Development of Household Food Waste Management Framework: A case study of Puerto Rico

Key words: *Framework, Household Food Waste, Management and Puerto Rico*

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Acronyms

AD - Anaerobic Digestion

AcoD - Anaerobic co-digestion

AWTT - Advance Waste Treatment Technologies

BOD - Biochemical Oxygen Demand

CAPEX - Capital Expenses

CE - Circular Economy

COD - Chemical Oxygen Demand

CSTR - Continuous Stirred Tank Reactor

DNER - Department of Natural and Environmental Resources

EPA - Environmental Protection Agency

EQB - Environmental Quality Board

FAO - Food and Agriculture Organization

FBI - Federal Bureau of Investigation

FEMA - Federal Emergency Management Agency

FSC - Food Supply Chain

FW - Food Waste

FWM - Food Waste Management

GDP - Gross Domestic Product

GHGs - Greenhouse Gases

HFW - Household Food Waste

HUD - Housing and Urban Development

LAC - Latin America and the Caribbean

MFW - Municipal food waste

MSW - Municipal Solid Waste

OLR - Organic Loading Rate

O&M - Operation and Maintenance

OPEX - Operational Expenses

OWtE - Organic Waste to Energy

PR - Puerto Rico

PREPA - Puerto Rico Electric Power Authority

REPS - Renewable Energy Portfolio Standard

SDGs - Sustainable Development Goals

SWM - Solid Waste Management

SWMA - Solid Waste Management Authority

UN- United Nations

UNSDGs - United Nations Sustainable Development Goals

US - United States

USD - United Stated Dollars

USDA - U.S. Department of Agriculture

USDANRCS - U.S. Department of Agriculture Natural Resources Conservation Services

USDARD - U.S. Department of Agriculture Rural Development

VS - Volatile Solids

WtE - Waste to Energy

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Chapter One
Introduction

1.1 Introductory Background

This Chapter introduces the importance of developing a sustainable waste management system to avoid adverse impacts from landfills and achieve the United Nations Sustainable Development Goals (UNSDGs). Implementing the anaerobic digestion (AD) process as a treatment method for managing food waste allows for a circular economy since the material are recycled to produce fertilizer and energy recovery. Therefore, organic Waste to Energy (WtE) technologies are a sustainable approach to manage household food waste and generate renewable energy. The study focuses on sustainable technology for waste management of household food waste in Puerto Rico. The methodology entails the research framework created by Saunder, Lewis, and Thornhill (2019) to determine the best techniques and procedures for data collection and analysis. By implementing pragmatism as research philosophy the study focused on the research question and develop a solution to a problem. The study used second literature to identify issues affecting the effectiveness of household food waste management with specific reference to Puerto Rico.

1.2 Problem Statement / Project Rationale

Municipal Solid Waste (MSW) landfills characteristics, influential factors, and environmental risks occur because of unscientific treatment, inappropriate garbage collection, and ethical concerns (Ma *et al*., 2022; Xu and Yang, 2022). Food loss is a significant issue in the United States (US) since it contributes to food security and environmental and financial problems (Babbitt *et al.*, 2022). By implementing a state-of-the-art food loss and waste management system, the UNSDGs can be achieved (Lemaire and Limbourg, 2019). In addition, post-consumption food waste management is critical for its potential for biofuel production (Pour and Makkawi, 2021).

A circular economy (CE) considers the value of the products and materials and their life cycle by taking advantage of the wasted natural resources for economic growth. Therefore, applying the circular economy principle to wasted food by recycling nutrients and energy recovery to avoid food loss. For example, converting food waste to generate bioenergy will help reduce environmental pollution and facilitate the implementation of a circular bioeconomy. Furthermore, implementing the circular economy principle to manage organic waste to generate compost minimizes waste management issues by closing the materials recycling loop and generating extra income. Rashid and Shahzad (2021) stated that a circular economy adds net revenue to the national economy. Food waste management (FWM) implements the circular economy principles by treating organic waste as a reusable resource, such as a sustainable supply of high-value energy through anaerobic digestion (AD). This project will explore the development of household food waste management in Puerto Rico.

The application of alternative food waste management technologies has to understand the environmental, economic, and social impacts to achieve the intended sustainability goals (Trabold and Nair, 2018). Organic Waste to Energy (OWtE) technologies help mitigate environmental impacts by supplying the energy demand while complying with the carbon emissions goals by reducing GHG emissions. The AD process is a promising source of sustainable energy, and it also provides economic and social benefits by providing a source of sustainable energy (Silva-Martinez et al., 2020). Appropriately managing and utilizing food waste through anaerobic digestion is crucial for solving environmental and economic concerns (Cai et al., 2022). For example, challenges in post-consumption food waste management and assessing its potential for biofuel production (Pour and Makkawi, 2021). The SDGs can be achieved through hydrogen's energy and environmental benefits from biogas using food waste (Cudjoe, D., Zhu, B., and Wang, H.,2022).

Food waste management allows for biofuels and composting, the recycling of nutrients, and carbon fixation (Girotto et al., 2015). Efficient food waste management is crucial to understanding the engineering aspect of food waste's collection, storage, and biotransformation into useful value-added products such as biofuels (Haldar *et al.*, 2022). Food waste management is vital to the transition into a circular economy and to contribute to the SDGs (Adelodun, B., Kim, S.H., and Choi, K.S., 2021). Food waste is a global issue due to its significant ecological, social, and economic impacts (Cudjoe, D., Zhu, B., and Wang, H., 2022). Therefore, the development of an integrated system able to reduce household food waste is urgently needed (Cappelletti *et al*., 2022).

1.3 Research Question

Given the narrative given in section 1.2 above, the Research Question for this project will be as noted below:

What sustainable framework could be develop for household food waste management in Puerto Rico?

1.4 Research Aim and Objectives

The project aims to develop a household food waste management framework using Puerto Rico as a case study.

The objectives are as follows:

a) Review literature in the subject area to include household food waste management and the various frameworks that have been adopted in the public domain with a specific focus on Puerto Rico (Chapter Two).
b) Identify issues and impediments that are currently affecting the effectiveness of household food waste management in the Caribbean with specific reference to Puerto Rico (Chapter Two - Summary of Literature Review).
c) Propose a methodological approach for addressing the issues relating to household food waste management in the Caribbean using Puerto Rico as a case reference (Chapter Three).
d) Using the issues noted in b) and the methodology noted in c) above, provide a succinct discussion and findings as it relates to household food waste management in Puerto Rico (Chapter Four).
e) Propose and make recommendations to policy makers and their advisers on the approach to effective management of household food waste in Puerto Rico (Chapter Five).
f) Summarise, conclude and state the likely future work that would enhance the outlook of the undertaken project (Chapter Five).

1.5 Developed Methodology

The methodology used in the study was based on the research framework developed by Saunder, Lewis, and Thornhill (2019) to determine which data collection techniques and analysis procedures apply best. This dissertation adopts pragmatism as a research philosophy since it uses quantitative and qualitative data to provide a practical solution to an issue. Deductive research was the research approach since it states that an idea should be tested before being rejected. The research strategy was based on case studies, archival research, and action research. This research adopted a cross-sectional timeframe since it was a short-term study. The study collected data from secondary sources, and the researcher ensured that the data was appropriate and relevant to the research need. The data analysis method used for this research project was content analysis. The researcher acknowledged the ethical considerations and limitations the research may present.

1.6 Proposed Contributions

This section contains the research contribution (Chapter Five)

The Research Contribution of this project as follows:

i. Propose an assessment to sustainable manage HFW in Puerto Rico

ii. Examine the potential use of AD with CHP

iii. Assess the implementation of a WtE facility in Puerto Rico

1.7 Structure of Report

Chapter 1 - Introduction

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Chapter 2 - Literature Review

Chapter Two
Literature Review

2.1 Introduction

This Chapter reviews the literature in an attempt to develop an effective Household Food Waste Management (HFWM) framework in the Caribbean, using Puerto Rico as a case study. First, general issues relating to public-domain waste management will be explored. In addition, issues relating to the public debate regarding the circular economy will be synthesized. Next, the different waste management technologies will be evaluated. Then, aspects of household food waste will be explored. Finally, the Chapter concludes by summarising literature with the object of deducing the Problem Statement and the associated Research Question.

2.2 General Issues of Waste Management in Public Domain

Ma *et al*., (2022) discussed leachate from MSW landfills from a global perspective, such as characteristics, influential factors, and environmental risks. A landfill is the most popular method for disposal of MSW even tho it generates a large amount of stench, methane, and leachate. Landfill leachate can be described as landfill wastewater, and it contains high-level pollutants such as degradable organic matter (DOM), inorganic macro components (IMC), heavy metals (HM), and others. The percentage of food waste influences landfill leachate pollutants and the effect on the environmental (Ma *et al*., 2022). For example, in the early aerobic phase of landfilling, concentrations of organic components in leachate can be very high. Differently, the concentration of ammonia nitrogen may lead to long-term contamination. Examine the environmental risks and potential mitigating measures for pursuing sustainable MSW management due to the potential contamination of landfill leachate (Ma *et al*., 2022). Ma *et al*., (2022) stated the influential factors for MSW landfill leachate pollutant concentrations, such as landfill age, waste compositions, temperature, precipitation, and others. Landfill leachate contains many pollutants and may leak into the surrounding water and soil environment due to inappropriate site selection, design, and operation of landfills. Therefore, it is helpful to understand the physicochemical characteristics of landfill leachate and their influential factors and environmental impacts to promote sustainable MSW management (Ma *et al*., 2022). Food waste is the most highly soluble and has a much higher initial water content. These two properties make food waste most biodegradable, resulting in large amounts of organic matter (Ma *et al*., 2022). Food waste composition is the most significant factor because it is a rapidly biodegradable component of MSW and has more highly soluble organic matter and ammonia nitrogen than other fractions, thus becoming the dominant source of COD and NH3-N in landfill leachate (Ma *et al*., 2022).

Xu and Yang (2022) discussed municipal hazardous waste management with reverse logistic exploration. The authors argued that the main focus of waste management is collecting and treating municipal waste that cannot be recycled (Xu and Yang, 2022). The main influential factors affecting solid waste management are unscientific treatment, inappropriate garbage collection, and ethical concerns; the aftermath of these decisions causes soil erosion and degradation and air and water pollution (Xu and Yang, 2022). Municipal waste management approaches are reprocessing, composting, combustion, and landfilling. Inadequate storage, transportation, treatment, or disposal operations may damage. Solid Waste Management (SWM) is the field concerned with managing solid waste while complying with the appropriate principles of public wellbeing, economy, engineering, conservation, aesthetics, and other relevant principles (Xu and Yang, 2022). Since the 1990s, global consumption of various products has increased due to population growth and varying income levels (Xu and Yang, 2022). The post-consumption leftovers are found in the environment regardless of whether they are in the air, water, or land (Xu and Yang, 2022).

Pour, and Makkawi (2021) discussed post-consumption food waste management and its potential for biofuel production. The authors argued that the expected global world food waste production would increase by 33% within the next decade (Pour and Makkawi, 2021). The current annual food waste stands at around 1.6 billion tonnes, worth around a $ 1.2 trillion loss (Pour and Makkawi, 2021). Food waste is causing severe environmental concerns as it contributes 6% to the total global greenhouse gas (GHGs) emissions (Pour and Makkawi, 2021). This article discusses the latest trends and challenges in post-consumption food waste management and assesses its potential for biofuel production (Pour and Makkawi, 2021). Food loss has increased significantly through the years along with global population growth. Food waste is one of the most significant components of municipal solid waste (MSW) and can account for up to 50%–60% of the total waste (Pour and Makkawi, 2021). Therefore, there is increasing interest in recycling this waste using methods of minimum impact on the environment, low cost, sustainability, and suitable for transforming the waste into valuable products (Pour and Makkawi, 2021). Strict regulations on waste management and the growing worldwide interest in sustainability make this possible. Food waste is considered a subset of food loss, mainly consisting of remains of matters prepared initially for human consumption (Pour and Makkawi, 2021). The study highlighted the benefits of converting food waste into energy. Due to the interruption of the supply chain by bad weather or natural disasters, such as hurricanes or floods, food can be lost (Pour and Makkawi, 2021). The Food and Agriculture Organization (FAO) has estimated that around 936 billion USD worth of food is lost annually, in addition to billions of dollars spent on transportation and proper disposal (Pour and Makkawi, 2021).

