Joint master of Mediterranean Initiatives on renewable and sustainable energy

DEANSHIP OF GRADUATE STUDIES, AL- QUDS UNIVERSITY

Assessment of Transboundary Sludge Pollution and Its Conversion into Energy

Case Study: Nablus West Wastewater Treatment Plant

Eman Omar Morshed Mansour

M.Sc. Thesis

Jerusalem-Palestine

1445/ 2024

Assessment of Transboundary Sludge Pollution and Its Conversion into Energy

Case Study: Nablus West Wastewater Treatment Plant

Prepared By:

Eman Omar Morshed Mansour

B.Sc Civil Engineering, Palestine Polytechnic University, Palestine

Supervisor: Prof. Jawad A.Shoqeir
Earth and Environmental Sciences Department, Al-Quds University, Palestine
Co-Supervisor:Dr. Husain Alsamamra
Physics Department, Al-Quds University, Palestine

A thesis submitted in partial fulfillment of the requirement for the degree of
Master of Renewable Energy and Sustainability

Faculty of Engineering-Al-Quds University

Jerusalem-Palestine

1445/2024

Al-Quds University

Deanship of Graduate Studies

Thesis Approval

Assessment of Transboundary Sludge Pollution and Its Conversion into Energy

Case Study: Nablus West Wastewater Treatment Plant

Prepared by: Eman Omar Morshed Mansour

Registration No.: 22112615

Supervisor: Prof. Jawad A.Shoqeir

Co-Supervisor: Dr. Husain Alsamamra

Master thesis submitted and accepted, Date: 15/05/ 2024.

The names and signatures of the examining committee members are as follows:

1- Head of Committee: Prof. Jawad A.Shoqeir Signature

2- Co-Supervisor: Dr. Husain Alsamamra Signature

3- Internal Examiner: Dr. Omar Ayyad Signature

4- External Examiner: Dr. Subhi Samhan Signature Subhi Samhan

Jerusalem-Palestine

1445 / 2024

Dedication

I dedicate my success and the joy of my graduation today to my first teacher, my beloved role model, and the source of my confidence—the one who removed the thorns from my path and paved the way for my success. I carry your name with pride, my dear father, whose pure soul is absent from this world but forever present in my heart. May your soul rest in peace.

To the one who taught me patience, dedication, and strength, who believed in me and my abilities, whose prayers were the secret of my success, and whose big heart always had room for me—my dear mother.

To my firm side and the security of my days, to those who strengthened my resolve. To the best and brightest of my days, the apple of my eyes—my siblings: Ahmad, Moath, Shifa, Amna, Dua'a, and Israa. To my sisters in law, Bara'a and Sewar.

To my beautiful family, who tolerated my busyness and were always a safe refuge and a source of hope for moving forward. My lifelong companions: Ala'a, Mohammad, Hamza, Maria, Mira, and Sophia.

I dedicate my graduation to those who wished to see me broken but were disappointed, as I only grew stronger and more courageous.

To my strong, ambitious self, who endured all the pitfalls and persevered despite the difficulties.

Declaration

I certify that this thesis submitted for the degree of the master is the result of my research, except where otherwise acknowledged, and that this thesis, neither in whole nor in part, has been previously submitted for any degree to any other university or institution.

The work was done under the supervision of Prof. Jawad A.Shoqeir, Earth and Environmental Sciences Department, Al-Quds University. And Dr. Husain Alsamamra, Physics Department, Al-Quds University.

Name: Eng. Eman Omar Morshed Mansour

Signed:

Date: 15/05/ 2024

Acknowledgments

I extend my heartfelt gratitude to Professor Jawad A. Shoqeir for his invaluable guidance, consistent support, and insightful feedback throughout this research journey. His expertise and encouragement have been instrumental in shaping this thesis, and I am profoundly grateful for his guidance, which expanded my knowledge horizons and created numerous opportunities for me. I am truly proud to have had him as my supervisor.

I also wish to express my sincere appreciation to Dr. Husain Alsamamra, my co-supervisor, for his valuable follow-up and dedication to ensuring the quality and rigor of this study.

My gratitude extends to Dr. Omar Ayyad and Dr. Subhi Samhan for their thorough examination of this thesis as internal and external examiners, respectively. Their valuable insights and constructive feedback have significantly enhanced the quality and credibility of this research.

I would like to acknowledge Dr. Hassan Sawalha from Palestine Polytechnic University, my teacher of biomass energy, for providing valuable information and presenting innovations in energy production from biomass in an inspiring way.

Thanks to Dr. Mohamed Abd Al-Hamid for the valuable information, guidance, and constant support he never skimped on me. He contributed greatly to enriching my knowledge and developing my skills, and I thank him greatly for his valuable guidance and contribution to the success of this academic stage.

I extend my thanks to all the faculty members and staff of my university, Al-Quds University, and my colleagues for being part of my journey in obtaining a master’s degree.

I am deeply indebted to my family for their unwavering encouragement, love, and understanding throughout this journey. Their patience and support have been a constant source of strength and motivation.

Finally, I express my gratitude to all who contributed in any way to the completion of this thesis. Your support and encouragement are deeply appreciated.

Eng. Eman Omar Mansour

Abstract

This thesis explores the potential of converting sludge into energy to address transboundary sludge pollution in the West Bank region, with Nablus West WWTP's adoption as a case study. It investigates the effectiveness of this approach in mitigating environmental pollution and promoting sustainability. Specifically, the study examines the impact of sludge-to-energy conversion on treatment costs per cubic meter of wastewater and evaluates the energy output per unit of sludge generated. Through comprehensive analysis, including cost-benefit evaluation and environmental impact assessment, the research offers valuable insights into the viability and benefits of this renewable energy solution. The findings underscore the significant energy generation potential from both local wastewater treatment plants and the broader West Bank population's sludge production. Through investment in sludge-to-energy conversion, these resources can be utilized to address the energy problem in Palestine while mitigating environmental and financial burdens linked with transboundary pollution. By promoting sustainable waste management practices and the utilization of renewable energy, the research contributes to advancing environmental sustainability and addressing transboundary environmental challenges, ultimately benefiting all stakeholders. The data from the sludge treatment operations at the Nablus West WWTP and the projected figures for the entire West Bank population underscore the substantial energy production and cost savings potential inherent in sludge-to-energy conversion. At the Nablus West WWTP alone, with a sludge production rate of 6,600 kg/day, methane production of 1,320 m³/day, and energy production of 3,938.32 kWh/day. Extrapolating these figures to the entire West Bank population, where the sludge production rate reaches 14,400,000 kg/day, methane production hits 2,880,000 m³/day, and energy production reaches 8,588,761.60 kWh/day. This comparison highlights the scalability and efficiency of sludge-to-energy conversion, with substantial benefits both at individual wastewater treatment plant levels and on a broader scale across the entire population. The study highlights the substantial benefits of sludge-to-energy conversion for addressing environmental pollution and advancing sustainable development in regions affected by transboundary sludge pollution. Comprehensive analysis reveals reduced greenhouse gas emissions, significant cost savings in wastewater treatment operations, and increased energy production efficiency. These findings support the widespread adoption of sludge-to-energy conversion technologies in wastewater treatment facilities to enhance environmental sustainability and economic efficiency.

Table of Contents

List of Tables

List of Figures

List Of Abbreviations

Abbreviation	Representation
AI	Artificial Intelligence
°C	Degree Celsius
cap	Capita (person)
$C_6H_{12}O_6$	D-glucose
CHP	Combined Heat and Power
CH_4	Methane
CO_2	Carbone dioxide
CW	Constructed Wetland
CBA	Cost-Benefit Analysis
EAS	Ecosystem Activation System
H_2S	Hydrogen Sulfide
IEC	Israel Electric Company
KPIs	Key performance indicators
KFW	Kreditanstalt für Wiederaufbau
KWh	Kilo Watt Hour
m^3	Cubic Meter
MJ	Megajoules
MCM	Million Cubic Meters
NH3	Ammonia
NIS	Israeli New Shekel
nm^3	Normal cubic meter
PA	Palestinian Authority
PE	Population Equivalent
pH	Power of Hydrogen, referred to as acidity or basicity
PM	Particulate Matter
PV	Photovoltaic
SDGs	Sustainable Development Goals
SRB	Sulfate-Reducing Bacteria
USAID	United States Agency for International Development
USD	United States Dollar
UV	Ultraviolet
VOCs	Volatile Organic Compounds
WEF	Water-Energy-Food
WWTP	Waste Water Treatment Plant

Chapter One:

Introduction:

1.1 General Background

As the world becomes more urbanized and industrialized, dealing with wastewater, especially the byproducts from wastewater treatment, is becoming a bigger challenge (Soares, 2020). One major concern is sludge, a thick byproduct that can harm the environment if not handled properly (Sharma et al., 2022). Therefore, it is necessary to understand and address the issue of transboundary sludge pollution, which goes beyond borders and affects nature and communities (Marks et al., 2020). The research will introduce a suggestion to explore a solution for managing sludge, converting this sludge into electrical energy, and providing a greener and more sustainable way to handle sludge (Capodaglio & Olsson, 2019).

Wastewater management has become a critical aspect of urban and industrial development worldwide. The increasing global population, coupled with rapid urbanization and industrial expansion, has elevated the demand for effective wastewater treatment (Goh et al., 2022). The literature emphasizes the multifaceted challenges faced in treating and managing wastewater, ranging from technological constraints to socioeconomic and environmental considerations (Chrispim et al., 2019).

Wastewater treatment in Palestine faces several challenges across social, economic, political, and managerial aspects (Sharifi & Simangan, 2021). Socially, there's resistance and a lack of awareness about sustainable practices. Economically, costs for treatment and sludge disposal are significant hurdles (Guo et al., 2021). Political complexities and economic constraints further complicate the establishment of cohesive policies and solutions. Transboundary issues exacerbate the environmental impact, especially with inadequate disposal measures (Büttner et al., 2022). The limited resources, urban expansion, and political intricacies in the region make wastewater management complex (Abusharbak & Al-Sa’ed, 2000). Regulatory constraints and transboundary agreements add to the challenges for Palestinian authorities (Atawneh, 2020) (Stamatopoulou-Robbins, 2021).

Studies highlight the importance of adopting sustainable and innovative approaches to wastewater management to address the complexities arising from population growth, urbanization, and industrial activities (Jovarauskaitė & Balundė, 2021). Efficient wastewater treatment not only safeguards public health by preventing the release of harmful contaminants but also plays a pivotal role in environmental conservation. The disposal of sludge poses significant challenges to environmental sustainability (Singh, Kumar, et al., 2020). Traditional methods like land application and landfilling, once widely practiced, are now scrutinized due to their environmental impact (Nassar, 2015). Literature underscores the necessity for alternatives. Studies investigating sludge pollution underscore the broader implications on ecosystems, water bodies, and human health (Varady et al., 2023). The environmental consequences of untreated or improperly treated sludge include soil degradation, water contamination, and adverse effects on aquatic life (Dai, 2021). For example, soil degradation can occur when heavy metals and other toxic substances from sludge accumulate in the soil, reducing its fertility and potentially entering the food chain (Fresquez et al., 1990). Water contamination can result from runoff or leaching of pollutants such as pathogens, nutrients, and organic matter from sludge into groundwater or surface water bodies, leading to eutrophication and the proliferation of harmful algal blooms (Dregulo & Bobylev, 2021). This nutrient overload can deplete oxygen levels in water, causing dead zones where aquatic life cannot survive (Singh, Hariteja, et al., 2020). Additionally, the presence of harmful bacteria and viruses in contaminated water can pose serious health risks to humans and animals alike (Lipchin, 2013).

