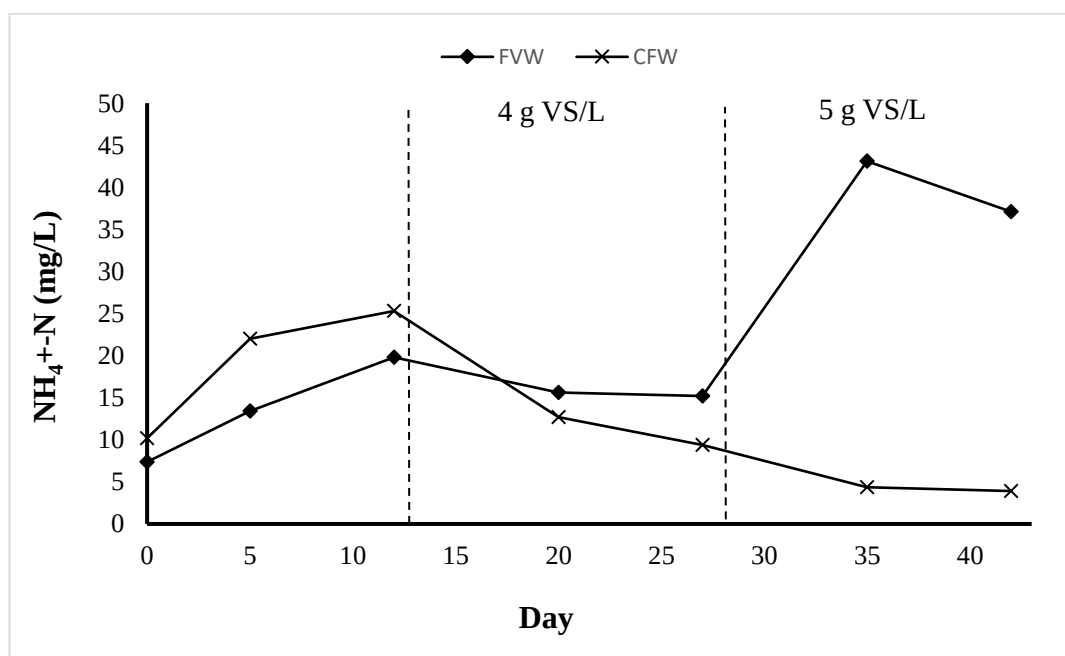


Fig. 17: Variation of NH₄⁺-N in both digesters at different organic loading rates

4.2 Discussion

The findings of this research have provided insight into the quantities and composition of household food waste produced at the university campus and its potential utilization for biogas production using anaerobic digestion. However, the results should be interpreted with caution due to the limitations of the current research. This section provides a reflection on the research process and a discussion of the main findings and their implications.

4.2.1 Household food waste quantification

The results of this study show that the average amount of food waste generated by the sampled households was 3.99 ± 0.54 kg/household/week (0.87 kg/capita/week). This is comparable to other studies conducted in urban areas in various developed countries that have reported food waste generation rates ranging from 3.51 to 3.76 kg/household/week using direct measurement (Edjabou et al., 2016; Hanssen et al., 2016; Sosna et al., 2019). However, this rate is lower than the food waste generation rate of 5.28 kg/household/week reported in a study conducted in Saudi Arabia (Quested et al., 2020). The lower rate observed in this study may be due to the much smaller sample size, although the sampling period in this study was longer compared to four days in the other study. It should be noted that this study only included single-family units on the university campus, which limits its representative in the context of Bahrain. Other studies measured food waste from different types of households, including those living in multi-family dwellings (Hanssen et al., 2016; Edjabou et al., 2016).

Comparison with national figures was not feasible due to the small scale of the study, and the fact that most people living on campus are non-Bahraini

nationals. The Bahrain food bank reports that on average, each person wastes around 2.1 kg of food each week, compared to the 0.87 kg found in this study. However, the main aim in this study was to estimate the amount of food waste produced by households on campus, in order to assess the potential for converting it to energy. Furthermore, the figures from national reports are approximations of the amount of food waste generated by all sectors and sent to landfills, divided by the total population. As a result, there are currently no estimates that pertain solely to food waste generated by households in Bahrain.