Babbitt *et al.*, (2022) discussed how transforming wasted food will require systemic and sustainable infrastructure innovations. The authors argued that 40% of the food produced in the United States is wasted, therefore wasting resources which causes issues for food security, more economical costs, and environmental problems (Babbitt *et al.*, 2022). Nonetheless, food waste can be used for sustainability purposes, such as recycling carbon and nutrients and converting food wastes into bioenergy (Babbitt *et al.*, 2022). However, modern food systems infrastructures are expensive, resource intense, and vulnerable to climate change, natural disasters, geopolitical instability, cyber threats, contamination, and global health crises. In the U.S., food waste is disposed of in landfills, leading to methane emissions and climate impacts. Globally, wasted food accounts for 8% of all greenhouse gas emissions. While wasted food reflects inefficient food production and consumption practices, it also represents an opportunity for environmental, economic, and social gains. Past efforts to minimize or manage waste have often met limited success because they fail to consider economic, social, policy, technology, and environmental interconnections inherent to this system.

Lemaire and Limbourg (2019) discussed how food loss and waste management could achieve sustainable development goals. The authors argued the need to establish a state-of-the-art food loss and waste management system to address the United Nations Sustainable Development Goals (Lemaire and Limbourg, 2019).

2.3 Overall Principles of Circular Economy

Do et al., (2021) defined circular economy (CE) as the maximum retainment of the products and materials value for a more extended period by taking advantage of the wasted natural resources for economic growth. Further, the mitigation of food loss is one of the United Nations Sustainable Development Goals (UNSDGs) (Do et al., 2021). In other words, the CE principle contemplates the triple R principle - reduce, reuse, recycle depending on the environment's condition (Do et al., 2021). Therefore, food loss and waste (FLW) is a complex and multi-faceted issue to implement in the CE (Do et al., 2021). The CE includes strategies for closing, slowing, or narrowing resource loops. Closing completes a resource circle by connecting the post-use of a resource with the production stage via recycling. At the same time, slowing loops reduce the speed of resource flow by extending the in-use period with long-life design and maintenance, repairs, and remanufacturing services. The cradle-to-cradle philosophy regards all materials made of two distinct types of nutrients: technical and biological. Food is classified as consumable products made of non-toxic and beneficial biological nutrients that can be safely re-introduced to the environment, either directly or via a cascade of consecutive use To build natural capital. This biological metabolism contrasts with durable products made of technical nutrients (e.g., polymers, alloys) that are not suitable for returning safely to the environment and should be designed with minimal energy and the highest quality retention. Building upon cradle-to-cradle philosophy, the CE also drives a shift in the material composition of consumable items from technical to biological nutrients to make products serving a restorative purpose (Do et al., 2021). Building on performance economy, the CE focuses on the products' performance, such as having an extended life cycle and consuming less energy and resource (Do et al., 2021). Adopting the blue economy principles, the CE encourages the use of resources in a cascading manner and promotes the use of one person's wastes as resources for others, as well as minimizing resource leakage (Do et al., 2021). Food waste is used to extract bioactive compounds before the residues of this process are used for lower-value energy and composting production. Ideally, the food system design follows the natural regenerative mechanism (Do et al., 2021). Therefore, the CE supports establishing the industrial symbiosis concept, which involves the mutually beneficial exchanges of materials, energy, water, and wastes between parties with geographic proximity to design out waste (Do et al., 2021).

Slorach et al., (2019) discussed the environmental and economic implications of recovering resources from food waste in a CE. Globally around a third of the food produced is wasted, requiring significant resources for its treatment and disposal and wasting valuable resources (Slorach et al., 2019). The CE principle design avoids food loss and wasted food by treating it differently to recycle nutrients (Slorach et al., 2019). The authors discussed the life cycle environmental and economic implications of recovering energy and material resources from food waste. The results show that per tonne of waste treated; anaerobic digestion has the lowest environmental impacts (Slorach et al., 2019).

Organic Waste Management (OWM) currently adopts the linear economy principle, while the CE focuses on reducing, recycling, and reusing materials (Rashid, M.I., and Shahzad, K., 2021). The study investigated the economic and environmental monetary values by converting organic food waste (OFW) into compost, following the circular economy principles (Rashid, M.I., and Shahzad, K., 2021). Implementing the circular economy principle to manage organic waste to generate compost minimizes waste management issues by closing the materials recycling loop and generating extra income. It adds net revenue to the national economy (Rashid, M.I., and Shahzad, K., 2021).

Usmani et al., (2021) stated that untreated food waste poses a significant threat to the environment by emitting greenhouse gases (GHGs) into the atmosphere, deteriorating water quality, and contaminated land. Therefore, food waste management (FWM) is implementing the circular economy principles by focusing on treating organic waste as a reusable resource, such as a sustainable supply of high-value energy through AD (Usmani et al., 2021).

Sadeleer et al., (2020) discussed waste prevention, energy recovery, and recycling through directions for household food waste management in light of circular economy policy. The authors argued that waste amounts are growing with increasing wealth and population. Therefore, food waste reduction has made it on the political agenda, together with ambitious material recycling and greenhouse gas (GHG) emissions targets. Sadeleer et al., (2020) analyzed the environmental benefits of waste management systems for household organic food waste, such as recycling by anaerobic digestion (AD). The respective waste management strategies achieve avoided GHG emissions. The authors state that food waste recycling with AD obtains better recycling rates and GHG emissions.

2.4 Waste Management Technologies

Trabold and Nair (2018) discussed conventional food waste management methods. The authors argued the need to understand the technologies' benefits and disadvantages and how the food waste material phase influences the technically viable options. The composting method offers beneficial use pathways for food waste materials. Nonetheless, these processes require a high level of waste homogeneity and purity. To consider the application of alternative food waste management technologies. In all cases, it is necessary to comprehend the full spectrum of environmental, economic, and social impacts to ensure that the application of alternative food waste management technologies achieves the intended sustainability goals (Trabold and Nair, 2018). It has been known that most current food system waste practices are environmentally and economically detrimental, and more sustainable solutions are needed. Conventional waste management methods must be understood. Humans never consume 30% to 40% of the food resources produced (Trabold and Nair, 2018).

Organic Waste to Energy (OWtE) technologies significantly contribute to supplying the regional energy demand and meeting national carbon emission goals (Silva-Martinez *et al*., 2020). It can potentially enhance waste and energy systems in the region by lessening environmental impacts along with social and economic benefits, such as increasing access to a sustainable energy supply (Silva-Martinez *et al*., 2020). AD is an efficient technology for treating solid organic wastes and producing biofuels (Silva-Martinez *et al*., 2020). However, bio waste, such as household organic wastes, is not sufficiently recognized as a valuable energy source with significant potential in Latin America and the Caribbean (LAC) countries (Silva-Martinez *et al*., 2020). Biochemical, organic waste treatment technologies are based on the decomposing organic matter under microbial action to produce biogas and digestate, such as biofertilizers (Silva-Martinez *et al*., 2020). The conversion technologies utilize microbial processes to transform degradable waste such as food into biogas under anaerobic conditions. The main reason to implement AD is that it requires low investment cost and low maintenance, resulting in multiple successful biodigesters designs and the adoption of small-scale technologies (Silva-Martinez *et al*., 2020). In Puerto Rico, benefits from using manure and residues from local dairy farms have motivated interest in using small-scale AD technologies. In the case of the Caribbean, there is currently a large-scale plant under construction in Puerto Rico to treat urban waste mixed with Napier grass feedstock (Silva-Martinez *et al*., 2020). No incineration plants exist, and urban waste is landfilled or recycled in Puerto Rico.

Mahmudul *et al., (*2022) discussed the implementation of the AD technique to manage food waste (FW) by converting it into sustainable energy. Therefore, this paper aims to study sustainable energy production's technological, economic, and environmental feasibility from household FW. In addition, Mahmudul *et al., (*2022) discussed household FW's technological, economic, and environmental feasibility as a sustainable energy source. In addition to different waste-to-energy (WtE) technologies, the operational parameters and the challenges in developing a biogas plant. FW plays a vital role as a source of sustainable renewable energy since it is rich in nutrients, energy, and water and can be used to produce high-quality renewable fuels, such as biogas (Mahmudul *et al.,* 2022). Further, it can benefit the country's economy significantly and reduce GHG emissions (Mahmudul *et al.,* 2022). The authors stated that worldwide population growth is rapidly increasing, leading to continuing crises concerning energy security and climate crises. Mahmudul *et al., (*2022) explain how using renewable energy such as biogas is critical in mitigating GHG emissions. Researchers are trying to discover economically viable renewable energy sources to overcome energy and environmental concerns. Approximately one-third of food produced is worth $750 billion and accounts for 6.8% of global annual GHG emissions by being discarded in the food supply chain (Mahmudul *et al.,* 2022). FW disposal has negative impacts on the environment, for example, environmental degradation and vast quantities of GHGs emissions, specifically methane and carbon dioxide pollution. The authors focused on developing different techniques for converting FW into a high-value-added product. Mahmudul *et al., (*2022) state that biogas production from the AD process offers many advantages such as broader feedstock flexibility, reduced GHG emissions, low footprint production, and high energy sustainable fuel generation. Further, WtE technologies can address FW and related concerns, such as air pollution, health consequences, fuel security, and fossil fuel import reliance (Mahmudul *et al.,* 2022). AD is an outstanding alternative to FW treatment since it provides environmental safety and energy use. However, the lack of use of the AD process is due to higher capital investment, long processing periods, and the required efficient control of some essential factors. Waste generation volume correlates with the size of the population and economic growth. AD is one of the most effective and efficient ways of processing high moisture content waste. Mahmudul *et al., (*2022) described the AD process in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In the first stage, substrates break down into simple molecules, such as fatty acids, simple sugars, and alcohol. Second, acidogenesis transforms products from acetates of the first phase. In the third stage, acetogenesis produces organic acids and hydrogen by converting soluble molecules into acetic acid, alcohol, carbon dioxide, and hydrogen. The last stage uses methanogenic bacteria to produce methane and carbon dioxide from the products of acetogenesis. Factors to consider to avoid digestion failure are the bacteria's environment and mobility within the digester (Mahmudul *et al.,* 2022). For example, the ability of the AD process to efficiently digest feedstocks with lower or higher than average pH values and having temperatures ranging from 2 ◦C to more than 100 ◦C are suitable for biological methanogenesis(Mahmudul *et al.,* 2022). The biogas plant requires neutralized feedstock, meaning a favorable C: N ratio for efficient AD functioning. Building a biogas plant can reduce GHG emissions in various ways, including reducing emissions from landfills by reducing the amount of waste transferred to landfills and creating energy using green sources rather than fossil fuels. Sustainable waste management policies and upgrading waste recycling and treatment through composting are crucial for the development of a country (Mahmudul *et al.,* 2022).

AD process provides a fundamental approach for food waste treatment and valorization and produces considerable digestate (Cai et al., 2022). Therefore, appropriately managing and utilizing food waste, such as anaerobic digestion, is highly desirable for solving environmental and economic problems. Furthermore, the process develops a natural potential difference-assisted landfill technology for food waste treatment and energy recovery. The results demonstrate that the electrochemical assistant accelerates the stabilization of digestate and provides an extra 14.89% of organic matter removal and 20.92 mW/m2 of electrical energy recovery over conventional treatment (Cai et al., 2022).