Transboundary movement of sludge pollution introduces a layer of complexity to wastewater management. The literature examines the environmental and socio-economic impacts of sludge pollution that extend beyond political boundaries (De Man, 2016). In regions with geopolitical challenges, such as the Palestinian territories, studies highlight the added difficulties in coordinating effective waste management practices (Al-Saidi et al., 2024).

The economic burden associated with transboundary sludge movement, including financial transactions between authorities, is a focal point of investigation (Alonso et al., 2023). Researchers analyze the financial implications on governmental budgets, emphasizing the interconnectedness of economic and environmental policies. Sludge disposal strategies that minimize ecological harm and contribute to resource recovery are critical for sustainable management (Hareuveni, 2009). For example, implementing advanced treatment technologies like anaerobic digestion not only reduces the volume and toxicity of sludge but also recovers valuable resources such as biogas, which can be used for energy production (Hao et al., 2020). Additionally, nutrient recovery processes can extract phosphorus and nitrogen from sludge, producing fertilizers that can be reused in agriculture (Jimenez et al., 2017), thus closing the nutrient loop and reducing the need for chemical fertilizers. These strategies not only mitigate environmental impacts but also provide economic benefits by reducing disposal costs and generating revenue from recovered resources (USAID Infrastructure Needs Program II, 2012).

Studies explore the environmental consequences of improper sludge disposal, especially when considering its transboundary movement (Petroody et al., 2021). The challenges associated with sludge disposal become more pronounced in regions with geopolitical complexities, adding layers of intricacy to waste management practices. Changing our perspective on waste management requires seeing sludge not only as a challenge but also as a valuable resource. The literature on converting sludge into electrical energy explores innovative solutions to address both waste management and energy generation (Whiting & Azapagic, 2014). This approach aligns with the broader global push towards sustainable and renewable energy sources. To address this environmental challenge, the proposed solution is sludge-to-energy conversion through methane gas production. If sludge is not treated, the anaerobic decomposition of organic waste can lead to significant gas emissions, particularly methane. In landfills, where oxygen is limited, the organic matter in sludge breaks down anaerobically, releasing methane, a potent greenhouse gas that contributes to climate change. Proper sludge treatment is essential to mitigate these emissions and reduce the environmental impact (Sathya et al., 2023). When untreated sludge undergoes decomposition, it releases methane gas into the atmosphere (Al-Saidi et al., 2024). Methane is a potent greenhouse gas, with a much higher heat-trapping cap (Lalawmpuii & Rai, 2023). Therefore, the release of methane from untreated sludge contributes to global warming and climate change by intensifying the greenhouse effect. Additionally, untreated sludge may also emit other harmful gases such as hydrogen sulfide and volatile organic compounds, which can have adverse effects on air quality and human health (Georgeson et al., 2016). Hydrogen sulfide (H_2S) is produced in wastewater treatment plants through the anaerobic decomposition of organic matter by sulfate-reducing bacteria (SRB) in environments with low oxygen levels, high organic material, and sulfate ions, such as sludge digesters (Godoi et al., 2018). This gas poses several problems, including health risks, corrosion of infrastructure, odor disturbance, and environmental pollution (Jazi, et al, 2022). However, by effectively collecting and utilizing H_2S, wastewater treatment plants can transform it into valuable commercial products, thus enhancing environmental sustainability and economic efficiency. Key commercial uses of hydrogen sulfide include the production of elemental sulfur and sulfuric acid, both crucial in various industries, and as a fuel in fuel cell technology, leveraging its high energy content to generate electricity (Spatolisano et al., 2022).

The greenhouse gas inventory in Palestine, reveals significant emissions across various sectors, with notable contributions from energy, agriculture, and waste management. Energy-related activities accounted for approximately 67.9% of the total greenhouse gas emissions, primarily driven by fuel combustion, manufacturing industries, and transportation. Agriculture constituted 11.6% of the emissions, largely attributed to livestock-related methane emissions and nitrogen oxide emissions from managed soils. Waste management activities contributed 20.5% to the total emissions, with significant methane emissions from solid waste disposal and wastewater treatment. The data, excluding parts of Jerusalem annexed by Israeli Occupation in 1967, underscores the urgent need for comprehensive strategies to mitigate greenhouse gas emissions and promote sustainable practices in Palestine (Palestinian Central Bureau of Statistics, 2021a). The greenhouse gas inventory in Palestine for CO_2, CH_4, and N_2O emissions indicates significant contributions to the total inventory. CO_2 emissions account for 65.6% of the total greenhouse gas inventory, CH_4 emissions contribute 22.2% to the inventory, while N_2O emissions represent 12.2% of the inventory (Palestinian Central Bureau of Statistics, 2021a).

The problem of transboundary sludge pollution in wastewater treatment plants intersects with the Water-Energy-Food (WEF) Nexus (UNDP, 2020). This problem highlights the interconnectedness of water, energy, and food systems, which is crucial for achieving sustainable development goals (Hák et al., 2016). Specifically, inefficient sludge disposal methods contribute to water pollution, impacting water quality and availability of Water-Nexus. Additionally, the disposal of sludge presents challenges in optimizing energy use, which is essential for sustainable development Energy-Nexus. Moreover, the environmental repercussions of sludge disposal on soil quality and potential runoff into water bodies pose threats to food systems, necessitating sustainable sludge management practices Food-Nexus. Addressing these challenges is paramount for promoting environmental sustainability and achieving long-term development objectives (Delibacak et al., 2020).

Researchers and practitioners have investigated various technologies for harnessing energy from sludge, such as anaerobic digestion, pyrolysis, and microbial fuel cells. These studies assess the technical feasibility and environmental implications of such conversion methods, providing insights into the potential of transforming a waste stream into a valuable energy resource (Castellanos et al., 2024).

The collaborative approach involving environmental scientists, policymakers, and energy production experts is crucial given the transboundary nature of sludge pollution. This study assesses transboundary sludge pollution, its environmental impacts, and potential socio-economic consequences, while also exploring the feasibility and effectiveness of converting problematic sludge into clean, usable energy.

Aligning with the broader objectives of sustainable development, the research proposes transformative solutions that integrate environmental protection with energy generation. Instead of just discovering the depth of the problem, it seeks to contribute to a more sustainable and resilient future by harmonizing environmental protection with energy production.

Consequently, the primary objective is to demonstrate the potential to reduce the environmental impact of sludge while utilizing it to generate electricity, aligning with the increasing demand for clean and renewable energy.

1.2 Problem statement

The problem of research is summed up in the quantities of sludge resulting from wastewater, which is considered a financial and environmental burden if it remains in its current quantities and if its pollutant crosses through the valleys into the Israel-Palestine border, which increases the financial burden it causes. Alternatively, the quantities of this sludge are increasing, and if not managed properly, the resulting pollution and costs will also rise. The research problem focuses on the pollution caused by transboundary sludge originating from wastewater treatment plants.

Moreover, The issue is the financial strain faced by the Palestinian Authority (PA) due to the transboundary movement of wastewater, which requires them to pay Israel for handling it. This puts pressure on the PA's budget, potentially affecting important areas like tax payments and overall financial stability (Al-Saʽ ed, 2010). The Israeli Sewage Infrastructure Development Administration determines the fees for wastewater treatment, which are deducted from Palestinian tax transfers to Israel. This deduction amounted to 34 million USD between 1994 and 2008 (De Man, 2016) equivalent to approximately 125 million NIS. The annual payment rate is estimated at 90 million NIS to 120 million NIS, presenting a significant challenge for the Palestinian government (PWA, 2022).

This financial burden is compounded by other sectoral challenges. In the energy sector, the Palestinian Authority (PA) faces limitations due to the Israel Electric Company (IEC) controlling the supply of conventional energy (electricity) to the Palestinian territories. This control restricts the PA's ability to manage and reduce energy costs independently. In the water sector, the PA grapples with severe water scarcity exacerbated by Israel's control over water resources, significantly limiting water availability for Palestinian use.

To address these challenges, there is a pressing need for non-conventional water resources and renewable energy sources. One promising approach is sludge-to-energy technology, which can simultaneously tackle the issue of sludge management and contribute to renewable energy production. Figure 1 shows that By converting sludge from wastewater treatment plants into biogas through anaerobic digestion, the PA can reduce sludge volumes, lower disposal costs, and generate a sustainable energy source. This biogas can be used for electricity generation or as a fuel for heating, reducing dependence on the IEC and enhancing energy security.

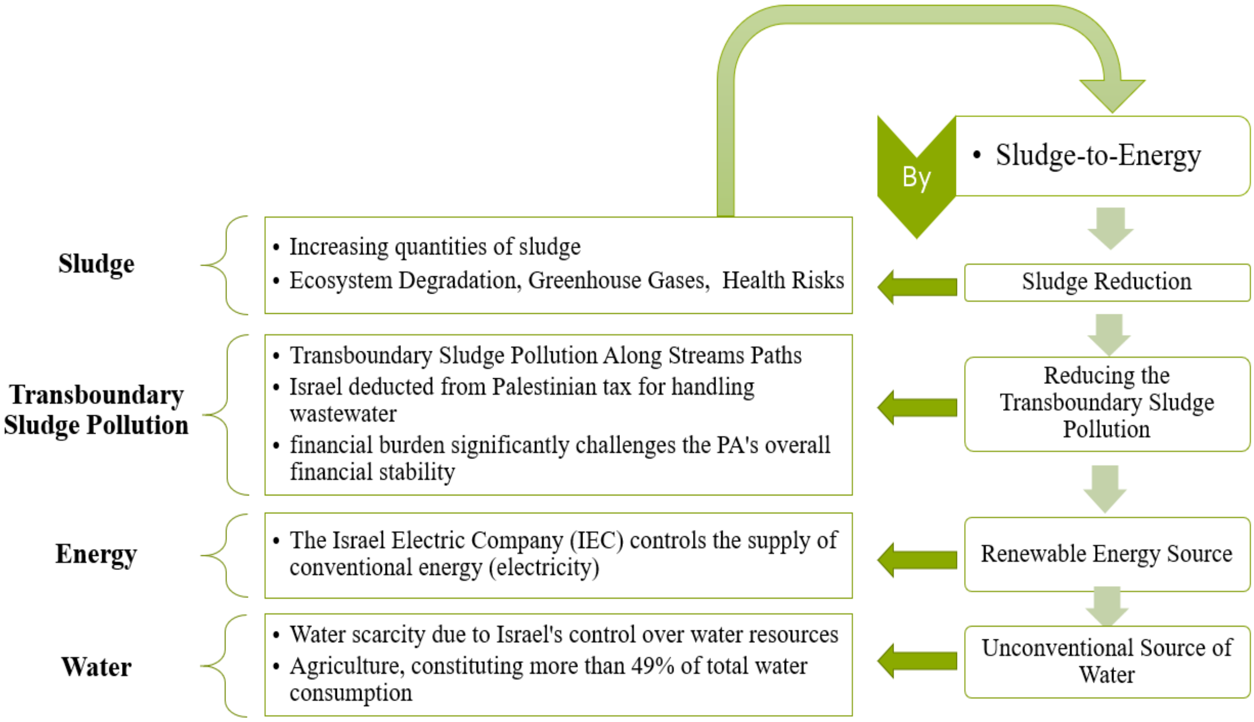

Figure 1; The research problem and its connection to solutions for converting sludge-to-energy.

Research Question(s) and Hypothesis

- What is the efficacy of converting sludge into energy and its potential impact on mitigating environmental pollution and promoting sustainable development in regions affected by transboundary sludge pollution? How does this impact the treatment cost per cubic meter? what is the amount of energy produced per cup of sludge generated?