The percentage of avoidable food waste generated by the sampled households was 63.3% of total food waste, which is slightly higher than percentages reported in other countries ranging from 54% to 59% (Lebersorger and Schneider, 2011; Quested et al., 2013; Hanssen et al., 2016; Elimelech et al., 2018). However, it was similar to the 64% reported by Abdelaal et al. (2019) in Qatar, although the study included food waste from food outlets and student residential complexes. On the contrary, the study in Saudi Arabia reported a significant percentage of 78% avoidable food waste (Quested et al., 2020). It is worth mentioning that certain food categories such as dairy products, condiments, sauces, and beverages were not included in the current study, which could lead to an underestimation of the total percentage of avoidable food waste. This was mainly due to difficulties in sorting and weighing since the study was conducted individually. Moreover, these categories were not suitable for anaerobic digestion, hence they were excluded from the analysis.

Contrary to previous studies, which reported that fruit and vegetables waste was the main component of avoidable food waste (lebersorger and

Schneider, 2011; Quested et al., 2013; Bernstad and Andersson 2016; Elimelech et al., 2018), this study found that cooked food leftovers were the dominant fraction of avoidable food waste with 44.7%, followed by fruit and vegetable waste with 38.6%. This could be due to cultural approaches to everyday shopping, cooking, and eating habits, which place a high value on generosity and hospitality (Baig et al., 2019a).

The results obtained during Ramadan showed a significant increase in the amount of food waste generated per household, which is consistent with the hypothesis that cultural and religious context can influence waste quantities and compositions. According to Baig et al. (2019b), a reported 24.5% increase in food waste generation was observed during Ramadan in Saudi Arabia. Similarly, a 1.5-fold increase in food waste generation was reported in Bahrain during Ramadan (Forbes et al., 2021). Moreover, the current study found a significant increase in avoidable food waste during Ramadan. This further highlights the influence of the cultural context on food waste quantities and compositions of food waste.

4.2.2 Characterization of food waste

The physicochemical characteristics of food waste were determined to identify its potential as a feedstock for anaerobic digestion. The results of the analysis of food waste samples collected from the households showed that the waste was predominantly composed of organic matter, with a high content of volatile solids (VS). The high organic content of food waste is an important factor in its suitability for anaerobic digestion, as it serves as a source of energy for the microorganisms involved in the process. A high volatile solid percentage was found to be desirable for biogas and methane production (Li

et al., 2013). Waste from fruits and vegetables contains low total solids and high volatile solids, making it easy to break down in an anaerobic digester (Jiang et al., 2012). The TS and VS% values (refer to 4.1.2) obtained in this study were in accordance with the values reported in the UAE with TS and VS values of 31% and 96.7% (Sowunmi et al., 2016). Moreover, Zhang et al. (2013) reported TS and VS values of 23.1% and 90% for raw fruits and vegetables waste, which are similar to the values reported in this study. The average moisture content of FVW and CFW were within the typical range of moisture content found in food waste studies, which is between 75% and 84% according to Paritosh et al. (2017).

In this study, FVW had a higher COD content than CFW, which is consistent with previous studies (Li et al., 2013). This could be due to fruit and vegetable waste containing a higher amount of organic matter, such as cellulose and hemicellulose, which are more difficult to break down than the organic matter found in cooked food waste (Ji et al., 2017). A very high COD content may hinder the activity of microorganisms and affect the process stability (Blasius et al., 2020). The COD value for cooked food waste fell within the range found in previous studies, which is between 103.7 g/L (Perin et al., 2020) and 279.8 g/L (Komemoto et al., 2009).

The pH values of FVW and CFW were consistent with values reported in the literature, where the pH of food waste ranges between 5.28 (Wang et al., 2014) and 5.63 (Meng et al., 2015). These values are considered acidic, which is not ideal for the methanogenesis stage. The ideal pH range for anaerobic digestion is generally between 6.5 and 7.5, according to Perin et al. (2020). However, the initial hydrolysis and acidogenesis stages typically occur at a pH between 4.5 and 6.5 (Li et al., 2019). The $\text{NH}_4^+\text{-N}$

concentrations of the CFW and FVW substrates were consistent with previous studies, which reported $\text{NH}_4^+\text{-N}$ concentrations 96 mg/L (Chen et al., 2016) and 203 mg/L (Wu et al., 2015). Overall, the results indicate that the household food waste produced on campus has good potential as a feedstock for anaerobic digestion.