Sailer *et al*., (2022) discussed the improvement of the energetic utilization of household food waste and the impact of temperature and the atmosphere during storage. The authors argued that the percentage of household food waste in municipal waste is substantial. The objective of this study was to assess the impact of storage duration and temperature to determine the energy potential of household food waste during anaerobic digestion (AD). Household food waste is the major component of the organic fraction of municipal solid waste (OFMSW). This waste stream is often collected in separate biowaste bins at the household level. High concentrations of carbohydrates together with low pH values might cause instabilities such as hyperacidity during AD (Sailer *et al*., 2022). Furthermore, organic waste-based AD process fundamentals and enhancements, digestion types, and effects on mitigating greenhouse gas emissions have been reviewed (Sailer *et al*., 2022).

2.5 Household Food Waste

Girotto et al., (2015) described food waste as organic matter intended for human consumption, and its increase is causing problems in all sectors of the waste management process. Furthermore, food waste allows for the production of biofuels and composting, the recycling of nutrients, and carbon fixation (Girotto et al., 2015).

Cappelletti et al., (2022) discussed household food waste management strategies by developing an integrated system to reduce household food waste. The Food and Agriculture Organization (FAO) first defined food waste as edible material intended for human consumption, arising at any point in the Food Supply Chain (FSC) that is instead discarded, lost, degraded, or consumed by pests. The leading causes of food waste are the consumers' inclination to buy more food than needed because of the incorrect planning of purchase, often related to the lacking awareness about the food stocks available at home, retailers' pricing strategies, stock of items bought for special occasions that have never occurred, and the confusion about the product expiration dates (Cappelletti et al., 2022).

Haldar et al., (2022) discussed the understanding of the management of household food waste and its engineering for sustainable valorization- a state-of-the-art review. The authors argued that an increased population causes higher demand for energy, more waste output, and adverse environmental impacts. Approximately 1.6 gigatons/yr is generated globally in food waste, representing an economic revenue of 750 billion USD. The study demonstrates the possibilities of food waste management. The engineering aspect in food waste collection, storage, and biotransformation into useful value-added products such as biofuels are critically reviewed for efficient management of food waste. The world population of 7 billion will reach 9.8 billion by 2050. The worldwide demand for food will rise as the world's population grows, putting strain on the global food supply system. Large/Vast quantities of food waste are accumulated due to industrialization and poor waste management. According to the Food and Agriculture Organization (FAO), around 1.3 billion tons of food is lost and squandered annually, costing the world economy 750 billion dollars. As per the estimation of the FAO, over 936 billion USD of food is squandered every year, along with billions of dollars used for transport and appropriate disposal method. Improper garbage management causes a variety of environmental problems and health hazards. The fundamental challenges in proper waste management are collection, storage, and segregation. Bioprocesses were explored as possible sustainable techniques for converting FW to various products such as chemicals, biofuels, fertilizers, and animal feed. The article explores household FW quantification approaches, emphasizing approaches that address composition analysis for FW characterization and challenges faced due to the lack of a critical and complete assessment of FW quantification methods. The comprehensive categorization of food waste is crucial for the management of food waste. The concentration of biogas and energy production can be calculated, for example, by assessing the components of the raw materials utilized in the anaerobic digestion. Similarly, the water content, C: N ratio, and pH are significant elements in optimizing the composting effectiveness of the food waste. An average of 2.8 kg of FW was generated from each household per week, in which 1.5 kg of waste was categorized as avoidable, and the rest of the waste was influenced by grocery and restaurant stuff. Food waste includes much water on an average of nearly 80% of the mass in most circumstances. This renders food waste vulnerable to microbial decay and unsuitable for long-term storage.

Adelodun, Kim, and Choi (2021) stated how food waste management is increasingly important to transition into a circular economy and achieve sustainable development goals. Therefore, the authors studied the quantity and composition of food waste generation rates among the sampled households by considering two critical influencing factors seasonality and housing types. First, food production requires substantial agricultural land to grow crops and rear animals and an enormous quantity of water for crop irrigation and animal drinking. Second, reliable energy sources are needed at different stages of food production, such as processing, transportation, and storage, leading to significant greenhouse gas emissions (Adelodun, B., Kim, S.H., and Choi, K.S., 2021).

Cudjoe, D., Zhu, B., and Wang, H., (2022) discussed how food waste is a worldwide issue due to its significant ecological, social, and economic impacts. In addition, vast food waste has resulted in severe environmental implications. Hydrogen gas from biogas derived from food waste is considered a potential source of clean energy production. The present study assesses how the energy and environmental benefits of hydrogen from biogas using food waste could contribute to realizing sustainable development goals (Cudjoe, D., Zhu, B., and Wang, H., 2022).

2.6 Summary of Literature Review

The summary of literature is as noted below:

i. Ma *et al*., (2022) discusses municipal solid waste (MSW) landfills characteristics, influential factors and environmental risks caused by leachate pollutants.

ii. Xu and Yang (2022) argue that some of the influential factors affecting solid waste management and the environment is unscientific treatment, inappropriate garbage collection and ethical concerns.

iii. Pour and Makkawi (2021) discuss the post-consumption food waste management and its potential for biofuel production, since the global world production of food waste is expected to increase causing more economic loss.

iv. The United States (US) has a severe food loss problem, therefore wasting resources which causes issues for food security, more economic costs, and environmental problems (Babbitt *et al.*, 2022).

v. Food Waste Management (FWM) can achieve the United Nations Sustainable Development Goals (UNSDGs) by implementing a state-of-the-art food loss and waste management system (Lemaire and Limbourg, 2019).

vi. Do et al., (2021) defines circular economy (CE) as the maximum retainment of the products and materials value for a longer period of time by taking advantage of the wasted natural resources for economic growth.

vii. The circular economy principle considers the life cycle environmental and economic implications of wasted food; therefore, the recycling of nutrients and energy recovery should be implemented to avoid food loss (Slorach et al., 2019).

viii. The implementation of the circular economy principle to manage organic waste to generate compost minimizes waste management issues by closing the materials recycling loop, generating extra income, and adds net revenue to the national economy (Rashid and Shahzad, 2021).

ix. Food waste management (FWM) is implementing the circular economy principles by focusing on treating organic waste as a reusable resource, such as a sustainable supply of high-value energy through AD (Usmani et al., 2021).

x. Sadeleer et al., (2020) discussed circular economy policies such as waste prevention, energy recovery, and recycling concerning household food waste management.

xi. Trabold and Nair (2018) discusses the importance of understanding the full spectrum of environmental, economic, and social impacts to ensure that application of alternative food waste management technologies achieves the intended sustainability goals.

xii. A possible way to supply the energy demand while complying with the carbon emissions goals is by implementing Organic Waste to Energy (OWtE) technologies, such as anaerobic digestion (AD), which will contribute in improving waste and energy systems in the region and it will help mitigate environmental impacts and provide economic and social benefits by providing access to a sustainable energy supply (Silva-Martinez et al., 2020).

xiii. Anaerobic Digestion (AD) is a promising source of sustainable energy and is capable of benefiting the country's economy significantly and reducing GHG emissions (Mahmudul et al., 2022).

xiv. The appropriate management and utilization of food waste through anaerobic digestion is highly desirable for solving both environmental and economic concerns currently (Cai et al., 2022).

xv. Sailer *et al*., (2022) studied critical factors (storage duration and temperature) affecting household food waste energy potential during AD.

xvi. Food waste allows for the production of biofuels and composting the recycling of nutrients and carbon fixation (Girotto et al., 2015).

xvii. Cappelletti *et al*., (2022) argued that the development of an integrated system is able to reduce household food waste.

xviii. Haldar et al., (2022) discusses the engineering aspect in the collection, storage, and biotransformation of food waste into useful value-added products such as biofuels are critically reviewed for efficient food waste management.

xix. Food waste management is increasingly important to achieve the transition into a circular economy to achieve the sustainable development target goals (Adelodun, B., Kim, S.H., and Choi, K.S., 2021).

xx. Food waste is a worldwide issue due to its significant ecological, social, and economic impacts., since high amount of food waste has resulted in severe environmental implications (Cudjoe, D., Zhu, B., and Wang, H., 2022).

Chapter Three
Methodological Approach

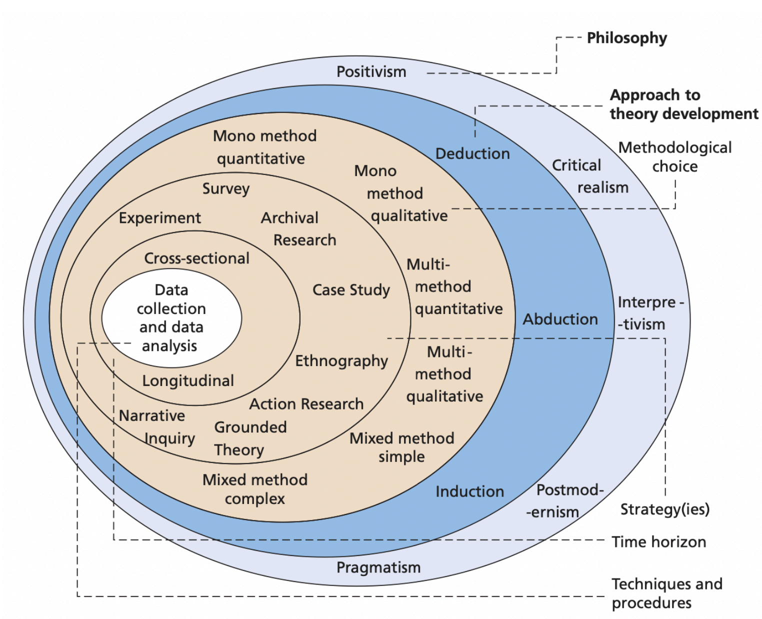
3.1 Introduction

This Chapter described the methodology used in the study for development of household food waste management framework in Puerto Rico. This Chapter will consist of (6) sections: research philosophy, research approach, research strategy, choice of methods, time horizons, techniques and procedures for data collection and analysis and ethical considerations.

3.2 Research Framework

The research framework is based on a structured set of guidelines developed by Saunders, Lewis and Thornhill (2019) known as the 'research onion' (Figure 1). The methodology comprises of the issues from the outer layer to the inner layer, such as choice of data collection techniques and analysis procedures.

Figure 1. Research Onion



(Saunders, Lewis and Thornhill, 2019)

3.3 Research Philosophy

Saunder, Lewis, and Thornhill (2019) explained research philosophy as assumptions the researcher believes to be accurate, authentic, and knowledgeable. It frames the beliefs and values behind the design, collection, and analysis of the data in the research study. Therefore, it is an essential tool for determining the appropriate research design. Conducting a research philosophy helped refine the study's research strategy and the research method to answer the research question posed (Saunder, Lewis, and Thornhill, 2019). The four paradigms for organizational analysis were a helpful tool for understanding different research philosophies and their relationships to various research paradigms. There are four major research philosophies: positivism, interpretivism, realism, and pragmatism. Connections between paradigms and research philosophies need to be seen in terms of philosophical affinity rather than equivocality and treated with caution and reflexivity (Saunder, Lewis, and Thornhill, 2019).

This research attempts to develop knowledge of the household food waste management framework in Puerto Rico. According to Saunder, Lewis, and Thornhill (2019), positivism research philosophy is a scientific method designed to yield pure data and facts uninfluenced by human interpretation. Positivism research philosophy is independent, and maintains an objective stance, and has one actual reality. Its methods are typically deductive and use quantitative data. This method allowed for a through investigation and understanding of the smallest part of the study in a controlled manner to allow the exploration and pure observations of the research matter. As a positivist, the researcher tries to remain neutral and detached from the research and data to avoid influencing its findings. They claim to be external to the data collection process as little can be done to alter the substance of the data collected.

Interpretivism as a research philosophy is complex, socially constructed, has different meanings and realities and is subjective. This method is inductive and uses qualitative data. The purpose of interpretivism research is to create new, richer understandings and interpretations of social worlds and contexts. With its focus on complexity, richness, multiple interpretations, and meaning-making, interpretivism is explicitly subjectivist. Crucial to interpretivism philosophy is that the researcher has to adopt an empathetic stance. The challenge for interpretivism is to enter the social world of the research participants and understand that world from their point of view.