1.3 Research Significance and Relevance

This research holds multifaceted significance and relevance. Firstly, it tackles the critical issue of sludge management by proposing a sustainable solution to alleviate the burden on wastewater treatment stations and the environment. Through the innovative approach of converting sludge into electrical energy, this research not only addresses wastewater management challenges but also harnesses renewable energy sources. Moreover, it carries particular importance for the Palestinian Authority (PA) in combatting transboundary valley pollution. By advocating for sustainable solutions grounded in green economy principles, such as sludge-to-energy conversion. This initiative not only aligns with global sustainability efforts but also addresses the PA's specific challenges in wastewater management and cross-border pollution mitigation. In addition, the proposed technology in sludge management contributes to achieving the third strategic goal in the Water Authority's strategy is to improve the structure and services of sanitation and wastewater treatment and increase its use in various fields. The Water Authority has adopted the achievement of this goal through a set of main results related to the implementation of this strategy shown in Figure 2, with emphasis on the compatibility of the research goal with Achieving the Water Authority's strategy.

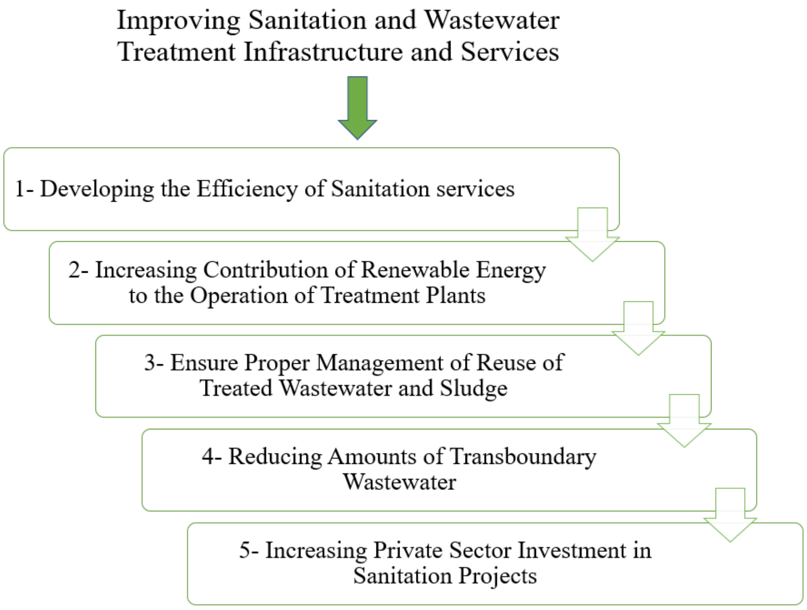

Figure 2; The third strategic goal of the Palestinian Water Authority's strategy.(PWA, 2022)

The research holds significant implications for sludge-to-energy, marking a pivotal shift in waste management practices. By harnessing the energy potential within sludge. The endeavor aligns with the global drive towards sustainable energy solutions, offering a renewable and efficient approach to wastewater treatment. Furthermore, the exploration of sludge-to-energy conversion resonates with the Water-Energy-Food (WEF) Nexus framework, which underscores the interconnectedness of these essential resources, Figure 3 shows the relationship between water, energy, and food. In regions like Palestine, where challenges such as water scarcity and energy security prevail, understanding and addressing the WEF Nexus dynamics are paramount for achieving sustainable development goals.

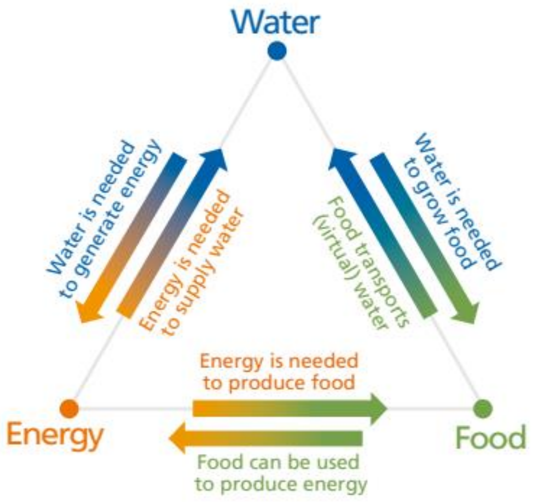

Figure 3; The Water-Food-Energy Nexus.(Escap, U. N. ,2013)

The proposed method contributes to multiple Sustainable Development Goals (SDGs) shown in Figure 4, including clean water and sanitation, affordable and clean energy, and sustainable cities and communities. Moreover, in the context of the complex reality of sewage management in the Occupied West Bank, the research offers insights into overcoming political, infrastructural, and environmental challenges. By advocating for collaborative solutions and innovative approaches like sludge-to-energy conversion, the study aims to pave the way for more sustainable and resilient wastewater management practices in the region.

Figure 4; Sustainable development goals that research contributes to achieving. (UNDP, 2024)

Through a comprehensive analysis of technical feasibility, environmental impacts, and economic viability, this research provides valuable insights for policymakers, practitioners, and stakeholders involved in wastewater management. By evaluating the potential of sludge-to-energy conversion in mitigating environmental pollution and promoting sustainable development, particularly in regions affected by transboundary sludge pollution, the study seeks to advance knowledge and practices in wastewater treatment and renewable energy generation. Moreover, by conducting a case study at a wastewater treatment plant in Nablus, the research provides practical recommendations and guidelines for implementing sludge-to-energy conversion initiatives in similar contexts. Ultimately, the findings of this thesis aspire to inform evidence-based decision-making and facilitate the transition towards more sustainable and resilient wastewater management systems globally.

1.4 Objectives

The main objective of this study is to examine the feasibility and potential benefits of converting Sludge-to-Energy at wastewater treatment plants (in Nablus West WWTP case shall be evaluated), with a specific focus on its impact on mitigating environmental pollution and promoting sustainable development in regions affected by transboundary sludge pollution.

1.4.1 To determine the amount of energy produced per unit of sludge generated in West Bank.

1.4.2 To analyze the sludge-to-energy conversion and the treatment cost per cubic meter of wastewater.

1.4.3 To assess the effectiveness and analyze the impact of mitigating transboundary sludge pollution compared to the potential benefits of converting sludge into energy in problem-solving and promoting collaboration across borders.

- Evaluate the effectiveness of converting sludge-to-energy and its potential role in reducing environmental pollution in regions affected by transboundary sludge pollution.

1.4.4 To analyze the financial losses experienced by the Palestinian Authority in comparison to the expenses associated with transboundary environmental pollution

1.4.5 To estimate the current volume of sludge generated from wastewater treatment in Palestine, then to modulate the expected quantities considering the establishment of additional treatment plants, and forecast the potential volume if all wastewater undergoes treatment within the region.

1.5 Thesis Structure

The thesis contains five chapters as follows:

- Chapter One: Introduction.
  It provides an overview of the research topic, its problem, its significance, and the objectives of the study. Additionally, Chapter One introduces the concept of sludge-to-energy conversion as a potential solution to these challenges and highlights the relevance of the study in addressing them. The chapter also outlines the structure of the thesis, including the subsequent chapters and their respective focuses.

- Chapter Two: Literature review.
  This chapter provides a comprehensive review of existing literature relevant to the research topic. It examines previous studies, academic papers, and theoretical

frameworks related to wastewater management, sludge treatment, renewable energy, and sustainable development. The literature review synthesizes key findings, identifies gaps in current knowledge, and highlights theoretical perspectives that inform the research approach.

- Chapter Three: Methodology

  In Chapter Three, the methodology employed in the research is delineated in detail. This chapter elucidates the research design, including the approach, strategies, and methods used to address the research questions and achieve the study objectives.

- Chapter Four: Analysis and Discussion of Results

  Chapter Four of the thesis delves into the detailed analysis and discussion of the research findings. It systematically presents and interprets the results obtained from both quantitative and qualitative data, addressing each research question or objective. The chapter critically evaluates the findings, drawing connections to existing literature and theoretical frameworks.

- Chapter Five: Concluding Remarks

  Within this chapter, a synthesis of the study's discoveries is provided, accompanied by some recommendations for future actions.

Chapter Two:

Literature review:

2.1 Introduction

Chapter Two provides a thorough literature review focusing on wastewater management, renewable energy utilization, and sludge-to-energy conversion. It begins with an introduction, setting the stage for understanding the current state of research in the field. The review delves into traditional wastewater treatment methods and their associated challenges, highlighting the growing interest in renewable energy as an alternative solution (Hao et al., 2020). Specifically, it explores the potential of Combined Heat and Power (CHP) systems to generate electricity from biogas produced during sludge digestion processes (Bacenetti et al., 2019).

2.2 Sludge-to-Energy Conversion Tuiqniques

Wastewater treatment plants (WWTPs) in Palestine play a crucial role in managing and treating sewage to protect the environment and public health. These facilities are essential for addressing the challenges posed by urbanization, population growth, and industrial activities (Sallam et al., 2024). The primary objectives of WWTPs include the removal of pollutants from wastewater before its discharge back into the environment. The wastewater treatment process typically involves several stages (Al-Joulani, 2019) shows in Figure 5 that the wastewater treatment process involves several sequential phases aimed at cleansing the incoming wastewater. It begins with preliminary treatment, which focuses on removing large objects and sediment through screening and sedimentation. Subsequently, in the primary treatment phase, physical separation processes are employed to allow the settling of suspended solids, leading to the formation of sludge as a byproduct (Hasan et al., 2021). Following primary treatment, the wastewater undergoes secondary treatment, where biological processes are utilized to degrade organic matter, facilitated by the introduction of microorganisms. Finally, in some instances, tertiary treatment may be conducted to address specific contaminants or nutrients that may still be present in the water (George P. Yerousis, 2011).

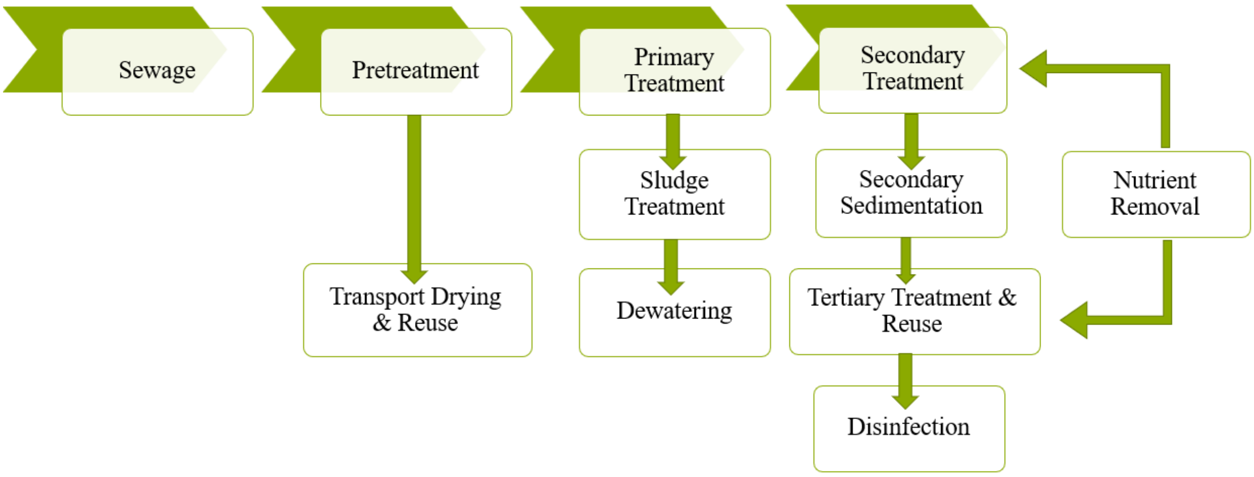

Figure 5, The Wastewater Treatment Process Stages. (UNDP, 2024)

Despite the effectiveness of these treatment processes, one of the challenges faced by WWTPs in Palestine is the disposal of the generated sludge. Traditional methods of sludge disposal, such as land application or landfilling, can pose environmental risks if not managed sustainably.