4.2.3 Anaerobic digestion performance

The OLR, VS_r , COD_r and the biomethane potential were used to evaluate the performance of anaerobic digestion (Nagao et al., 2012). Variations in the organic loading rate from 2 to 4 g VS $\text{L}^{-1} \text{d}^{-1}$ were introduced and the steady state was determined by the methane composition and volatile solid reduction. Sharp declines in methane composition and volatile solids reduction indicated process failure. The results show enhanced digestion performance for both reactors with increasing the organic loading rate. However, the fruit and vegetable waste digester's performance declined when the OLR was increased to 4 g VS $\text{L}^{-1} \text{d}^{-1}$ as indicated by the fluctuation in methane content of the biogas and the lower degradation of organic matter in terms of VS_r and COD_r .

Based on analysis of the performance parameters including the methane composition, VS_r , COD_r and the experimental biomethane potential, the optimal organic loading rates were 3 and 4 g VS $\text{L}^{-1} \text{d}^{-1}$ for FVW and CFW, respectively. The optimal organic loading rate values obtained in this study were in line with previous studies with an optimal OLR ranging between 2 and 5 g VS $\text{L}^{-1} \text{d}^{-1}$ (Wang et al., 2014; Li et al., 2015; Liu et al., 2018). The fruit and vegetable waste digester had a methane potential of 370.9 mL $\text{CH}_4/\text{g VS}$ and achieved a maximum VS_r and COD_r of 85.3 and 85.4% at OLR of 3 g VS $\text{L}^{-1} \text{d}^{-1}$. While the cooked food waste had a methane potential of 380.6

mL CH₄/g VS and the maximum achievable VS_r and COD_r values were 89.2% and 92.9% at OLR 4 g VS L⁻¹ d⁻¹. The methane potential in this study was an estimated value due to inability to measure the biogas produced during the experiments. The flow cells connected to the digesters were not functioning, therefore, the calculation of biogas yield was not viable. While this compromises the accuracy of the results, adjustments were made to the estimated value based on experimental degradation results to provide a better estimation of the actual biomethane potential of the food waste. The values obtained in this study at the optimal organic loading rate were comparable to findings from previous studies. The methane potential for fruit and vegetable waste varied in the literature between 425 and 581 mL CH₄/g VS, while for cooked food the range is between 348 and 643 mL CH₄/g VS under similar conditions to the ones used in this study (Bernstad et al., 2013; Zhang et al., 2013; Blasius et al., 2020). In the UAE, the methane potential of food waste was found to be 517 mL/ g VS.

During the anaerobic digestion of food waste, the stability parameters of pH, IA/PA, and NH₄⁺-N were monitored. Overall, both digesters showed good process stability except for the fruit and vegetable waste when operating at an organic loading rate higher than 3 g VS L⁻¹ d⁻¹. The results of this study were compared to previous studies in the field. For instance, Wang et al. (2014) conducted a lab-scale study on the anaerobic co-digestion of kitchen waste and fruit/vegetable waste and found that the pH value varied between 7.04 and 7.2 when the digester was operated at OLRs of 1 to 3 g VS L⁻¹ d⁻¹ but decreased to 6.89 at an OLR of 3.5 g VS L⁻¹ d⁻¹. Similarly, Li et al. (2017) investigated the instability mechanisms for mesophilic anaerobic digestion of vegetable waste and found that the pH value was between 7.0 and 7.4. In this study, the

pH range for the FVW digester was between 6.9 and 7.1 at OLRs of 2 and 3 g VS L⁻¹ d⁻¹. Both FVW and CFW experienced a slight drop in pH at the beginning of the experiments, likely due to the accumulation of volatile fatty acids during the hydrolysis stage, which leads to a decrease in pH (Zhang et al., 2013).