Critical realism philosophy focuses on explaining what we see and experience in terms of the underlying structures of reality that shape observable events. Reality is the most crucial philosophical consideration. Critical realists see reality as external and independent but not directly accessible through our observation and knowledge. Critical realist research takes the form of an in-depth historical analysis of social and organizational structures and how they have changed over time. Critical realism recognizes external factors and internal beliefs that influence the relationships between people and individual behaviors. It allows the study to consider diverse social entities' structures and processes, providing a worldview perspective. Given the nature of the study, using critical realism as a research philosophy allowed the researcher to adopt a coherent philosophical position and discover the underlying reality behind the development of the household food waste management framework. Critical realism also helped the researcher in understanding the events that led Puerto Rico to develop/need a strategic household food waste management framework. Critical realists are less objectivist than positivists. Therefore, a critical realist researcher would strive to know how the socio-cultural background and experiences might influence the research. Therefore the researcher seeks to minimize such biases and be as objective as possible.

However, the research used in the study is quantitative and qualitative data. The study was conducted under the pragmatism research philosophy since it is helpful for qualitative, quantitative, or mixed methods research. It helps understand the issues and problems encountered by focusing on the research question and the main issue. What unifies pragmatists is their conceptualization of scientific progress as the increased effectiveness of theories in guiding problem-solving behavior. Within pragmatism, conceptual standards are treated as having contextually situated practical value rather than an ontological privilege. A pragmatic study focuses on finding/providing solutions to practical problems. Pragmatic research philosophy can integrate multiple research methods such as qualitative, quantitative, or mixed. In this study, we used both. Pragmatism researchers seek to overcome objectivism–subjectivism in their research and, as such, are likely to engage in multi-paradigmatic research. Pragmatism asserts that concepts are only relevant where they support action. It strives to reconcile objectivism and subjectivism, facts and values, accurate and rigorous knowledge, and different contextualized experiences. For a pragmatist, research starts with a problem and aims to contribute practical solutions that inform future practice.

3.4 Research Approach

Deductive research has a rational approach meaning that the idea should not be rejected without being tested first (Saunder, Lewis, and Thornhill, 2019).

3.5 Research Strategy

The research strategy was based on case studies, archival research and action research. Action research is included since waste management is a current issue in Puerto Rico and the community is working towards a solution. For the purpose of this research, using archival research and case studies allowed and in-depth exploration of household food waste management framework as a sustainable source of energy and waste management. It provided the research with multiple perspectives, real-life context, a rich analysis and understanding of the situation and offering a possible solution.

3.6 Research Choices

The research gathered qualitative and quantitative data to demonstrate the feasibility of the study. Quantitative research examines the relationship between variables and analyses them in forms of statistics and graphs; whereas qualitative research is interpretive in a way that the researcher should make sense of meaning expressed about the topic being studied. This research adopted a mixed method research allowing the researcher to explore the household food waste management from diverse perspectives. Using qualitative and quantitative data for this research brought more comprehensiveness and understanding of the complexity of implementing a Waste to Energy (WtE) plant for household food waste management in Puerto Rico.

3.7 Time Horizon

Time horizon is defined as the timeframe of the research. Cross sectional research is a short-term study where different variables are studied at a given time. This research adopted a cross-sectional timeframe. The development of household food waste management framework used data gathered in recent years.

3.8 Data Collection

In order to collect data from secondary sources for this research project, the researcher ensured that the data was appropriate and relevant to the research need. It was also vital for the researcher to evaluate the data quality and verify that the source was reliable and viable. The researcher used documents from official websites. In addition, the researcher may use missing data from other websites, such as official publications from the US Department for Business Energy, Environmental Protection Agency, and other governmental documents. The researcher also has direct access to published books and journals. The researcher reviewed seventy-five publicly available documents relating to household food waste management. The study data collection was obtained via a series of methods. First, the researcher conducted secondary literature research using keywords (Framework, Household Food Waste, Management, and Puerto Rico) which provided a broad selection of documents. Most of the articles used are from recent years.

3.9 Data Analysis

The data analysis method used for this research project was content analysis. Content analysis is based on describing and analyzing various types of documents: official, semi-official, or unofficial. It can also be from primary or secondary sources and statistical sources such as census records, financial statements and others.

The research combined qualitative and quantitative methods to the content analysis, which allowed us to further explore the development of household food waste management as a sustainable and renewable source. This research analyses the documents regarding authenticity, credibility, representativeness, and meaning.

The sections that were analyzed for the framework of a WtE facility are:

- Feedstock: Household food waste capacity, calorific value (CV), total thermal available
- Technology: total energy, electricity, heat produced, capacity
- Financial: capital expenses (CAPEX), operational expenses (OPEX), waste services fee, tax (corporation)

3.10 Ethical Considerations

This research used documents that are publicly available and pre-existing on the internet. The researcher understood the ethical issues related to using documents from the public domain and ensured ethical diligence and appropriateness when studying the online content. The researcher was honest during data collection and analysis; therefore, this project contains valid information.

3.11 Limitations

The study presented certain limitations. The authors and the governments had data from different years, which made it difficult to obtain a more realistic measure. The researcher collected secondary data based on the official documents from the government's websites. The time to realized the project was the biggest limitation.

3.12 Summary of Methodology

The methodology adopted the deductive approach along with pragmatism which enabled a new way of understanding the framework for household food waste management in Puerto Rico using secondary data. The research obtained secondary data and combined qualitative and quantitative methods to explore the diverse perspectives on household food waste management. The research was cross-sectional; therefore, a content analysis was applied to analyze possible management for HFW in Puerto Rico.

Chapter Four
Implementation-Discussion and Findings

4.1 Introduction to Sustainable Household Food Waste Development

This Chapter provides an overview of Puerto Rico, such as the description of its location, population, politics, economy, and environment current situation. A multi-varied analysis was realized to consider different variables, such as food waste, climate change, circular economy, and advanced waste treatment technologies, to provide viable, sustainable options to reduce organic waste in landfills. Implementing a WtE plant in Puerto Rico reduces waste and protects the island's natural resources. The study analyzed the financial implications of developing a WtE facility in Puerto Rico.

4.2 Overview of Puerto Rico

4.2.1 Location

The Commonwealth of Puerto Rico is located on the continent of North America, specifically southeast of Florida between the Caribbean Sea and the North Atlantic Ocean (Figure 2). Puerto Rico is one of the Greater Antilles located east of the Dominican Republic and west of the Virgin Islands. The island is located south of the Puerto Rico Trench, the deepest part of the Atlantic Ocean. The island is 100 miles by 35 miles consisting of an area of 3,515 square miles. The capital of Puerto Rico is San Juan, located in the island's northeast part. Puerto Rico has a tropical climate with minimal seasonal variation.

4.2.2 Population

In 2021 the census reported that Puerto Rico had a population of 3,263,584 people (Economic Development Bank for Puerto Rico, 2022). A year following Hurricane Maria, the population and poverty rate declined in Puerto Rico (Figure 3). However, Puerto Rico's population growth rate is declining by -0.5% due to migration to the United States. In addition, almost half of the mortality rate is higher than the natality rate (Table 1).

Figure 2. Location of Puerto Rico

Figure 3. Population Growth Rate

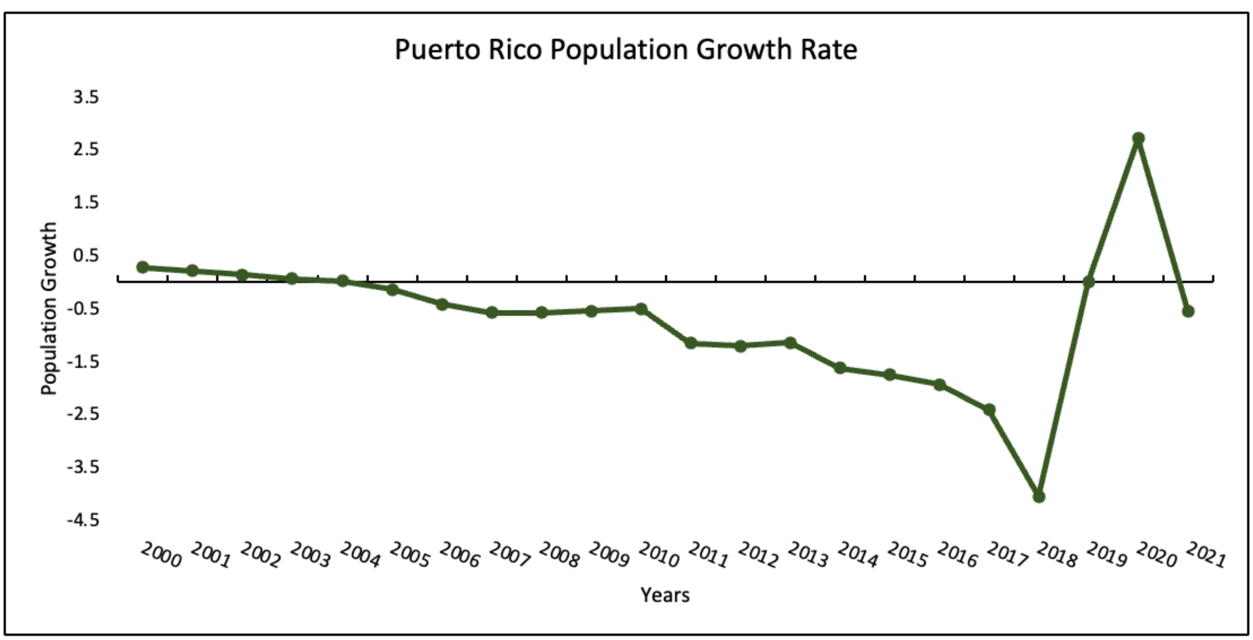


Table 1. Population Characteristics

Population	Value
Population Growth Rate	-0.5
Natality Rate	5.7 births / 1,000 population
Mortality Rate	10.0 deaths / 1,000 population
Net Migration Rate	-1.3 migrant / 1,000 population

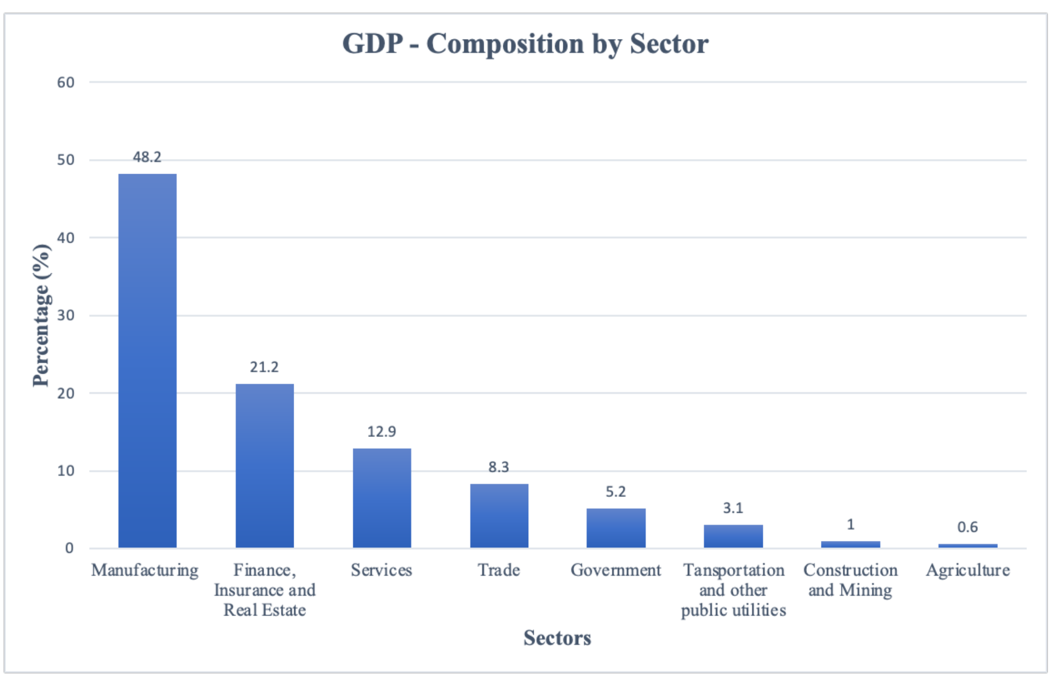
4.2.3 Political

Puerto Rico is an unincorporated territory of the United States of America with commonwealth status. Policy relations between Puerto Rico and the U.S. are conducted under the Office of the President (Economic Development Bank for Puerto Rico, 2022). Puerto Rico has a complicated relationship with the U.S. since it is neither a sovereign nation nor a U.S. state, which allows for certain benefits and disadvantages. This results in Puerto Rico's government having broader fiscal responsibilities than U.S. states. Puerto Ricans are U.S. citizens; however, they do not have the right to vote in U.S. presidential elections. Puerto Rico's government type is a presidential democracy, meaning a self-governing commonwealth associated with the U.S. Puerto Rico's legal system is based on civil law and within the U.S. Federal judicial system. Puerto Rico consist of a legislative and judicial branch. The Legislative branch consists of the Senate and House of Representatives. The Senate entails 27 members, and the House of Representatives consists of 51 members, elected by popular vote to serve four-year terms (Economic Development Bank for Puerto Rico, 2022). In 2019 the governor of Puerto Rico resigned due to corruption scandals, and large government employees have been investigated by the Federal Bureau of Investigation (FBI).