2.2.1 Traditional methods of sludge disposal

In Palestine, traditional methods of sludge disposal primarily include land application and landfilling.

Land Application: This method involves spreading the sludge on agricultural land. While it may provide some nutrient benefits to the soil, there are significant drawbacks. The application of sludge to land can lead to issues such as the accumulation of heavy metals and other contaminants in the soil (Zhang & Chen, 2020). Over time, this can adversely affect soil quality, potentially impacting crop health and productivity. Additionally, if not managed meticulously, the runoff from treated land may pose a risk of contaminating nearby water bodies (Hu et al., 2020).

Landfilling: Another common practice is disposing of sludge in landfills. However, this method presents environmental challenges. Sludge contains organic matter, and when disposed of in landfills, it undergoes anaerobic decomposition, producing methane gas. Methane is a potent greenhouse gas that contributes to climate change (Shadeed et al., 2017). Moreover, landfills can pose a risk of leachate formation—a liquid that results from the breakdown of waste—which may contain pollutants harmful to groundwater if not adequately managed.

The effects of these traditional sludge disposal methods in Palestine are multifaceted. Environmental concerns include the potential contamination of soil and water, contributing to ecosystem degradation. The release of methane gas from landfills adds to the greenhouse gas burden, exacerbating climate change challenges. Moreover, the impact on agricultural productivity and potential health risks for those living in proximity to disposal sites underscore the need for more sustainable and environmentally friendly approaches to sludge management (Rao Meda et al., 2021).

The impact of traditional sludge disposal methods in Palestine extends to water bodies and groundwater. When sludge is applied to agricultural lands, there is a risk of water pollution. The sludge may contain contaminants and heavy metals, which, when not managed properly, can leach into the soil and eventually reach water bodies such as rivers and streams. This can compromise water quality and harm aquatic ecosystems.

In the case of sludge disposal in landfills, there is a potential for the formation of leachate a liquid that can result from the breakdown of waste. If not adequately managed, leachate from landfills may contain harmful pollutants that can infiltrate the groundwater (Bigas et al., 2013). Groundwater, being a vital source of drinking water in many regions, is susceptible to contamination from these pollutants, posing risks to both human health and the environment (Larsen et al., 2016).

2.2.2 Methane Production:

In wastewater treatment plants, methane production typically occurs through anaerobic digestion and biogas production processes. Anaerobic digestion is a biological process that occurs in the absence of oxygen, where sludge derived from wastewater treatment is introduced into a dedicated reactor. In this reactor, bacteria break down the organic matter in the sludge, resulting in the production of biogas, which is primarily composed of methane and carbon dioxide (Hao et al., 2020). The generated biogas is then extracted and purified to obtain a high concentration of methane, making it a combustible energy source (Whiting & Azapagic, 2014). This biogas can be utilized for electricity generation or heating, contributing to sustainability efforts and reducing harmful emissions. Additionally, biogas can be used in power generation stations or as fuel for vehicles, offering an environmentally and economically efficient energy solution, as it is considered a renewable and sustainable energy source (Mills et al., 2014).

2.2.3 Anaerobic Digestion Processes in Wastewater Treatment:

Anaerobic digestion processes are central for converting organic sludge into valuable resources. The efficiency of this method is determined by various factors, including temperature and pH levels. Typically operating within a mesophilic (20-45°C) or thermophilic (45-65°C) range, anaerobic digestion relies on the activity of specific microorganisms, particularly methanogens. These microorganisms play a vital role in breaking down organic matter, following reactions such as $C_6H_{12}O_6 \rightarrow 3CH_4 + 3CO_2$. The process generates essential outputs, including biogas (comprising methane and carbon dioxide) and a stabilized, digested sludge with reduced organic content (Hao et al., 2020). Bioreactors are engineered to maintain optimal conditions, employing insulation, heating systems, and pH monitoring to ensure an environment conducive to anaerobic microorganism activity (Di Fraia et al., 2022).

The biogas produced, predominantly composed of methane (CH_4) and carbon dioxide (CO_2), holds significant importance as a valuable energy source (Cremonez et al., 2021). It results from the anaerobic digestion process applied to the sludge generated by wastewater treatment plants. Capturing the methane, a potent greenhouse gas, allows its utilization as a renewable energy source. The generated biogas can be harnessed for various purposes, with a primary focus on electricity generation (Nabaterega et al., 2021). The process involves utilizing the combustible properties of methane to fuel a generator, converting the chemical energy of the gas into electrical energy.

Converting methane into electricity is a dynamic process that involves harnessing the energy potential stored in methane gas to generate electrical power (George P. Yerousis, 2011). The primary method employed for this conversion is through the operation of a generator. In this process, methane is fed into the generator (Gao et al., 2020). The generator, typically powered by an internal combustion engine, utilizes the flammable properties of methane to drive a turbine or piston. As the methane undergoes controlled combustion, it releases energy in the form of heat. This heat energy is then transformed into mechanical energy, which ultimately powers an electric generator. The generator converts mechanical energy into electrical energy through the principle of electromagnetic induction (Whiting & Azapagic, 2014). This resulting electrical energy can be integrated into the power grid for broader distribution and utilization.

2.2.4 Organic fertilizer:

A valuable by-product of the methane production process, serves as a nutrient-rich soil amendment in agricultural practices. As sludge undergoes anaerobic digestion to produce methane, the remaining organic materials transform into nutrient-rich fertilizer (Jimenez et al., 2017). This organic fertilizer is characterized by its high content of essential nutrients like nitrogen, phosphorus, and potassium, essential for plant growth. Its application enhances soil fertility, promotes healthier plant growth, and contributes to sustainable farming practices (Shadeed et al., 2017).

One of the key advantages of organic fertilizer is its ability to improve soil structure and water retention. By promoting microbial activity and organic matter content in the soil, it enhances soil aeration and drainage (Jimenez et al., 2017). This not only fosters optimal conditions for plant root development but also mitigates issues related to soil erosion.

Moreover, organic fertilizers contribute to environmental sustainability by recycling nutrients from wastewater into the agricultural system. This closed-loop approach aligns with the principles of a circular economy, reducing the reliance on synthetic fertilizers and minimizing the environmental impact associated with traditional sludge disposal methods.

2.2.5 Water Reuse:

In the sludge-to-energy conversion process, water dynamics are critical. This involves a careful consideration of water resources throughout the energy production cycle. Integrating water management into energy generation highlights a vital synergy within the WEF Nexus (Commission for Western Asia, 2017).

Water dynamics play a pivotal role, emphasizing the need for balanced water use efficiency. The process recognizes the importance of water resources, aligning with the WEF Nexus's focus on the interconnected dynamics of water, energy, and food systems, addressing challenges sustainably (Scoullos et al., 2002).

Moreover, there's a substantial indirect impact on water bodies. Traditional sludge disposal methods can harm soil quality and water bodies (Salem H. S. et al., 2021). Conversely, converting sludge into electrical energy through methane production mitigates potential environmental repercussions, providing a more sustainable and water-conscious strategy within the broader WEF Nexus (Lalawmpuii & Rai, 2023).

In WWTP, treated wastewater holds potential for reuse, especially in irrigation. After treatment, the water becomes suitable for non-potable purposes, aligning with sustainable water management. Diverting treated wastewater for irrigation addresses environmental challenges and establishes a resourceful approach within the WEF Nexus framework, emphasizing the interconnection of water, energy, and food systems for sustainable development (Georgeson et al., 2016). Efforts are underway to explore alternative water sources aimed at alleviating the strain on available drinking water reservoirs. Seeking solutions to lessen the load on water sources, there is a growing emphasis on utilizing treated wastewater for agricultural irrigation. Agriculture, constituting more than 49% of total water consumption, remains a key area of focus for reducing water demand (Palestinian Central Bureau of Statistics b, 2021). Figure 6 displays the basic elements of the study.

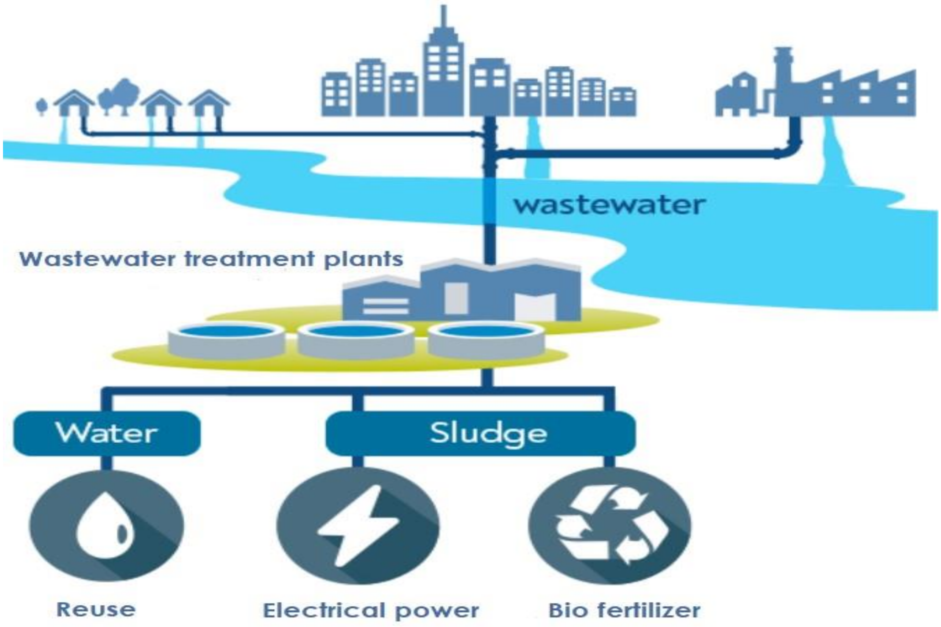

Figure 6; The basic elements of the study.

2.3 Transboundary Sludge Pollution

Transboundary sludge pollution refers to the contamination of soil, water bodies, or ecosystems by sewage sludge that originates from multiple sources across international borders (Um et al., 2022). This type of pollution occurs when sewage sludge, which contains organic and inorganic contaminants from domestic, industrial, and agricultural activities, is improperly managed, leading to its migration and adverse effects on neighboring regions or countries (Varady et al., 2023). Transboundary sludge pollution can result in environmental degradation, compromised water quality, public health risks, and ecological disruptions (Al-Sa’ed & Al-Hindi, 2012), necessitating collaborative efforts between nations to address and mitigate its impacts. Sludge pollution can be transmitted through several pathways, impacting various environmental media and regions. In waterways, surface runoff during heavy rains or flooding can wash sludge from treatment plants or disposal sites into rivers, streams, and lakes, leading to water contamination. Improperly disposed sludge can leach into the soil, contaminating groundwater sources. In the soil, sludge applied to agricultural land as fertilizer can introduce pollutants that are absorbed by crops or washed into nearby water bodies. In contrast, wind and water erosion can transport contaminated soil particles over long distances (Costantini et al,1995). In the air, aerosolization of dried or incinerated sludge releases fine particles and volatile compounds, leading to air pollution and subsequent deposition on land or water surfaces (Um et al., 2022). Decomposing sludge also emits noxious gases such as ammonia, hydrogen sulfide, and methane, contributing to air quality problems. Human activities, such as transporting sludge by trucks, ships, or pipelines, can result in accidental spills or leaks, spreading contamination along transport routes. Cross-border trade of sludge for disposal or recycling can introduce pollutants to regions with less stringent environmental regulations. Wildlife and livestock can ingest contaminated sludge or water, spreading pollutants through their waste or moving across different environments (Varady et al., 2023).