The IA/PA ratio was used as an indicator of process stability in this study. The IA/PA ratio is sensitive to variations in volatile fatty acids concentrations and therefore can be useful as an indicator of process stability when direct measurements of VFA is not possible. According to Martín-González et al. (2013), an IA/PA ratio below 0.3 can achieve a stable performance, maintaining VFA levels 2.5 and 3.5 g/L. Initially, the ratio increased for both digesters, indicating instability during the hydrolysis stage due to VFA accumulation and a subsequent reduction in methane production (Li et al., 2015). Throughout the experiments, both digesters have shown a stable performance, and the IA/PA was maintained at around 0.3. The notable exception was observed in the fruit and vegetable waste when the organic loading rate was 4 g VS L⁻¹ d⁻¹. This could be an indication of acidification occurring due to volatile fatty acids build up at higher OLRs, which explains the reduced methane production (Banks et al., 2012). Therefore, it would be useful to measure the volatile fatty acids concentrations to identify the limit for process inhibition for the specific type of food waste used. Gas Chromatography (GC) and High Liquid Performance Chromatography were explored in this as options for measuring the concentration of individual VFAs. However, due to lack of maintenance and unavailability of certain types of columns, it was not possible. Ammonia, in both its free (NH₃) and ionized (NH₄⁺) form, results from the breakdown of amino acids, peptides,

and proteins (Li et al., 2017). In both digesters, the concentrations of $\text{NH}_4^+\text{-N}$ were negligible. To achieve optimal methane fermentation performance when using food waste as a substrate, it is recommended to keep ammonium concentrations in the AD reactors below 2000 mg/L according to Chen et al. (2016).

Overall, the process performance in both reactors indicates that food waste produced by households on campus has good potential for biogas production using anaerobic digestion. The results of the digester performance showed that CFW demonstrated better performance over the whole duration of the experiment. However, the results of this study showed that fruit and vegetable waste still have potential as feedstock for anaerobic digestion. Researchers suggested co-digestion of fruit and vegetable waste with other types of waste to enhance the process performance. This could help balance the nutrients in the waste to increase biogas production and equipment efficiency, and lower processing costs. Methane content can be increased up to 69%, 70%, and 66.8% respectively when fruit and vegetable waste is co-digested with dairy manure, agricultural waste, and kitchen waste (El-Mashad and Zhang, 2010; Ros et al., 2013; Wang et al., 2014). Co-digestion also helps neutralize pH and provide nitrogen to the microorganisms' culture medium, solving the rapid acidification problem (Ji et al., 2017).

4.3 Conclusion and Recommendations

This research aimed to investigate the potential of household food waste produced at the University of Bahrain campus for biogas production using

anaerobic digestion. The study focused on quantifying and characterizing the food waste generated by the households and evaluating the anaerobic digestion performance with fruit and vegetables waste and cooked food waste as feedstocks.

The study found that the average amount of FW generated by households on campus was 3.99 ± 0.54 kg/household/week, with 63.3% of the waste being avoidable. Fruits, vegetables, and cooked food leftovers were the dominant categories of the food waste produced. Cultural and religious factors were found to have a significant influence on food waste, with higher generation of total (4.38 ± 0.49) and avoidable FW (2.86 ± 0.60) observed during Ramadan. This highlights the need for waste management strategies that consider the cultural and religious context of the studied area. Waste reduction campaigns and educational programs can leverage cultural and religious values to promote waste reduction behaviors and practices that are aligned with the local context (Abiad and Meho, 2018).

The analysis of the food waste characteristics and the anaerobic digestion performance suggests that anaerobic digestion can be an effective method for producing biogas from household food waste at the university campus. The characteristics of the FW were favorable for anaerobic digestion, with high organic matter present in both types of food waste. Although both substrates used in this study demonstrated comparable methane potential at optimal conditions (370.9 and 380.9 mL/g VS for FVW and CFW), cooked food waste demonstrated an overall better process efficiency in terms organic matter degradation with an average VS reduction 82.2% compared to 73.4% for fruits and vegetables. Moreover, the fruit and vegetable waste digester showed instability at higher organic loading rates, which limits the biogas production

over a longer period due to the need to operate at lower organic loading rates. Therefore, by selecting suitable feedstocks, waste management systems can optimize the production of biogas and reduce the environmental impact of organic waste.