4.2.4 Economy

Puerto Rico's currency is United States Dollars (USD). Puerto Rico had a public debt of over $70 billion and $55 billion in unfunded pension liabilities; therefore, in 2017, the government declared bankruptcy (Congressional Research Services, 2022). To restructure Puerto Rico's debt and achieve fiscal responsibility, Congress passed the Puerto Rico Oversight Management and Economic Stability Act (PROMESA) in 2016. After completing the most extensive public debt restructuring in U.S. history, Puerto Rico's government formally exits bankruptcy in 2022. It was possible because the territory's annual debt payments were reduced by nearly 80%. If the country were to become a state, then the debt would cease to exist, leaving many investors without their money. Puerto Rico residents are required to pay federal taxes and a separate income tax. Since Puerto Rico is not eligible for state funding, the government imposed a separate income tax to obtain the capital needed. The country's current economic situation is due to corruption, financial mismanagement, government instability, and past environmental catastrophes, leading to an economic crisis for decades. Puerto Rico's difficulty in progressing economically is due to the Jones Act, that state that Puerto Rico can only exchange and receive goods with and through the U.S., which negatively impacts Puerto Rico by increasing the cost of shipping. Further, poverty in Puerto Rico is still much higher than the U.S. national rate. Employment in the Commonwealth government has declined since 2009, but the public sector still employs about one in five workers (U.S. Energy Information Administration, 2022). Puerto Rico is classified as a high-income country due to its GDP. In 2022, Puerto Rico's GDP is of $66 billion (U.S. Energy Information Administration, 2022). Most GDP is in manufacturing, while the minimum is agriculture (Figure 4).

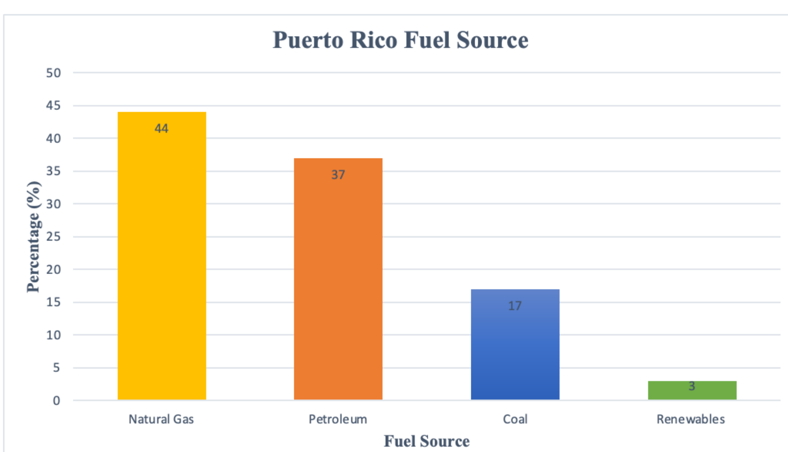
Figure 4. GDP by Sector



4.2.5 *Environment*

Puerto Rico is highly susceptible to climate change, and human impacts further contribute to the degradation of ecosystems. Through the years, Puerto Rico has encountered natural disasters such as hurricanes, storms, earthquakes, and a pandemic. The Caribbean hurricane season takes place from June to November, and it has recently brought destructive storms. The most catastrophic happened in 2017; hurricanes Irma and Maria destroyed most of Puerto Rico's electricity infrastructure, resulting in many citizens living without power for months. In addition, the island's electric power sector has endured decades of mismanagement and underinvestment. The Puerto Rico Electric Power Authority (PREPA) is a government agency that owns the electricity transmission system, while LUMA is a private organization responsible for the distribution system. For the fiscal year 2022, fossil fuel-fired power plants generated about 97% of Puerto Rico's electricity (Figure 5) (U.S. Energy Information Administration, 2022). Puerto Rico is challenged by its dependency on imported fossil fuels to meet its energy demand; therefore, it is highly vulnerable to fluctuations in the cost of oil. High world petroleum prices cause Puerto Rico's power prices to increase by two or three times the U.S. average (U.S. Department of Agriculture, 2017). Puerto Rico's energy consumption per capita is about one-third of that in the U.S. states (U.S. Energy Information Administration, 2022). Puerto Rico's per capita petroleum consumption is about four-fifths of the U.S., the electric power and transportation sector's largest petroleum consumer (U.S. Department of Agriculture, 2017). Further, the Commonwealth consumes approximately 27 times more energy than it produces. Puerto Rico does not produce natural gas or petroleum and has no proven reserves nor refines petroleum; therefore, most products are imported.

Figure 5. Puerto Rico Fuel Sources



Puerto Rico's high dependence on oil contributes to more significant environmental pollution and affects the health and safety of the people. Therefore, the federal government established the Mercury and Toxic Air Standards to mitigate some of these health hazards by modifying the island electric power generation system to comply with these standards (U.S. Department of Agriculture, 2017). In addition, to minimize its dependence on imported foreign oil and promote renewable energy development, in 2010, Puerto Rico enacted the island's first Renewable Energy Portfolio Standard (REPS) (U.S. Department of Agriculture, 2017). Currently, PREPA has failed to increase the use of renewable electricity sources. Nonetheless, under the Puerto Rico Energy Public Policy Act, PREPA must obtain 40% of its electricity from renewable resources by 2025, 60% by 2040, and 100% by 2050 (U.S. Energy Information Administration, 2022).

4.3 Overview of Waste

4.3.1 MSW Management

Puerto Rico lacks the knowledge and infrastructure to reduce waste, resulting in severe waste problems. The island's scarcity of waste management systems is due to difficult disposal conditions and lack of or aging infrastructure. The annual amount of MSW generated and disposed of in MSW landfills varies annually and is determined by several factors, such as the economy, consumer patterns, recycling and composting programs, and inclusion in a garbage collection service. Also, MSW landfills may receive other types of wastes, such as commercial solid waste, nonhazardous sludge, conditionally exempt small quantity generator waste, and industrial solid waste. MSW landfill can be publicly or privately owned (Table 2). There were 64 landfills on the island in 1994, and currently, they are 33, with the majority being overcapacity and operating below regulatory standards. For example, most landfills are noncompliant with Resource Conservation and Recovery Act regulations. Consequently, EPA has issued closure orders for twelve sites and is providing the island with millions of dollars to address hazardous and SWM. Puerto Rico's current landfill status comprises eleven closed and twenty-one open landfills (Figure 6). The federal government allows some landfills to operate under closure or compliance orders because there are no other viable options. Further, landfill directives demand the reduction of biological waste in landfills to mitigate GHGs emissions. Puerto Rico Solid Waste Management Authority (SWMA) and Environmental Quality Board (EQB) are responsible for managing and regulating solid waste on the island, while the municipalities are in charge of handling, collection, and treatment of the waste (U.S. Department of Agriculture, 2017). Landfills in P.R. must have recycling and composting programs; nonetheless, none practice composting (Environmental Protection Agency, 2016). Most landfills have reached capacity and closed in the northeastern part of the island, where most of the waste is generated. In the southwest, there are plenty of sites but relatively little waste. According to Federal Emergency Management Agency (FEMA), Puerto Rico is expected to run out of landfill space in two to four years.

Puerto Rico generates approximately 5.56 pounds of solid waste per person, and the national average per person daily in the U.S. is 4.91 pounds (Environmental Protection Agency, 2021). In addition, an estimation of the debris generated by Hurricanes Irma and Maria was 2.5 million tons, dramatically reducing the amount of available landfill space at disposal facilities (Environmental Protection Agency, 2021). According to EPA, only 10 percent of waste is recycled on the island, with 90 percent going to landfills. Puerto Rico does not have a food waste recycling program; therefore, the organic matter ends up in landfills. The island MSW's majority component is organic matter, with 60% made up of food scraps and other organic materials (Gashler, 2012). F.W. diversion from MSW has become an increasing concern due to the shrinkage of available landfill space and concerns about uncontrolled methane emissions (Environmental Protection Agency, 2014).

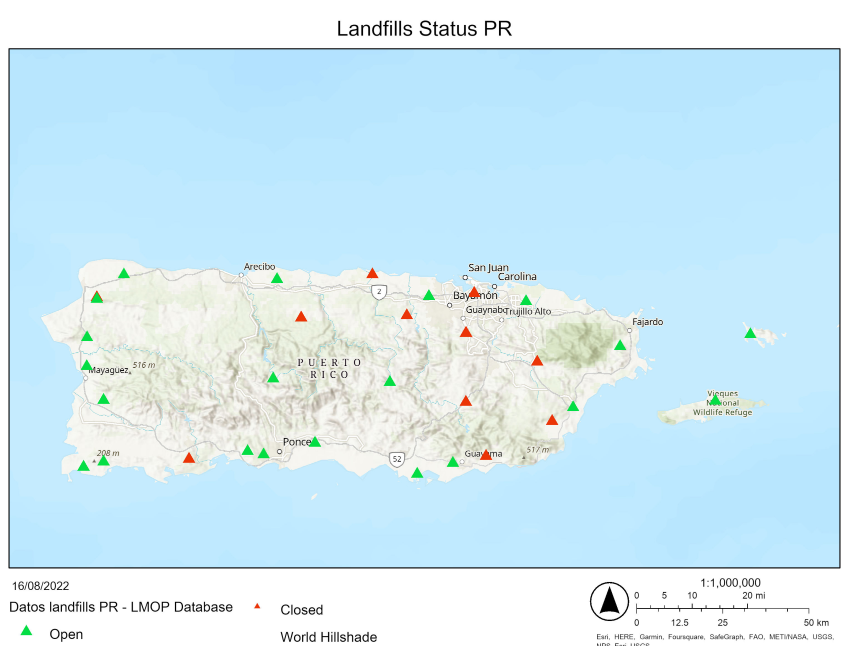
Table 2. Landfill Characteristics

Landfill Name	**City**	**Ownership Type**	**Landfill Owner Organization(s)**	**Year Landfill Opened**	**Landfill Closure Year**
Aguadilla Landfill	Aguadilla	Public	Municipality of Aguadilla		2009
Anasco Landfill	Anasco	Public	Municipality of Anasco	1967	
Arecibo Landfill	Arecibo	Public	Municipality of Arecibo	1973	2030