2.3.1 Transboundary Sewage Issue between Israel and Palestine

The transboundary wastewater streams between Israel and Palestine present a multifaceted challenge with far-reaching implications for both environmental sustainability and public health (Yaqob et al., 2014). These streams, originating from various sources in the West Bank, traverse Palestinian and Israeli territories, affecting groundwater resources and local communities along their paths. The pollution of groundwater, a crucial water source for Palestinian communities, poses a significant threat, particularly when untreated or inadequately treated wastewater is discharged directly into it (Brooks et al., 2011). This contamination not only compromises the quality of drinking water but also undermines the integrity of ecosystems and agricultural lands dependent on groundwater replenishment (De Man, 2016).

Moreover, the presence of wastewater streams passing through Palestinian communities exacerbates the situation, leading to adverse effects on public health and well-being (Water, 2013). Foul odors, insect proliferation, and health hazards associated with exposure to contaminated water further compound the challenges faced by residents in these areas. The transboundary nature of these streams complicates matters, requiring coordinated efforts and cooperation between Israeli and Palestinian authorities to address them effectively (Al-Sa'ed , et al., 2014).

The transboundary sewage issue underscores broader tensions and complexities inherent in the Israeli-Palestinian conflict, reflecting disputes over territorial control, resource management, and environmental stewardship. Resolving these issues demands not only technical solutions such as improved wastewater treatment infrastructure but also diplomatic efforts to foster mutual understanding, trust, and collaboration (Lipchin, 2013). By working together to mitigate the impacts of transboundary wastewater pollution, both Israel and Palestine can safeguard public health, protect natural resources, and promote sustainable development in the region.

2.3.2 Israeli Policy Towards the Palestinian Sewage Sector:

Israeli policy regarding sewage management in Palestine differs significantly from its approach in other sectors, involving practices of occupation that severely impact the lives of Palestinians. These practices include the demolition of infrastructure, displacement of populations, confiscation of resources, deprivation of rights and land, and imposition of restrictions on movement and basic rights (Lavee, 2014).

- Overview of Occupation Policy in the Water Sector:

After Israel's occupation of Palestinian territories following the 1967 war, Israel gained complete control over Palestinian water resources. Military orders transferred water authority in the West Bank and Gaza to the Israeli military government, granting Israeli water officers absolute authority (Yaqob et al., 2014). This included the power to prevent the establishment of new water projects without permits and to deny Palestinians access to their water rights.

- Destruction of Water Facilities and Access Limitations:

Israel implements destructive policies such as demolishing wells and destroying irrigation networks, tanks, and pipelines, which hinder Palestinian efforts to improve water infrastructure. Additionally, Israel restricts the drilling of wells and the construction of new water facilities, forcing Palestinians to rely on alternative, expensive water sources House of Water & Environment, 2012).

- Israeli Control Over Water Resources:

Israel controls nearly 85% of Palestinian water resources, preventing Palestinians from developing water facilities and determining the quantities of water they can use (PWA, 2013). Israel benefits from Palestinian water resources without adequately compensating them.

- Delaying Water Issues in Negotiations:

Despite signing the Oslo Accords, which stipulated providing Palestinians with additional water quantities, Israel has postponed fulfilling its commitments. Israel insists on delaying discussions on water issues in political negotiations, exacerbating tension and division between the parties (Yaqob et al., 2014). Figure 7 shows the West Bank geopolitical map according to Oslo Agreement.

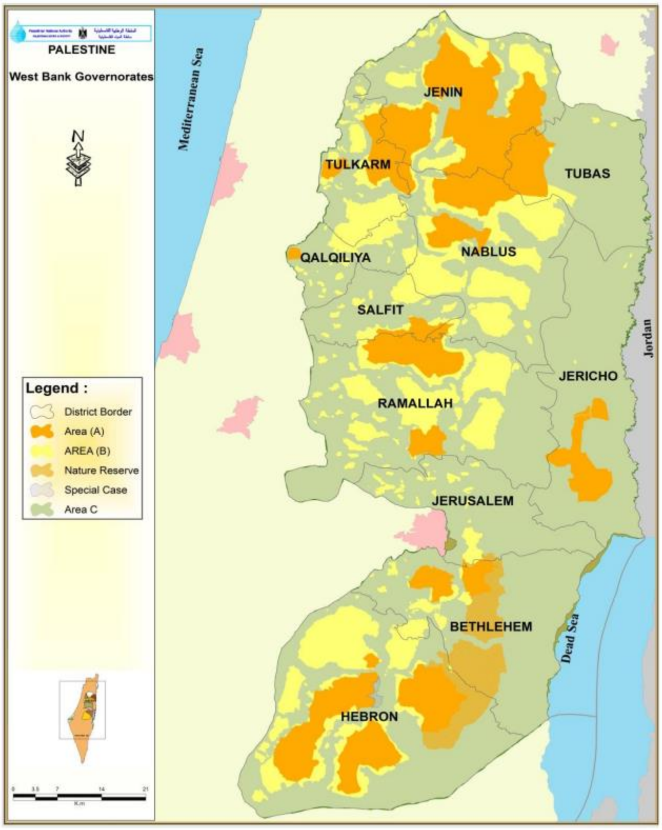

Figure 7: a geopolitical map for the West Bank according to Oslo agreement (Yaqob et al., 2014).

Israeli policies towards the sewage sector and environmental protection in the occupied Palestinian territories have significantly affected the environment and public health (EIB

Advisory Services, 2017). Since Israel's occupation of Palestinian territories in 1967, it has failed to adhere to environmental protection standards and adequately develop sewage infrastructure.

One of the main challenges is the behavior of Israeli settlements, which discharge untreated sewage into Palestinian territories, causing environmental pollution and threatening water resources and agricultural lands (Yaqob et al., 2016). This behavior destroys agricultural environments, contaminates water, impacts public health, and exposes residents to diseases.

Moreover, Israel restricts the development of environmental projects in Palestinian territories, preventing Palestinian authorities from implementing sewage infrastructure improvement projects (Al-Sa’ed & Al-Hindi, 2012). This restriction impedes environmental efforts, worsens pollution, and deteriorates the environmental situation in the region.

Overall, Israel's policies towards the sewage sector and environmental protection in the occupied Palestinian territories are considered inappropriate and destructive, necessitating international efforts to address these challenges and protect the environment and public health in the area.

2.3.3 Transboundary Wastewater Streams inside Israel:

Inside Israel, several wastewater treatment plants have been constructed within the Green Line to manage the wastewater discharged from Palestinian territories. Israel utilizes the treated wastewater for agricultural projects and groundwater recharge, deriving benefits from its reuse. However, the costs associated with the construction, rehabilitation, and operation of these WWTPs are deducted from the Palestinian tax revenue collected by Israel. According to a Beit Selem report in 2009, the deducted amount exceeded 200 million NIS by that time, encompassing both capital and operational expenses incurred for the treatment facilities.

The absence of a clear agreement between Israeli and Palestinian authorities regarding the treatment of discharged wastewater complicates the matter (House of Water & Environment, 2012). Israel sends invoices to the Palestinian Authority detailing the deducted amounts, albeit without transparent breakdown analysis. Some invoices specify the quantities of discharged wastewater without elucidating the calculation methodology, while others outline costs without correlating them with treated wastewater volumes.

At times, in response to Palestinian requests, Israel provides breakdown analyses for calculating the deducted amounts. However, these analyses may rely on estimated values rather than precise measurements. For instance, wastewater quantities from Beit Jala Wadi were calculated based on measurements conducted on the Biet Jala pipeline in 2006, whereas estimations were used for wastewater discharged from Birnabal, Al Jeeb, and Al Ram into Wadi Surik. The Israeli estimation of daily wastewater production at 100 liters per capita in certain cases appears unreasonable.

Notably, the Palestinian side does not participate in measuring or estimating wastewater quantity and quality (Tal et al., 2010). Furthermore, different tariffs apply for treating one cubic meter of wastewater inside Israel, varying based on location and discharge points. As of 2010, wastewater tariffs ranged from 0.97 NIS for Jenin area discharges in Wadi Al Muqatta to 2.12 NIS for Birnabala, Al Jeeb, and Al Ram discharges in Wadi Surik, with additional charges for the Value Added Tax.

2.3.4 The Israeli Policy Towards the Palestinian Wastewater Sector: (House of Water & Environment, 2012; Tal et al., 2010):

- Israeli Policy towards Transboundary Wastewater Streams:
    - Palestinian wastewater flows into Israel due to a lack of treatment facilities in the West Bank.
    - Israel treats some of this wastewater in facilities inside its territory and deducts costs from Palestinian tax money.
    - Several facilities treat Palestinian wastewater, including emergency reservoirs and treatment plants.
    - The treated wastewater is reused for agricultural irrigation and stream rehabilitation in Israel.
- Tariff Policy:
    - No clear policy exists for calculating the tariff for treating Palestinian wastewater.
    - Prices for treatment range from 0.8 NIS to 2.2 NIS per cubic meter depending on quality.
    - Israel deducts treatment costs directly from Palestinian tax revenue without providing a detailed breakdown analysis.
- Israeli Delays:

    - Israel's neglect contributes to the lack of wastewater treatment facilities in the West Bank.
    - Existing facilities are ineffective or non-functional.
    - Approval processes for new facilities are complex and prolonged, often involving rejection or delays by Israeli authorities.
- Attempts to Force PA Compliance:
    - Israel previously conditioned the construction of Palestinian treatment plants on connecting settlements to the facilities.
    - This policy delayed the approval of plans and faced rejection by the Palestinian Authority.
- Dispute over Treatment Standards:
    - Israel imposed advanced wastewater treatment standards on Palestinian facilities, increasing costs significantly.
    - Disagreements exist between Israeli and Palestinian authorities over the level of treatment required.
- Dependence on Donor Countries:
    - Donor countries face challenges implementing wastewater projects due to Israeli restrictions on Palestinian movement.
    - Funding for projects has been frozen or reduced, affecting wastewater treatment efforts.
- Breach of International Law:
    - Israel's neglect of wastewater treatment infringes on Palestinians' rights to water, sanitation, and livelihoods.
    - International humanitarian law and human rights conventions emphasize the right to clean water and sanitation for all individuals, which Israel's actions violate.

2.3.5 Sewage in the Occupied West Bank Reality (House of Water & Environment, 2012)

Sewage management in the Occupied West Bank presents a complex and challenging reality on the ground, marked by various environmental, political, and social factors (PWA, 2013). The management of sewage and wastewater in this region is crucial for public health, environmental sustainability, and the well-being of communities. However, several issues contribute to the complexity and difficulty in addressing sewage-related challenges in the West Bank.