Overall, the study highlights the potential for improved waste management at the University of Bahrain. The significant daily food waste due to the large campus population could be addressed by developing small-scale anaerobic digestion systems. Easier source-segregation and centralized waste production make this feasible for universities (Gallardo et al., 2016). Anaerobic digestion can also provide sustainable energy, reducing reliance on fossil fuels. However, the variability in waste production and the high cost and technical limitations of anaerobic digestion are important considerations. The process efficiency can be improved through automation, process control technologies, and pre-treatment methods.

There are several limitations to the current study that should be considered when interpreting the results. Firstly, the study was conducted on a small scale, with only a limited number of households included in the sample. Other sources of food waste including food complexes, restaurants, cafeterias, and student residential complexes need to be taken into consideration when designing a waste management strategy in universities. Moreover, the small sample size and the consideration of single-family units limits the generalizability of the results. However, the direct measurement approach used in this study provides valuable insights into the quantities and composition of household food waste. Furthermore, certain food categories such as dairy products, condiments, sauces, and beverages were not included in the current study, which could lead to an underestimation of the total

percentage of avoidable food waste. Finally, the estimated methane potential was based on experimental degradation results, which may not be as accurate as directly measuring the biogas produced during the experiments. Despite these limitations, the findings of this study provide valuable insight into the potential of household food waste for biogas production using anaerobic digestion in the Bahrain context due to the limited research in this field. These insights can be used to inform the design and implementation of sustainable waste management strategies that include the recovery of energy and resources from food waste through anaerobic digestion.

In terms of future work, it is recommended to conduct a larger-scale study to estimate the amount of food waste generated from different sources on campus. In the wider context of Bahrain, studies can be conducted to measure food waste generated by different types of households using larger sample sizes and to investigate the feasibility of establishing a centralized biogas plant to process food waste. Moreover, future studies should explore the potential of other feedstocks including co-digestion of food waste with other organic waste streams and to better understand the mechanisms involved in the anaerobic digestion process. Finally, there is a need to investigate the economic feasibility of implementing anaerobic digestion technology for food waste management in Bahrain.

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Appendix A: Consent From

Food Waste Collection from Households at the University of Bahrain

Participation in this project will help in quantifying the sources, types and amounts of food waste produced by households at the university campus. In addition, the obtained resources will be utilized in the biomass lab for generating renewable energy as a part of this research. Participants from households will be asked to dispose of their organic waste in separate containers that will be provided to segregate organic waste from non-organic waste. The organic waste collection will take place on a weekly basis for a period of 2 months since the waste needs to be continuously sent to the biomass lab, where it will be stored and fed into the lab-scale experiments. Once your participation is confirmed, details of the waste collection process and the schedule will be sent to make the process as convenient as possible.

If you're happy to participate, then please complete and sign the form below.

Consent form:

Note: All answers are kept confidential and are used for research purposes only.

- Name:
- Email:
- Phone number:
- Nationality:
- Number of household members
- How many meals does your household consume per day?

- In a normal week, how many times does your household do the following:

- Cook a main meal from raw ingredients.

- Eat out or order a takeout (as a main meal)

- Eat a meal left over from the previous day.

- How do you manage your food waste? (Trash, compost, donation, others)

- What kinds of food do you often waste? (Fruits, vegetables, bread, meat, fish, dairy,)

- Does your food waste mainly consist of cooked or uncooked food?

I agree to participate in this research, where the conditions are as follows:

- The research is aimed to study the potential for recycling food waste collected from households at the University of Bahrain. For this purpose, the form will be filled in with the head of the household.
- The information obtained will be used solely for educational and research purposes.
- At any time, I can refuse to answer certain question (s) or even put an end to the participation without prejudice to myself.
- All collected data will be handled to protect their confidentiality. Therefore, no names will be mentioned.
- The information will be coded, and all data not mentioned in the thesis will be destroyed at the end of the research study.