Landfill Name	City	Ownership Type	Landfill Owner Organization(s)	Year Landfill Opened	Landfill Closure Year
Arroyo Landfill	Arroyo	Public	Municipality of Arroyo	1977	2019
Barranquitas Landfill	Barranquitas	Public	Municipality of Barranquitas	1976	
Cabo Rojo Landfill	Cabo Rojo	Public	Municipality of Cabo Rojo	1993	2030
Carolina Landfill	Carolina	Public	Municipality of Carolina, PR	1969	2030
Cayey Landfill	Cayey	Public	Municipality of Cayey	1972	2017
Culebra Landfill	Culebra	Public	Municipality of Culebra	1982	
El Coqui Landfill	Humacao	Private	EC Waste	1973	2082
Fajardo Municipal Landfill	Fajardo	Public	Municipality of Fajardo, PR	1971	2022
Florida Landfill	Florida	Public	Municipality of Florida	1979	2009
Guayama Landfill	Guayama	Public	Municipality of Guayama	1979	
Guaynabo LF	Guaynabo	Public	Municipality of Guaynabo, PR	1956	2008
Hormigueros Landfill	Hormigueros	Public	Municipality of Hormigueros	1985	2030
Isabela Landfill	Isabela	Public	Municipality of Isabela	1978	
Jayuya Landfill	Jayuya	Public	Municipality of Juyuya	1978	
Juana Diaz Landfill	Juana Diaz	Public	Municipality of Juana Diaz	1970	
Juncos Landfill	Juncos	Public	Municipality of Juncos	1978	2012
Lajas Landfill	Lajas	Public	Municipality of Lajas	1979	
Mayaguez Landfill	Mayaguez	Public	Municipality of Mayaguez, PR	1976	2025
Moca Landfill	Moca	Public	Municipality of Moca	1967	

Landfill Name	City	Ownership Type	Landfill Owner Organization(s)	Year Landfill Opened	Landfill Closure Year
Penuelas Valley Landfill	Penuelas	Private	EC Waste		
Ponce Landfill	Ponce	Public	Municipality of Ponce, PR	1967	2058
Salinas Landfill	Salinas	Public	Municipality of Salinas, PR	1970	2048
San Juan LF	San Juan	Public	Municipality of San Juan, PR	1966	2001
Toa Alta Landfill	Toa Alta	Public	Autonomous Municipality of Toa Alta, PR	1966	2017
Toa Baja LF	Toa Baja	Public	Municipality of Toa Baja, PR	1974	2030
Vega Baja Landfill	Vega Baja	Public	Municipality of Vega Baja, PR	1970	2009
Vieques Landfill	Vieques	Public	Municipality of Vieques	1994	
Yabucoa Landfill	Yabucoa	Public	Municipality of Yabucoa	1972	2011
Yauco Landfill	Yauco	Public	Municipality of Yauco, PR	1970	2017

Figure 6. Landfill Current Status



4.3.2 Environmental Impact

The island's difficulty meeting its SWM requirements is due to the existing network of aging landfills. Landfill impact is due to the period it takes to reduce waste and gas emissions. The operation and management of landfills have been a challenge in Puerto Rico because most sites lack the basic environmental protective features, such as low-permeability liners to prevent leachate into the environment. Leachate management and groundwater monitoring are required both during active landfill operations and up to 50 years after closure (Dalke et al., 2021). Water contamination has become one of the critical issues in Puerto Rico due to the high quantity of waste because landfill leachate has contaminated portions of the island's groundwater resources which is a vital drinking water resource.

Further, landfill gas emissions are unmonitored and uncollected in almost all locations, creating significant hazards for residents (U.S. Department of Agriculture, 2017). Landfill gas is a gas produced due to the anaerobic decomposition of waste materials in the landfill. Landfill gas generally contains 40 to 60 percent methane on a dry basis. The remainder is carbon dioxide with trace levels of other compounds, such as nitrogen, oxygen, hydrogen, sulfides, and others (Code of Federal Regulations, 2009). According to EPA, landfill methane emissions were approximately 109.3 MMT CO2 Eq. (4,373 kt) in 2020, representing the third largest source of methane emissions in the United States (Environmental Protection Agency, 2022). Emissions from MSW landfills accounted for approximately 86 percent of total landfill emissions (94.2 MMT CO2 Eq.), contributing to global warming (Environmental Protection Agency, 2022). According to EPA, the majority of landfills in Puerto Rico are located in areas that result in environmental conflicts and impacts, such as flood valleys, wetlands, the potential to impact drinking water sources directly, and the potential to directly impact natural reserves (Environmental Protection Agency, 2021). Landfilling and incineration have traditionally been used to dispose of F.W., but both methods have caused severe environmental and health impacts. Therefore, innovating sustainable ways to manage MSW is needed to mitigate the contamination of the island's natural resources and avoid health issues.

4.4 Overview of Household Food Waste

Household food waste estimated in Puerto Rico is 216,854 tonnes per year (United Nations Environment Programme, 2022). An increase in population and different lifestyles contribute to more significant food loss. The island of Puerto Rico has an unreliable power system; therefore, it is custom for the island to be without power for hours, days, or even weeks without electricity. This situation increments the food waste amount per household since refrigerated food will go bad. Food waste comprises lipids, cellulose, starch, lignin, and protein, collectively comprising 82%–96% of the volatile content (Pour and Makkawi, 2021). The carbon mass content in the food waste is reported to be within the range of 40.0–60.0%, the hydrogen content is in the range of 5.0–13.0%, the nitrogen is within 1.5–6.0%, and the oxygen mass content is in the range of 17.0–41.0% (Pour and Makkawi, 2021). Usually, FW contains high water content making it prone to biological degradation and difficulty for extended storage. In addition, FW characteristics make it have a high energy content. In the case of households, these wastes are often combined with any trimmings occurring prior to cooking. While cooked food waste has a lower biogas potential than pre-consumer waste, it can still significantly contribute to biogas production (Environmental Protection Agency, 2014). Regulations governing post-consumer food waste disposal differ from pre-consumer wastes Environmental Protection Agency, 2014).

4.5 Implementation of Circular Economy

The development of a circular economy (CE) in the waste management sector will benefit the island in the long term since it will reduce the amount of food waste in landfills. The implementation of a circular economy occurs as default by recycling household food waste; attempts would be made to evaluate the challenges of the circular economy. AWTT is designed for practicing CE. A circular framework for food production and wasted food management offers a compelling alternative to inefficient and vulnerable linear food systems (Babbit et al., 2022). The conversion of food waste to generate bioenergy will help reduce environmental pollution and facilitate the implementation of a circular economy (Mohanty et al., 2022). The technology can be instrumental in providing renewable energy to industry and the agricultural community while closing the loop on the nutrient cycle.

4.6 Technology

4.6.1 Anaerobic Digestion

Implementing bio-methanation for HFW management helps mitigate organic matter in landfill. AD process characteristics make it one of the best technologies for treating organic matter (Table 3). AD technology for treating FW depends on the solid content, feeding mode, temperature, stage, and digester type (Mahmudul et al., 2022). The physical and chemical characteristics of the organic waste are essential information for designing and operating anaerobic digesters because they affect biogas production and process stability during AD. Digester technology has been developed with different approaches based on the operating temperature, feedstock type, moisture content, and mode of operation. The operating temperature determines the microbial communities that live in the digester. A high-rate digester would have a loading rate of 0.10 to 0.40 pounds of volatile solids (VS) per cubic foot per day (Wisconsin Department of Natural Resources Wastewater Operator Certification, 1992). High rate units have higher loading rates because their design includes uniform temperature and greater mixing capacity and are more profound and fed continuously. AD digester tanks are typically made of concrete or steel designed to capture and recover the biogas. Complete Mix or Continuous Stirred Tank Reactor (CSTR) digester is concrete or metal cylinder with a low height to diameter ratio. CSTR digesters can function at different temperatures with various mixing techniques and can accommodate a wide range of solids (Table 4). In addition, it generally provides the same period for hydraulic residence time (HRT) and solids residence time (SRT). Complete mix systems constantly operate with a continuous flow of reactants and products. This means that the feed assumes a uniform composition throughout the reactor and the exit stream has the same composition as in the tank.

AD processes are categorized as either a batch feeding system or a continuous feeding system. Continuous feeding AD systems can produce biogas constantly while the batch system cannot (Mahmudul et al., 2022). The microbial community in AD systems requires a relatively consistent feedstock stream daily. Underfeeding will reduce microbial population and methane production; overfeeding can result in excessive by-product formation and increased toxicity. Therefore, any feeding regime quantity or type changes need to be incorporated gradually.

FW is a highly desirable substrate for anaerobic digesters because of its high biodegradability and methane yield due to a high fraction of protein in the food waste, which increases the heating value of the gas (Pour and Makkawi, 2021). However, microbes in the digester environment also require other micronutrients, such as iron, phosphorus, sodium, magnesium, potassium, and calcium, for the growth and maintenance of cellular structures and activities. Furthermore, trace elements of copper, zinc, nickel, cobalt and others are required for enzymatic synthesis and function (Dalke et al., 2021).

According to Zhang et al., (2007), thermophilic digesters are better for dry feedstock, such as food waste. An estimate of the digester volume needed for treating Puerto Rico HFW is 2,000 m3, where 90% volume of the digester is filled with the feedstock. The temperature of the digester is set at 55 ◦C since the AD process is carried out under thermophilic conditions. The thermophilic approach is more desirable because of its more significant amount of biogas production and shorter retention time for superior pathogen removal. The total heat demand depends on the number of digesters and temperatures of the inside and outside digesters. In this case, the temperature differences between inside and outside digesters are unnecessary because of Puerto Rico's tropical climate throughout the year.

As biogas is produced, the digestate is pumped from the bottom of the digester through the outlet pipe and stored in open or covered tanks (Figure 7). All macro and micronutrients present in the feedstock ultimately pass through the digester and are present in the digestate. The biogas generated from the AD process can produce electricity and heat provided by a combined heat and power unit (CHP). The digester effluent can be used as compost or liquid fertilizer. Nitrogen (N) in the digest will be primarily in the form of soluble ammonia and thus present in the liquid after dewatering, whereas phosphorus (P), typically insoluble in compound form, will essentially end up in the fiber fraction. The distribution ratios of N and P in the fiber and liquid fractions will depend on the solids capture rate of the dewatering equipment. Concentration is an option that will allow for storage, transport to remote growing areas, and sale as liquid fertilizer.

Co-digestion of FW requires specific operating conditions dependent on temperature, pH, nutrient availability, hydraulic/sludge residence time (HRT/SRT), and organic loading rate (OLR). Anaerobic co-digestion (AcoD) of FW can be conducted with the CSTR digester since it accepts medium OLR, it takes approximately 20-30 days for optimal HRT, the technology is medium level and is compatible for co-digestion (Table 4). Operating under thermophilic conditions to obtain high biochemical reaction rates minimizes digestate pathogen levels, allows higher organic loading, and yields high biogas.

Two-stage systems prevent the digester from overloading and avoid acidification when processing FW. In addition, since each AD process stages function at different pH values, implementing a two-stage setup provides stability and higher efficiency by simultaneously providing nutrient balance and a strong buffering capacity (Dalke et al., 2021). The optimal pH for hydrolysis, acidogenesis, and acetogenesis is estimated at 5.5–6.5, while methanogenesis has higher pH variation sensitivity and an optimal range of 6.5–7.2 (Dalke et al., 2021). According to Dalke et al., (2021), FW feedstocks typically have lower pH values ranging from 4.2 to 5.3. The optimum HRT for AcoD of FW relies on the feedstock composition, operating conditions, and process kinetics and may range from 15 to 25 days (Dalke et al., 2021). Longer HRT may allow higher VS degradation and thus enhance methane yield, but reactors will require a larger volume to handle a particular OLR. A shorter HRT will allow for higher OLRs, but highly degradable substrates like FW may lead to rapid accumulation and digester acidification (Dalke et al., 2021). For a single-stage system processing FW, it is recommended that fermentation be conducted at a lower OLR and higher HRT to avoid system failure from acidification. Two-stage digestion processes have the potential for increased methane production from high strength FW at higher OLRs by implementing optimized conditions for fermentative and methanogenic microorganisms in stage one and stage two, respectively (Dalke et al., 2021).