- Political Context: The political situation in the Occupied West Bank significantly influences sewage management practices. The division of control between Israeli authorities and the Palestinian Authority creates administrative complexities and obstacles in coordinating infrastructure development and sewage treatment initiatives. Israeli settlements in the West Bank further complicate the situation, as they often have sewage systems that can impact nearby Palestinian communities. Transboundary streams have become conduits for sewage discharge, leading Israel to impose sanctions and penalties on Palestinians. Israel's policies, including delays in the wastewater sector in the West Bank, have exacerbated this situation. Furthermore, Israel deducts the costs of building facilities and treating sewage from Palestinian clearance tax revenues, even when the sewage is mixed with that produced by Israeli settlers.
- Limited Infrastructure: Many Palestinian communities in the West Bank lack adequate sewage infrastructure, leading to the discharge of untreated or partially treated wastewater into the environment. The absence of comprehensive sewage networks, treatment plants, and sanitation facilities results in contamination of water sources, soil, and air, posing serious health risks to residents.
- Resource Constraints: The Palestinian Authority faces resource constraints, including financial limitations and restricted access to materials and technologies necessary for sewage infrastructure development and maintenance. Limited funding and international aid for sewage projects hinder the implementation of comprehensive solutions to address wastewater management challenges effectively.
- Environmental Impacts: Untreated sewage poses significant environmental threats in the West Bank, including contamination of groundwater, surface water bodies, and agricultural lands. The discharge of raw sewage into streams, rivers, and valleys contributes to water pollution, soil degradation, and ecosystem damage, affecting biodiversity and natural habitats.
- Public Health Concerns: Inadequate sewage management practices directly affect public health in Palestinian communities. Exposure to contaminated water sources increases the risk of waterborne diseases, such as diarrhea, cholera, and hepatitis,

leading to higher rates of illness and mortality, particularly among vulnerable populations, such as children and the elderly.

- Legal and Regulatory Challenges: The legal framework governing sewage management in the West Bank is complex and fragmented, with overlapping jurisdictions and responsibilities between Israeli and Palestinian authorities. Disputes over land ownership, planning permissions, and environmental regulations further complicate efforts to address sewage-related issues effectively.
- Need for Collaborative Solutions: Addressing sewage challenges in the Occupied West Bank requires collaborative efforts between Israeli and Palestinian authorities, as well as engagement with international organizations and donor agencies. Comprehensive strategies should prioritize infrastructure development, capacity building, and community participation to ensure sustainable sewage management practices and safeguard public health and environmental quality.

2.3.6 Transboundary Wastewater Streams:

Transboundary wastewater streams refer to watercourses or drainage systems that flow across international borders, carrying sewage and wastewater from one territory to another (Yaqob et al., 2016). In the context of the Israeli-Palestinian conflict, transboundary wastewater streams play a significant role in shaping environmental and political dynamics between Israel and the Occupied Palestinian Territories.

These streams often originate in Palestinian communities in the West Bank and flow into Israel, where they may intersect with Israeli settlements or discharge into Israeli-controlled areas. The flow of wastewater across borders poses environmental and health risks to both Israeli and Palestinian populations, as untreated or poorly treated sewage can contaminate water sources, soil, and ecosystems (Hellegers, 2023).

Fifteen streams intersect the Palestinian/Israeli Green Line, spanning both Israel and the West Bank and Gaza Strip. The presence of 15 streams crossing the Palestinian/Israeli Green Line underscores the intricate interplay between environmental and geopolitical factors in the region (House of Water & Environment, 2012). These watercourses serve as conduits for various substances, including sewage and wastewater, originating from Palestinian Authority areas and flowing towards both Israel and neighboring bodies of water.

Among these streams, 12 are major watercourses that meander westward, ultimately emptying into the Mediterranean Sea. These streams play a crucial role in shaping the hydrological landscape of both Israel and the Occupied Palestinian Territories. They traverse diverse terrain, ranging from urbanized areas to agricultural lands, and carry a significant volume of water and contaminants (Salem H. S. et al., 2021).

Conversely, the remaining three streams diverge eastward, towards the Dead Sea and the Jordan River. These watercourses represent vital ecological corridors and contribute to the unique ecosystems of the region (Salem H. S. et al., 2021). However, they are also susceptible to pollution and degradation due to the influx of untreated sewage and wastewater from upstream sources. Figure 8 shows the most important wastewater stream locations.

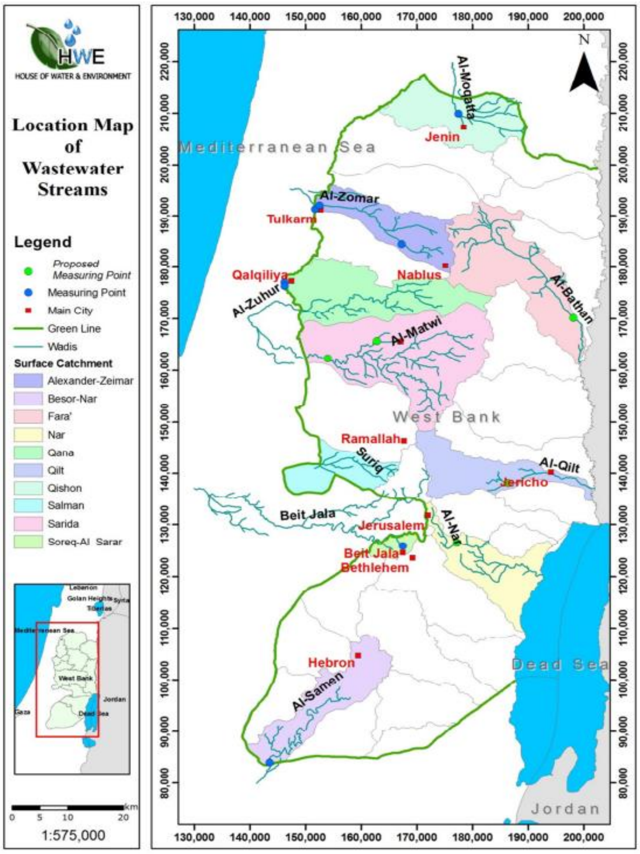

Figure 8: Streams Location Map (Salem H. S. et al., 2021)

The most important transboundary wadis and streams with Jordan appear in Figure 8 Which includes the following (House of Water & Environment, 2012):

- Wadi Al-Bathan (Wadi Al-Faraa), receives wastewater from East Nablus City which mixes with flowing fresh water from Al-Bathan springs and then flows by gravity towards the Jordan River.
- Wadi Al-Qelt, receives treated wastewater from Al-Bireh WWTP in addition to raw wastewater from east Ramallah city (Qalandia camp) and raw wastewater from Adam Colony. The discharged wastewater is flowing to the east towards the Jordan River.
- Wadi Al-Nar, receives wastewater from East Jerusalem (inside the Green Line), east Bethlehem city, and Biet Sahour.

The main transboundary wadis and streams between Israel and Palestine Shown in Figure 9, through which sewage from the West Bank flows and crosses the Green Line, include the following (House of Water & Environment, 2012):

- Wadi Zomar receives sewage from the cities of Nablus, Tulkarem, and surrounding areas then flows by gravity towards the Green Line to Yad Hanna WWTP.
- Wadi Al-Moqatta, receives sewage from Jenin and Jenin Camp then flows by gravity towards Gilbo′ WWTP inside the Green Line.
- Wadi Abu Nar, carries wastewater from Baqa Al Sharqiya, Nazlat, and surrounding areas and crosses the border to the Mediterranean Sea through Baqa Al Gharbiya inside the Green Line.
- Wadi Al-Zuhur, receives wastewater from Qalqilia City and flows through conduits under the separation wall until reaching Ner Elyaho WWTP inside the Green line.
- Wadi Suriq, receives wastewater from Ramallah City, Al-Jeeb, Bir Nabala, and Al-Ram and discharged by gravity towards the Green Line until reaching Suriq WWTP.
- Wadi Beit Jala, receives wastewater from Beit Jala and some parts of Bethlehem City and discharged by gravity towards the Green Line until reaching Suriq WWTP.
- Wadi Al-Samen, receives wastewater from Hebron City and Kiryat Arbaa Colony, the wastewater flows by gravity towards the Green Line until reaching Shoket WWTP.
- Wadi Al Matwi (Qana), receives wastewater from Salfit City and Ariel Colony crossing Burqin Village towards the Green Line.

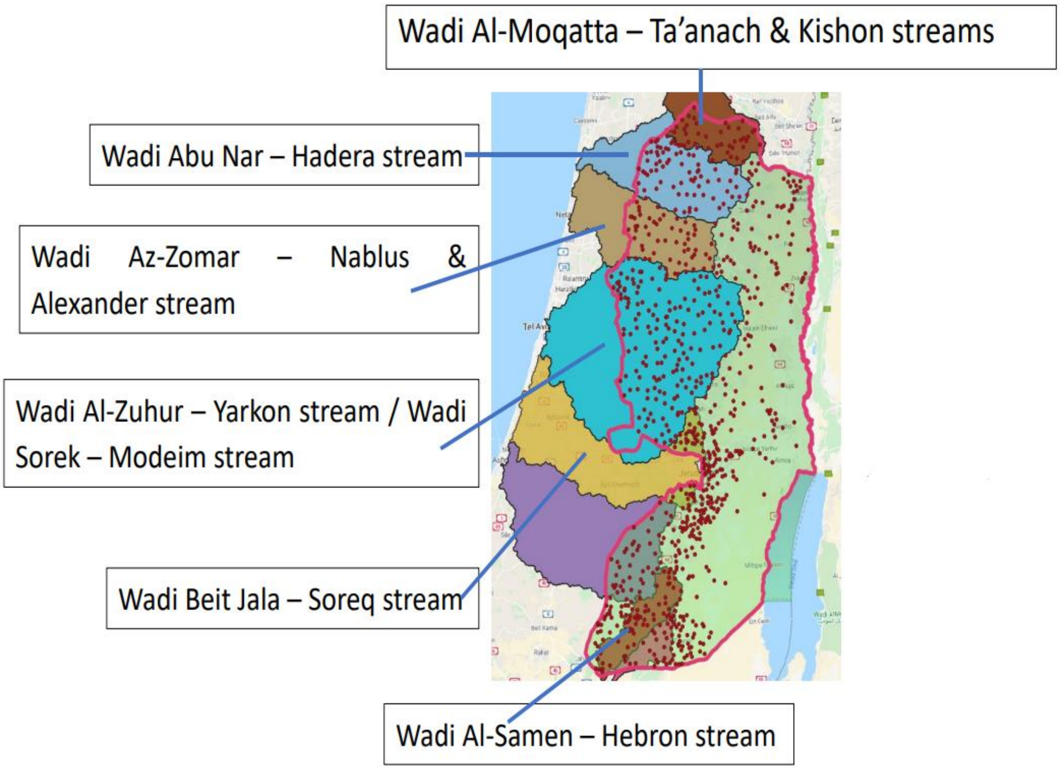

Figure 9: Streams between Israel and Palestine Location Map (Buge A, 2023)

Out of the 95.5 million cubic meters per year (MCM/y) of wastewater generated in the West Bank, only 9 MCM/y is treated in six facilities. Additionally, 19 MCM of transboundary wastewater is treated in Israel (Buge A, 2023). This situation poses significant public health risks and leads to social and environmental pollution, including contamination of aquifers and land devaluation (Um et al., 2022).

2.3.7 Wastewater Treatment Plants in Palestine:

Wastewater treatment in Palestine faces numerous challenges (Water, 2012), but significant progress has been made with the establishment and operation of several treatment plants, along with the ongoing construction of new facilities (Water, 2013). These developments mark substantial steps forward in addressing the region's wastewater management needs. However, ensuring the effective operation and maintenance of these plants remains crucial, especially considering potential capacity limitations in meeting growing demands. Despite these concerns, the focus on expanding wastewater treatment infrastructure signifies a commitment to improving water quality, protecting public health, and mitigating environmental risks in

Palestine (World Bank, 2018). Table 1, provides an overview of treatment plants in the West Bank.