الملخص

يعد هدر الغذاء مشكلة عالمية بسبب زيادة معدلات توليد النفايات والعواقب الاقتصادية والاجتماعية والبيئية التي يترتب عليها. تم تحديد القطاع المنزلي كمساهم رئيسي في هدر الغذاء عبر سلسلة التوريد الغذائي. علاوة على ذلك، تعتبر التحلل اللاهوائي تقنية واعدة لديها القدرة على توفير حل مستدام لتحويل النفايات العضوية من الغذاء من المواقع الخاصة بالنفايات إلى وقود حيوي يمكن استخدامه كمصدر للطاقة. يهدف هذا البحث إلى دراسة الإمكانيات المتاحة لتحويل النفايات إلى طاقة للنفايات العضوية المنزلية في مدينة جامعية البحرين. ويهدف البحث إلى قياس وتوصيف نفايات الطعام المنزلية وتقييم إمكانياتها كمصدر للتحلل اللاهوائي.

تتضمن المنهجية تصميم دراسة مقطعية تشمل عينات وتحليلات نفايات الطعام، وتوصيف نفايات الطعام، وعملية التحلل اللاهوائي. تم جمع النفايات باستخدام نهج القياس المباشر، حيث يتم جمع نفايات الطعام من باب المنزل. تم توصيف نفايات الطعام على أساس تحليل المواد الصلبة الكلية والمواد الصلبة القابلة للتحلل بالإضافة إلى الخصائص الكيميائية لنفايات الطعام. تم إجراء التحلل اللاهوائي في مفاعل دبابة مخلوطة مستمرة الحركة بحجم 10 لترا تحت ظروف متوسطة الحرارة (37 درجة مئوية)، وسرعة خلط 100 دورة في الدقيقة، وأحمال تحميل عضوية تتراوح بين 2 و 4 غ/ل م-1/يوم. تم إجراء التجارب على نفايات الفاكهة والخضراوات ونفايات الطعام المطبوخ لتقييم أدائها في التحلل اللاهوائي وتحديد الإمكانيات الميثانية.

أظهرت نتائج البحث أن معدل إنتاج النفايات الغذائية المتوسط كان 0.54 ± 3.99 كجم / منزل / أسبوع، وكان 63.3٪ منها يعتبر هدر غير ضروري. وأظهر تحليل الكميات والتركيبات زيادة كبيرة في معدلات إنتاج وتركيب الهدر الغير ضروري خلال رمضان. كان لدى النفايات المجمعة محتوى عالي من المادة العضوية بنسبة 94.2٪ و 95.2٪ من المواد الصلبة القابلة للتحلل للفاكهة والخضراوات و الطعام المطبوخ بالترتيب ، مما يجعلها مناسبة كمصدر لعملية التحلل اللاهوائي. وتم العثور على الإمكانيات الميثانية 370.9 و 380.6 مل / غم من المواد الصلبة القابلة للتحلل في الأحمال العضوية المثلى للفاكهة والخضراوات و الأكل المطبوخ على التوالي. بشكل عام، كان لدى نفايات الأكل المطبوخ أفضل أداء في التحلل اللاهوائي من كما يوحي بذلك الكفاءة الأعلى في التخفيف من الكتلة العضوية القابلة للتحلل والأكسجين الكيميائي ومعلومات استقرارية العملية مثل درجة الحموضة ونسبة القلوية المتوسطة إلى القلوية الجزئية ونيتروجين الأمونيوم.

يخلص البحث إلى أن نفايات الطعام الصادرة من المنازل لديها إمكانيات عالية للتحلل اللاهوائي، وأن التكنولوجيا يمكن تطبيقها في البحرين لتقليل انبعاثات الغازات الدفيئة وتقليل التخلص من النفايات وتوليد الطاقة المتجددة. يساهم البحث في الأدبيات المحدودة حول إدارة وتكنولوجيا التحلل اللاهوائي في البحرين ويوفر الأساس للبحوث المستقبلية.

جامعة البحرين

كلية العلوم



التحقيق في إمكانات تحويل النفايات إلى طاقة لنفايات عضوية منزلية مختارة

أطروحة مقدمة في استيفاء جزئي لمتطلبات درجة الماجستير في البيئة والتنمية المستدامة

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