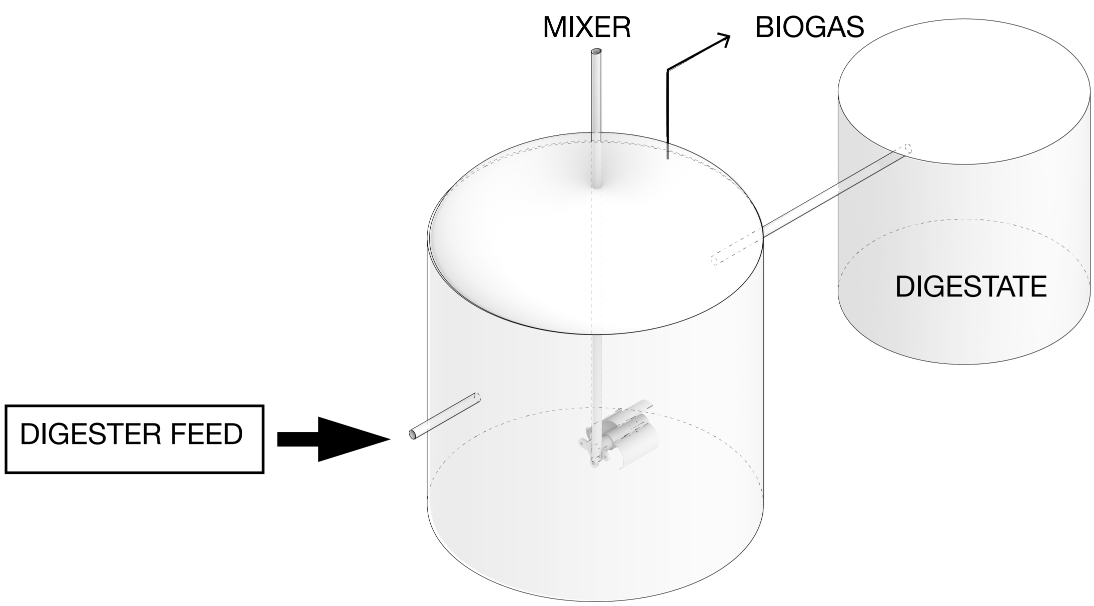
Table 3. Anaerobic Digestion Process Characteristics

Anaerobic Digestion	Characteristic
GHGs Emissions	Low
Soil Benefits	Digestate is Rich in nutrients
Energy produced	Large Source
Environmental benefits	Sustainable Closed Loop life Cycle
Processing time	Medium to Fast

Table 4. Digester Technology Characteristics

Variables	Complete Mix
Max allowable solid size	Coarse
Technology level	Medium
Operating Temperature	Mesophilic or thermophilic
Co-digestion compatible	Yes
Solid separation prior to digestion	Not necessary
Foot print	Medium
OLR	Medium
HRT	20-30 days
VS reduction	35-45%
Biogas yields	High
Costs	Medium
Suitable % solids	3-12%

Figure 7. Complete Mix Tank Reactor



4.6.2 Combined Heat and Power

The central part of a biogas plant is the digester, an airtight container in which bacteria break down organic waste through bio-methanation. The produced biogas is stored at the top of the digester in a gasometer dome with a spherical cap. Digester gas is approximately 70% methane and 30% carbon dioxide; the remaining amount comprises hydrogen sulfide, water vapor, and other trace compounds. The methane in biogas is a renewable natural gas replacement for the methane in fossil natural gas. Biogas may be used both as a fuel and to generate electricity. The combined heat and power (CHP) unit, also known as co-generation, is the most common for electricity generation. Implementing a CHP system depends on the AD technology used; therefore, the study proposed using the CSTR digester. The AD-CHP system comprises the collection of HFW, its treatment in the CSTR digester to produce biogas, followed by its subsequent treatment and utilization in a CHP plant to generate heat and electricity. The unit is an internal combustion engine, and integrated generator specifically engineered to operate on biogas. The lowest level of processing requires removing free water from the biogas and the slight pressurization of the biogas using a blower to flow into a boiler or IC engine.

Biogas processed to this level still contain hydrogen sulfide, water vapor, and carbon dioxide (Environmental Protection Agency, 2014). Therefore, using NaOH allows for dehumidification and desulphurization, and after the biogas is fed into the CHP plant to generate electricity and heat. Treated biogas is mixed with air and combusted using an internal combustion engine-generator set which produces approximately 40% of electricity; nonetheless, by implementing the recovery of thermal energy from a CHP unit, the overall efficiency increases to 80% estimated. Methane concentrations in digester gas will burn when the level reaches 56% but is not usable as a fuel until the methane level reaches 62%. Raw biogas has a heating value ranging from approximately 500 to 650 Btu per cubic foot, depending on its carbon dioxide content. Depending on the AD process and feedstock, the methane content of biogas is generally between 50% to 75%. The amount of biogas produced depends on various factors, including the type and amount of biomass used, the digester size, and temperature (IRENA, 2016). Low gas production indicates problems, such as toxicity, temperature, volatile acid to alkalinity ratio, mixing, or feed rates (Wisconsin Department of Natural Resources Wastewater Operator Certification, 1992).

IC engines and gas turbine engines can generate power with biogas. Implementing IC engines is due to lower capital cost, higher conversion efficiency, and broader operating range than a gas turbine engine (Environmental Protection Agency, 2014). Nonetheless, operation and management costs are higher for an IC engine. IC engines have several subsystems, such as fuel gas compression, conditioning and regulation, jacket water circulation, heating and cooling, lube oil circulation, jacket water supply and drain, lube oil supply, and drain, starting power from batteries, inlet combustion air with a filter and regulator, and an exhaust system with a muffler, among others. The fuel gas, lube oil, and jacket water subsystems require the most attention and maintenance (Environmental Protection Agency, 2014).

The power generated by the CHP unit depends on its electrical capacity and the annual operating time. Further, the methane emissions from covered tanks are recovered and fed to the CHP system to produce additional electricity. The electricity generated can be used at the facility or sold to the national grid, while the heat generated by the CHP engine will be used for heating the digester. Another use of biogas is converting it to RNG, which involves the removal of carbon dioxide, hydrogen sulfide, water vapor, and other contaminants, compressing the gas to pipeline pressure or higher.

4.6.3 Waste-to-Energy

The proposed WTE facility provides a viable option to sustainably dispose of organic solid waste in Puerto Rico and reduce pressure on the island's natural resources. The WtE facility is designed to handle half of the HFW generated in Puerto Rico; therefore, developing two WtE facilities is required for total HFW management. The WtE facility comprises the AD-CHP system for treating HFW and producing electricity and heat. The proposed project design includes the following components: HFW receiving and processing building, CSTR digesters, effluent storage tank, biogas storage tank, CHP system, and an emission control system. Additionally, the facility consists of a storage building and other associated infrastructure and buildings. The waste reception and short-term storage may be an aboveground or in-ground tank with a pump for transferring the waste to the CSTR digester. The WtE plant is considered high-rate AD; therefore, the digester contains a mixing system to maintain thoroughly mixed conditions and internal or external heat exchangers for digester heating. This homogenization ensures maximum contact between substrate and microbe, enhancing the digestion process and biogas quality. The WtE facility works in a single-stage configuration, where all stages of bio-methanation occur in the same digester. Nonetheless, several units may be required for co-digestion processing, including feedstock storage and pretreatment to remove inert materials and improve digestibility and biogas purification.

The WtE plant estimates working days to be 335 days, allowing for one-month maintenance. The feedstock will be delivered to the plant. The facility would receive and process approximately 350 tonnes per day of HFW. The WtE plant consists of five CSTR digesters of 2,000m3, where 90% of the volume is occupied by FW and the other 10% for gases. According to EPA, food waste density is two cubic yards (EPA, 2016). The digester can treat 1,800m3 of HFW, meaning it would take approximately six days to fill the tank to achieve 90% (Table 6). The digester requires a 10% parasitic load, a pH value of five, and a retention time of twenty days (Table 7). The digestate generated would be used as fertilizer. After the bio-methanation process is complete, the biogas undergoes the process of dehumidification and desulphurization using NaOH. This process allows the biogas to be used in the CHP plant, specifically the IC engine, to generate electricity and heat. The WtE plant generates 15,325MWh of electricity and 14,595MWh of heat annually, therefore, recovering 62% of energy from feedstock (Table 7). The plant has a feedstock capacity of 125,000 tonnes annually, which generates 48,650MWh per year of energy. The heat generated is to be used by the digesters since Puerto Rican households have no heating system due to their tropical climate. Further, biogas could be used by natural gas plants operated by PREPA.

Considering the facility would encompass approximately an area of 200m x 200m, some factors must be considered to determine the suitable location to develop the WtE plant (Figure 8). First, since the plant generates odors and will have ongoing traffic, the facility should be located away from residential areas and minor roads to avoid affecting neighboring residents and businesses, potentially causing complaints, notices of violation, regulatory fines, or even shutdown orders.

Table 5. Food Waste Generation

FOOD WASTE CAPACITY	**VALUE**
Total FW (tonnes / yr)	250,000
Total FW (tonnes / month)	20,833
Total FW (tonnes / day)	694
Half FW (tonnes / yr)	125,000
Half FW (tonnes / month)	10,417
Half FW (tonnes / day)	347
Half FW (kg / day)	350,000
Half FW (m3 / day)	300

Table 6. WtE Consideration Factors

Case of Considerations	Value
The amount of household food waste (kg/capita/yr)	74
Days of operation of AD complex in a year	335 days
Volume of digester occupied by feedstock (m3)	90%
pH level of the digesters	5
Retention Time	20 days

Table 7. WtE Performance

WtE Performance	Estimate
Parasite Load for WtE	10%
Total Available MWh	48,650 MWh per year
Plant Type	CHP
Electricity Generated (MWh)	15,325
Heat Generated (MWh)	14,595
Energy Recovery from feedstock (%Power)	32%
Energy Recovery from feedstock (%Heat)	30%

Uncontrolled strong odors may also negatively impact the health and welfare of the WtE plant employees; therefore, the facility consists of odor control systems that could be separate from or combined with HVAC systems, which can include ductwork, blowers, biofilters, and scrubbers. The preferred locations for the WtE facility would be one in the east and another in the west. One suitable location to develop the WtE facility is in the southwest region of Puerto Rico, due to little land use, small population, responsible distance to waterways, and safe of flood hazards (Figure 7). Another suitable location to develop the other WtE facility is northeast of the island.