Table [1]: Main Existing Wastewater Treatment Plants in Palestine (Ref Eng. Adel Yasin,2022; Samhan & Shoqair, 2024)

Wastewater Treatment Plant	Location	Start of Operation (year)	Treated Water Production (m^3/day)	Design Capacity (cap/day)	Served Population (PE)
Nablus Western WWTP	Nablus	2013	14,000	110,000	120,000
Al-Bireh WWTP	Al-Bireh	2000	5750	50,000	50,000
Misilya WWTP	Jenin	2019	120	4,000	3,635
Saer WWTP	Hebron	2016	1500	8,000	8,000
Kharras WWTP	Hebron	2022	1100	1,900	9,000

Table [2]: Technology used in wastewater treatment plants in Palestine (Ref Eng. Adel Yasin,2022; Samhan & Shoqair, 2024)

Wastewater Treatment Plant	Types of technology	Tertiary treatment	Sludge treatment
Nablus Western WWTP	Primary settling-activated sludge	filtration (sand filter) and disinfection (UV)	anaerobic digestion + sludge dewatering
Al-Bireh WWTP	Activated sludge process (CAS)	disinfection Ultraviolet (UV)	filter press + centrifuge
Misilya WWTP	CW (French hybrid configuration) (vertical + horizontal)		
Saer WWTP	Activated sludge process (EAS)	sand filters and disinfection (chlorine)	static thickener + forecasted dewatering + forecasted composting
Kharras WWTP	Primary settling (Imhoff tank), CW (vertical + horizontal)		

2.3.8 Challenges and Opportunities:

Challenges:

1. Technological Complexity: The conversion process involves intricate technological steps, including anaerobic digestion and methane capture (Hao et al., 2020). Implementing and maintaining these technologies can be complex and require skilled expertise. Moreover, Israeli authorities have required an extremely high effluent quality standard, considerably above the internationally recommended, and well beyond the capacity of the PA and Palestinian people to afford (World Bank, 2009).
2. Initial Investment: Establishing the infrastructure for sludge-to-energy conversion requires a significant upfront investment (Commission for Western Asia, 2017). This financial barrier may pose challenges for municipalities or regions with limited resources, which makes the PA reliant on donors (World Bank, 2009).
3. Variable Sludge Composition: The composition of sludge can vary, affecting the efficiency of the conversion process. Inconsistent sludge quality may necessitate adjustments in the technology used, making standardization challenging (Shadeed et al., 2017).
4. Regulatory Compliance: Meeting environmental regulations and safety standards associated with the production of energy from sludge can be demanding (Nash et al., 2020). Stringent regulations may require continuous monitoring and adaptation to ensure compliance.
5. Wastewater projects encounter the lowest approval rates and longest delays. There are main issues that delayed wastewater projects: Israeli insistence on connecting settlements; challenges locating plants away from cities and investing in Area C; and disputes over effluent ownership in a water-scarce environment (World Bank, 2009).

Opportunities:

1. Renewable Energy Production: Converting sludge into energy contributes to renewable energy generation. The captured methane can be utilized for electricity generation, reducing reliance on non-renewable energy sources and lowering carbon emissions (Nash et al., 2020).
2. Waste Reduction: The process helps in managing and reducing the volume of sludge, addressing waste management challenges. This aligns with sustainable practices,

promoting a circular economy approach by turning waste into a valuable resource (Xiao et al., 2020).

3. Energy Independence: Localized energy production from sludge enhances energy security by reducing dependence on external sources. It provides wastewater treatment plants with a more self-sufficient and resilient energy supply (Cremonez et al., 2021).
4. Economic Benefits: While there are initial costs, the long-term economic benefits can be significant. The production of energy from sludge can create economic opportunities, including potential revenue from excess energy production (Mills et al., 2014).
5. Environmental Stewardship: The conversion process contributes to environmental sustainability by minimizing the environmental impact of sludge disposal. It reduces the release of harmful substances into soil and water, protecting ecosystems (Büttner et al., 2022).

Balancing these challenges and opportunities requires a comprehensive approach, including investment in research and development, continuous technological improvement, and collaboration between governmental bodies, environmental agencies, and the private sector. The successful implementation of sludge-to-energy conversion aligns with broader sustainability goals and promotes a more resilient and eco-friendly approach to wastewater management.

2.4 Wadi Zomar

Wadi Zomar, also known as Wadi Al Shaeer, is a significant geographical feature in the region, covering an area of 600 square kilometers. The primary channel, known as Zomar in Arabic or Alexander in Israel, spans a total length of 44 kilometers, with 17 kilometers being naturally perennial flowing from the Nablus-Tulkarem area to the Mediterranean Sea as shown in Figur 10. It plays a crucial role in the hydrology and ecology of the surrounding areas (Attili & Alsàed, 2020). However, it has also become a focal point for environmental concerns due to pollution from various sources, including domestic and industrial wastewater.

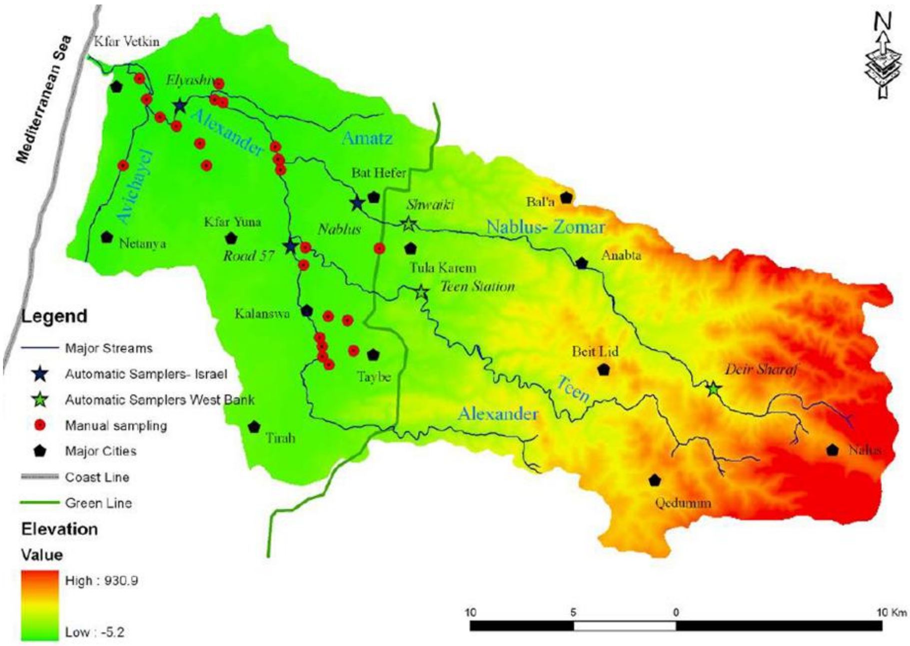

Figure 10: Wadi Zomar (Tal et al., 2010).

In addition to West Nablus City, wastewater from Ein Beit Alma Camp and some adjacent communities, such as Beit Iba, Deir Sharaf, Zawata, and Anabta, is also collected and discharged into Wadi Zomar (Attili & Alsàed, 2020). These communities are partially served by sewage networks, contributing to the wastewater flow into the wadi.

Similarly, wastewater from Tulkarem City, Tulkarem Camp, and Nur Shams Camp is collected and partially treated in Tulkarem ponds before being discharged into Wadi Zomar. From there, it also flows towards the Green Line (House of Water & Environment, 2012).

It's worth noting that wastewater from both Nablus and Tulkarem areas undergoes further treatment inside the Green Line at the Yad Hanna WWTP. This treatment process aims to mitigate the environmental impact of the wastewater before its final discharge. Unfortunately, the plant is incapable of effectively treating the volume and composition of sewage it receives, leading to pollution in the Alexander stream and posing serious sanitation and environmental risks to residents (Tal et al., 2010). To address this, Israel had previously allocated funds, totaling 34 million NIS, from Palestinian tax revenues for the construction of the treatment plant. Additionally, Israel has regularly deducted amounts ranging from 17 to 25 million NIS annually (Yaqob et al., 2016), citing reasons related to sewage treatment, environmental penalties, and compensation for damages.

The pollution of Wadi Zomar has serious implications for both human health and the environment. The discharge of untreated sewage and industrial waste into the wadi not only contaminates the water but also poses risks to wildlife and ecosystems downstream. Additionally, the pollution can seep into the soil and groundwater, affecting agricultural land and potentially harming crops and livestock (Alsadi, et al., 2014).

Efforts to address the pollution of Wadi Zomar have been hindered by political and bureaucratic challenges. Delays in the construction of sewage treatment plants and infrastructure have exacerbated the problem, leading to ongoing pollution and environmental degradation.

Despite these challenges, there have been initiatives to improve the situation. Projects aimed at constructing sewage treatment plants and implementing pollution control measures along Wadi Zomar are underway, albeit with some delays and obstacles (Sathya et al., 2023). International assistance and funding have been crucial in advancing these efforts, demonstrating the importance of collaboration and cooperation in addressing transboundary environmental issues.

Overall, Wadi Zomar serves as a stark reminder of the complex environmental challenges faced in the region and the need for concerted efforts to protect and preserve its ecological integrity for future generations. Despite facing numerous challenges, the Palestinian Water Authority successfully implemented the Wadi Zomar project. This project aimed to protect the environment from wastewater and sludge transported through the Wadi Zomar stream and improve sanitation services by cleaning the valley stream of wastewater and safeguarding water sources in the western basin. The project involved the installation of healthy exchange lines, ranging from 400 to 800 millimeters in diameter, and drainage networks spanning over 80 kilometers. Additionally, household connections were established in eight communities. Initiated in 2012, the project reached completion in early 2019 (M.Mezher et all., 2019).

The construction of the Nablus West Sewage Treatment Plant and associated sewage trunk lines along Wadi Zomer faced ongoing delays until 2010 when approvals and permits were eventually secured by the Israeli authorities. Funding from Germany facilitated the development of the sewage plant and trunk lines, providing crucial benefits to nine Palestinian communities situated along Wadi Zomar, such as Beit Lid, Ramin, Kafr al-Labad, Bala'a, and Kafr Rumman (West & Yousef Abu Jaffal, 2022). Moreover, it enabled the expansion of existing networks in Tulkarm, Anabta Municipality, Tulkarm, and Nour Shams camps.

Establishing a treatment plant in Nablus offers a comprehensive solution to transboundary pollution in Wadi Zomar. By treating sewage at its source, it improves water quality, fosters collaboration among stakeholders, and ensures long-term sustainability. Cleaner water benefits both the environment and community health, making the investment crucial for addressing pollution effectively.

2.5 Nablus Western Wastewater Treatment Plant

The Nablus Western Wastewater Treatment Plant, operational since November 2013, serves approximately 120,000 PE and treats 14,000 cubic meters of water daily (Taha & Al-Sa’ed, 2017). Utilizing a Conventional Activated Sludge (CAS) system, the plant addresses carbonaceous, nitrogen, and phosphorous removal, along with sludge stabilization and anaerobic digestion (D. Jazi et all,2022). Funded by KFW, additional filtration and chlorination units were integrated into the plant's processes. Positioned 12 km west of Nablus City, the plant receives wastewater through a gravity sewer system. In 2022, the plant treated 4,595,600 cubic meters of wastewater with an electrical consumption of 2,966,000 kWh, maintaining laboratory results in line with Palestinian standards (West & Yousef Abu Jaffal, 2022).

2.5.1 Nablus West WWTP facilities (West & Yousef Abu Jaffal, 2022):

At the wastewater treatment plant as shown in Figure 11 the process begins with a stone trap to remove large debris, followed by screens and grit/grease removal units to further purify the wastewater. Next, primary sedimentation tanks settle organic solids to form primary sludge, which is thickened for digestion. Aeration tanks activate aerobic bacteria to digest organic material, with significant power consumption. Final sedimentation tanks settle activated sludge, with excess treated in anaerobic digesters.