Figure 8. Puerto Rico Suitability Map Main Parameters

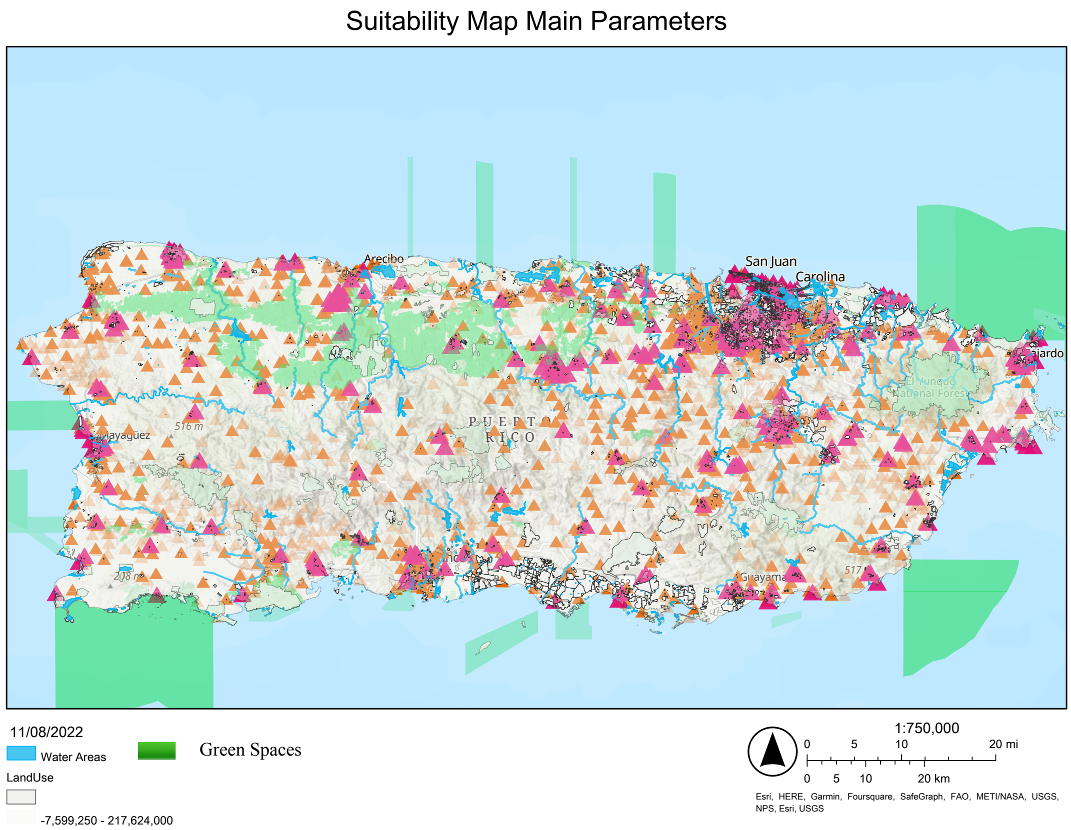
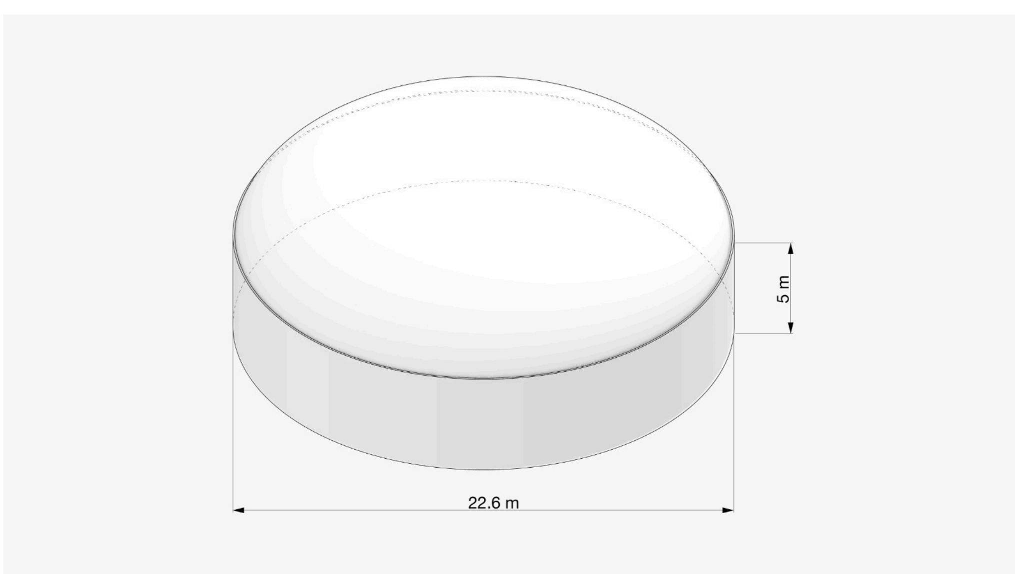


Figure 9. Digester Tank Design



4.7 Economic and Financial Analysis

WtE plant's major annual expenses include operation and maintenance (O&M) for the anaerobic digester and the CHP. A full-scale biogas plant requires full-time employees. The technology proposed is not the most expensive nor the cheapest, and the size determines cost (Table 8). The technology implemented allows for the HRT to be generally equal to SRT. Therefore higher capital and operational costs are balanced against the system's stability and energy production reliability. The capital expenses (CAPEX) for the AD technology are estimated at $30 million and the CHP equipment at $23 million, resulting in $53 million total. The OPEX is estimated at $2 million per year without including the transportation of the feedstock to the plant because it only considered the WtE plant functions and employees. The WtE facility has a construction period of two years. The study proposed a 30% equity and a loan estimation of $37,100,00 to be paid in 24 years with an interest rate of 10% (Table 10). Tipping fees are a significant source of revenue for the WtE plant since the waste fee per tonne is $30, and the sale of electricity is $280 per MWh. The annual revenue of the WtE plant is projected to be approximately $9.5 million.

In comparison, the annual OPEX is projected to be $6 million, resulting in an annual net gain of approximately $3.5 million. Capital costs for WtE facilities are high; however, different funding sources are available or public-private partnerships as a cost-effective alternative to municipal ownership. Puerto Rico has available funding sources or services for solid waste(Table 10). This model will be a reference point for future innovations, and it also provides possible Funding Sources or Services for Solid Waste Activities (Environmental Protection Agency, 2014).

Table 8. Financial Model

Factor	Estimate
Feedstock	
Capacity	125,000 t/yr
CV	7
Operational Days	335 days
Total available MWh	48,650 MWh per year
Technology	
Parasite load for plant	10%
Total Energy Produced (MWh)	29,920
Electricity produced (MWh)	15,325
Heat produced (MWh)	14,595
Capacity of plant	3.72 MW (1.82 MW Heat and 1.90 MW Electricity)
Construction Period	First two years
Financial	
Capital ($ million)	$53,000,000
Operational costs ($ million)	$2,000,000
Loan	70% with 30% equity, 8% loan and repayment either at a fixed over a given year, or on basis of available surplus until loan is paid.
Loan/Equity periods	Equity invested in first year/loan in second year
Inflation rate (%)	0%
Power and Heat Inflation (%)	0% because of fixed FIT for 30 years - except where described differently
Currency devaluation rate (%)	0%
Waste Service fee (USD/tonne)	$30
Tax (Corporation)	10%

Table 9. Cost Model

	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10
Expenditure										
Capital Investment										
Loan		37,100,000								
Equity	15,900,000									
Loan Repayment		4,129,222	4,129,222	4,129,222	4,129,222	4,129,222	4,129,222	4,129,222	4,129,222	4,129,222
Operational			2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000	2,000,000
Total Expenditure	15,900,000	4,129,222	6,129,222	6,129,222	6,129,222	6,129,222	6,129,222	6,129,222	6,129,222	6,129,222
Income										
Sale of Electricity			4,290,930	4,290,930	4,290,930	4,290,930	4,290,930	4,290,930	4,290,930	4,290,930
Sale of Heat			-	-	-	-	-	-	-	-
Waste Fee			3,750,000	3,750,000	3,750,000	3,750,000	3,750,000	3,750,000	3,750,000	3,750,000
Subsidy Capital	-									
FIT			1,532,475	1,532,475	1,532,475	1,532,475	1,532,475	1,532,475	1,532,475	1,532,475
Carbon subsidy			-	-	-	-	-	-	-	-
Total Income	-	-	9,573,405	9,573,405	9,573,405	9,573,405	9,573,405	9,573,405	9,573,405	9,573,405
Cash Flow	- 15,900,000	- 4,129,222	3,444,183	3,444,183	3,444,183	3,444,183	3,444,183	3,444,183	3,444,183	3,444,183
Irr=	15%									

Table 10. Possible Funding Sources

Activities	Sources	Funding
Planning for Solid Waste Management	USDA-RD	Solid Waste Management Grants
	HUD Community Develoment Block Grant	Mitigation (CDBG-MIT)
Infrastructure Investment	DNER	Clean Water State Revolving Fund
	FEMA	Hazard Mitigation Grant Program (HMGP)
	USDA	Community Facilities Loan and Grant Program Water and Waste Disposal Loan and Grant Program
	USDA-NRCS	Landscape Planning Programs Financial Programs
Economic Development	USDA	Rural Business Development Grant

Chapter Five
Conclusion and Future Work

5.1 Introduction

This Chapter summarizes the study conducted on developing a sustainable framework for household food waste management in Puerto Rico. It also presents vital information for possible developments for future projects in the waste management sector in Puerto Rico.

5.2 Conclusion

The study aligns with the SDG Target 12.3 of the 2030 Agenda for Sustainable Development. Municipal food waste (MFW) is an excellent anaerobic digester feedstock with an excellent specific methane yield. Thus, the disposal of food waste and other organic materials can become a source of revenue rather than just an expense. Food waste quality and composition vary depending on the source, region, and collection method but are significantly more biodegradable than other commonly used feedstocks. It also has relatively high macro- and micro-nutrient contents to facilitate healthy digester bacterial growth and enhance effluent fertilizer value. However, impurities must be removed from the municipal food waste stream to prevent mechanical failure of facility components and produce marketable co-products. Sustainable waste management in Puerto Rico depends on how environmentally conscious the people are, its economic state, its flexibility, and how accessible are the nearest waste management plant. The drastic decline in GDP is due to hurricanes Irma and Maria that left the island without power and in destruction. To this day, PR is not 100% restored. After the country experienced a variety of earthquakes in the south part of the island, and in 2020, the covid-19 pandemic started, leaving the island stuck in progression.

In light of rapidly rising costs associated with energy supply and waste disposal and increasing public concerns with environmental quality degradation, conversion of food wastes to energy is becoming a more economically viable practice. Puerto Rico's green growth strategies include the government introducing several action plans on renewable energy sources. The study focuses on the anaerobic digestion method for managing food waste. Their economic state is essential because it is an investment in contributing to bettering the environment. This method would reduce the amount of organic matter ending in landfills, and it can produce organic fertilizer and biogas. In addition, it would mitigate air pollution and water and soil contamination. AcoD as a waste management strategy is a beneficial method for reducing the portion of FW in landfills, which in turn helps reduce GHG emissions. Creating a WtE plant would create new job opportunities in the economic sector to better the island's economic crisis. This would solve the waste and energy problem while creating employment. The project focuses on the current waste management issues of Puerto Rico and the impact of a recycling program.

5.4 Future Work

For future FW management applications in the US, strict air quality, landfill regulations, renewable energy policies, and economic intensives are essential for transforming current FW handling and treatment strategies. In addition, new emerging concepts, such as CE and decarbonization, are critical for shaping future FW management practices. The proposed project could be applied mainly to Culebra and Vieques islands located on the east side of the main island of Puerto Rico. According to the census of Puerto Rico, the number of people living in poverty in Vieques has multiplicand in the past five years. Therefore, a WtE plant would benefit the island's lack of waste management and provide renewable energy, promoting the economy by creating new job opportunities. In addition, the island's electricity system is depleting itself, and insufficient capital to restore the grid makes the proposed project a viable, practical solution. However, the lack of data in this part of the island (Vieques and Culebra) limits the accessibility of innovations.

The AD-CHP plant considered in the study currently operates without an organic Rankine cycle (ORC) system, hence the need to evaluate the environmental implications of ORC as a potential technology. The ORC technology could solve the above issues by utilizing waste heat to generate additional electricity. The ORC is a proven option for recovering energy from low-temperature heat and an effective means of increasing energy conversion efficiency in AD plants. The implementation of ORC generates additional power without requiring extra fuel. In addition to increasing the system's overall energy efficiency, they also lead to lower emissions of pollutants per unit of energy. Therefore, implementing the ORC system reduces most impacts because of its additional electricity. Further, odor control is a significant factor to consider when choosing the location of the WtE facility; therefore, an odor management plan needs to be in place even tho AD only generates smells between the time of receiving the waste until it gets to the digester. For example, an air ducting system needs to recirculate the foul-smelling air into the waste-to-energy process.

The proposed development would need legal agreements with PREPA and the transportation infrastructure. Therefore, the study is limited to transportation infrastructure. Factors limiting a better recycling system in Puerto Rico are lack of educational support, limited municipal funding, lack of access to recycling, and challenging waste disposal dynamics. Recycling programs in Puerto Rico need to be better developed in how they are coordinated, managed, and implemented. These recommendations are specific to municipalities, state governments, and Puerto Rican citizens.

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