Figure 11: Nablus West WWTP (wwtp.nablus.org)

2.5.2 Sludge Facilities Operation:

The wastewater treatment plant employs a series of processes to manage and treat sludge effectively. Excess sludge is thickened using belt thickeners and mixed with primary sludge for digestion in the anaerobic digester shown in Figure 12. The digester facilitates a 21-day treatment period under carefully monitored conditions, producing biogas containing methane. Gas storage and burning mechanisms ensure efficient gas utilization. Dried sludge is handled through drying beds, while the belt filter presses further dewater-digested sludge. Supporting facilities include a laboratory, generator, and workshop, with ongoing improvements to enhance efficiency and control odors.

Figure 12, Digester tank in Nablus West WWTP with the gas flare (West & Yousef Abu Jaffal, 2022)

2.5.3 Problems and Challenges :

1. Unavailability of Local Maintenance Companies for CHP:
    - Lack of local expertise and maintenance services for Combined Heat and Power (CHP) systems poses challenges in ensuring optimal performance and addressing issues promptly.
2. Sludge Disposal:

a. High Cost of Sludge Disposal:

- The current cost of sludge disposal in Zeharet Al-Fenjan at 75 NIS/ton is deemed high, impacting overall operational expenses.

b. Restrictions on Sludge Reuse in Agriculture:

- Adherence to Palestinian standards prohibits the reuse of sludge in agriculture due to its high water content, which stands at 75%. This limitation hinders sustainable disposal options and potential resource utilization.

Chapter Three:

Methodology

3.1 Research Question and Objectives

The research question explores the efficacy of converting sludge into energy and its potential impact on mitigating environmental pollution and promoting sustainable development in regions affected by transboundary sludge pollution. Additionally, it investigates the relationship between this conversion and the treatment cost per cubic meter of wastewater, as well as the amount of energy produced per unit of sludge generated. The research question is directly linked to the research objectives as follows:

1. **Energy Production Analysis:**
    - Objective 1.4.1 involves determining the amount of energy produced per unit of sludge generated, which directly addresses the research question's concern about the amount of energy produced from sludge.
2. **Cost Analysis:**
    - Objective 1.4.2 Analyze the cost of sludge-to-energy conversion and treatment per cubic meter of wastewater which links directly to the research question's interest in understanding the impact on treatment costs per cubic meter of wastewater.
3. **Assessing Effectiveness and Environmental Impact:**
    - Objective 1.4.3 evaluates the effectiveness of converting sludge into energy in mitigating transboundary sludge pollution and promotes collaboration across borders. This objective directly addresses the research question's concern about the potential impact on mitigating environmental pollution and promoting sustainable development.
4. **Financial Analysis:**

- Objective 1.4.4 focuses on analyzing the financial losses experienced by the Palestinian Authority due to transboundary environmental pollution and compares them to the expenses associated with sludge-to-energy conversion.

5. **Estimation of Sludge Generation:**

    - Objective 1.4.5 aims to estimate the current and projected volume of sludge generated from wastewater treatment in Palestine, including an analysis of the potential volume if all wastewater undergoes treatment within the region.

By aligning the research objectives with the research question, this study aims to provide a comprehensive analysis of the feasibility and potential benefits of converting sludge into electrical energy, specifically in the context of mitigating environmental pollution and promoting sustainable development in regions affected by transboundary sludge pollution.

3.2 Data Collection

- Quantitative data about the volume of sludge produced from wastewater treatment in Palestine was sourced from a variety of established outlets, including pre-existing reports, government databases, and pertinent literature. This multi-faceted approach ensured a comprehensive and reliable dataset for analysis.

- The principal reservoir of data for the case study was the annual periodic reports disseminated by the wastewater treatment plant in Nablus, accessible via the facility's electronic platform. These reports furnished detailed insights into plant operations, performance metrics, and maintenance endeavors, offering invaluable context for understanding the unique dynamics of the West Nablus WWTP.

- Supplementary insights not encompassed within the formal reports were garnered through interviews with representatives from the West Nablus plant. These qualitative inputs served to enrich the analytical framework, providing nuanced perspectives on operational challenges, technological capacities, and potential avenues for enhancement. By amalgamating data from both primary and secondary sources, this research methodology endeavored to furnish a comprehensive assessment of sludge-to-energy conversion technologies and their implications for sustainable wastewater management in the Nablus West WWTP.

- To determine the energy output per unit of sludge generated, a dual methodology was employed. This involved a blend of theoretical computations and empirical evidence gleaned from analogous sludge-to-energy conversion endeavors. By marrying theoretical models with real-world observations, a more precise estimation of energy generation could be achieved, accounting for factors such as sludge composition and conversion efficiency.

- The assessment of treatment costs per cubic meter of wastewater hinged upon available financial documentation, encompassing both initial investment and ongoing operational expenses associated with conventional wastewater treatment modalities. In addition to analytical calculations based on these financial values. This financial data provided crucial insights into the economic consequences of various treatment methodologies, facilitating informed decision-making processes.

3.3 Data Analysis

Data analysis in this study involved several key steps to derive meaningful insights and conclusions:

- Quantitative Data Analysis: The quantitative data collected on the volume of sludge produced from wastewater treatment in Palestine was analyzed using statistical methods. This analysis aimed to identify trends, patterns, and variations in sludge generation over time and across different regions. Descriptive statistics were calculated to summarize the central tendency and dispersion of the data using the IBM SPSS Statistics 20 program and google.colaboratory tool. Moreover, hypothetical scenarios are constructed to project the potential volume of sludge generated if all wastewater within the region undergoes treatment. Following scenario construction, a comparative analysis is conducted, involving critical calculations and analyses to assess the financial implications, environmental impacts, and sustainability considerations associated with each scenario. Relevant metrics and indicators are utilized to evaluate the feasibility and implications of different approaches to sludge management and wastewater treatment. Through this methodological framework, a comprehensive understanding of the potential outcomes of various scenarios is attained, facilitating informed decision-making regarding sludge management practices and wastewater treatment strategies.

1. **Case Study Analysis (Nablus West WWTP):**

- The annual periodic reports from the wastewater treatment plant in West Nablus were analyzed to gain insights into plant operations, performance metrics, and maintenance activities. Key performance indicators such as treatment efficiency, energy consumption, and waste disposal rates were assessed to evaluate the effectiveness of current wastewater management practices. Additionally, qualitative data obtained from interviews with plant representatives (Ms. Rola Abu Salama). were analyzed to identify operational challenges, technological capabilities, and opportunities for improvement.
- Integration of Data Sources: Data from both primary and secondary sources were integrated to provide a comprehensive assessment of sludge-to-energy conversion technologies and their implications for sustainable wastewater management in the Nablus locale. This integrated analysis allowed for a holistic understanding of the economic, environmental, and social factors influencing the adoption of sludge-to-energy conversion technologies and informed the development of recommendations for policymakers and stakeholders. the operational data sourced from the Western Nablus Wastewater Treatment Plant over five years was used in calculations and data analysis within the specified timeframe to understand the energy production dynamics and sludge generation.

Total electrical consumption;

$$\text{Average Consumption (kWh)} = \sum \text{Total Consumption} / \text{Number of Years} \; \ldots \quad (1)$$

Total CHP electrical production;

$$\text{Average Production (kWh)} = \sum \text{Total Production} / \text{Number of Years} \; \ldots\ldots\ldots \quad (2)$$

$$\text{Average Percentage Contribution from CHP electrical energy} = (\text{Average Production} / \text{Average Consumption}) \times 100\% \; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where;

- Total Consumption and total Production found from West Nablus WWTP published data collection.
- Number of Years = 5

West Nablus WWTP Energy Sources Cost Calculations and Analysis;

The cost of Operating a WWTP with traditional electricity

Operating Cost (NIS/m^3*) = Energy Consumption (kWh/* m^3*)×Electricity Rate (NIS/kWh)…*(4)

Total Cost (NIS/m^3*) = Cost of Operating with Traditional Electricity (NIS/*m^3*+Additional Cost that Israel deducts from Palestinians' tax money (NIS/*m^3*)* ………………………….. (5)

Where;

- Electricity rate: 0.54 NIS / kWh according to Ms. Rola Abu Salama's interview
- Palestinians' tax money deducted by Israel = 1.545 NIS/m^3(e Austrian Development Cooperation, 2012)

The cost of Operating a WWTP with electricity produced in the CHP generator;

Cost per cubic meter (NIS/m^3*) = (Capital Cost (NIS) / Total Treated Wastewater Quantity* m^3*) × Total kWh/* m^3 ………………………... (6)

Where;

- Capital Cost: 2,600,000 USD according to the West Nablus WWTP website.

The cost of Operating a WWTP with electricity produced in PV

Total Cost (NIS/m^3*) = Cost of Solar Panels+Cost of Inverters+Cost of Mounting Structures and Electrical Components+Cost of Labor and Installation+Annual Maintenance Cost …* (7)

Average Energy Consumption per Cubic Meter (kWh/ m^3*) = Total Energy Consumption / Total Wastewater Volume* ……………………………………..... (8)

Contribution (%) = (Total Renewable Energy Generation / Total Electrical Consumption) × 100 % ………………………………………………………. (9)

Where;

- Total Renewable Energy Generation (PV) in the study duration = 841,325 kWh

  - Total Electrical Consumption in the study duration of 5 years = 15,992,600 kWh
  - Cost of Solar Panels = Capacity of PV System × Cost/ Watt
  - Cost of Inverters = Capacity of PV System × Cost/ Watt
  - Cost of Mounting Structures and Electrical Components = 0.20 × (Cost of Solar Panels + Cost of Inverters)
  - Cost of Labor and Installation = 0.30 × (Cost of Solar Panels + Cost of Inverters + Cost of Mounting Structures and Electrical Components)
  - Annual Maintenance Cost (NIS/m^3) = 0.05 × (Cost of Solar Panels + Cost of Inverters + Cost of Mounting Structures and Electrical Components + Cost of Labor and Installation), all prices data from qudra.ps website.

This comparison is employed to evaluate the economic feasibility and potential cost savings associated with utilizing different energy sources for operating a wastewater treatment plant (WWTP). By comparing the costs of traditional electricity, electricity generated from a combined heat and power (CHP) generator, and electricity produced from photovoltaic (PV) solar panels, we can assess which option offers the most cost-effective solution. This analysis helps in decision-making regarding the adoption of renewable energy sources. Additionally, it provides insights into the financial implications and benefits of investing in renewable energy infrastructure for WWTPs.

- Energy Output Analysis: The energy output per unit of sludge generated was analyzed by comparing the theoretical computations with empirical evidence obtained from the sludge-to-energy conversion project in West Nablus WWTP. This comparative analysis helped validate the accuracy of the theoretical models and provided insights into the efficiency of energy generation processes. Any discrepancies between the theoretical and empirical data were examined to understand potential factors influencing energy production.

  Empirical value;

  $$\text{The electrical energy produced from a Cup of Sludge (kWh)} = \text{Biogas Produced from a Cup of Sludge} \times \text{Average kWh per } m^3 \text{ of biogas} \quad \ldots\ldots\ldots (10)$$

  Where;

  - *Biogas Produced from a Cup of Sludge* (m^3) *=*
    Average Biogas Production Rate × Volume of Sludge (m^3)
  - *Biogas Produced from a Cup of Sludge* (m^3) *= The total biogas produced for each year / The total kWh produced for each year*

- *Biogas production rate (m^3/m^3) = Gas Production (nm^3/d) / Wastewater Volume (m^3)*

Theoretical value;

Electrical Energy Produced from a Cup of Sludge in Ideal Conditions to compare with Electrical energy produced from a Cup of Sludge from West Nablus WWTP;

Energy output (kWh) = Biogas volume (m^3) × Energy content of methane (MJ/m^3) × Efficiency of CHP generator ………………………………………………….. (11)

Where;

- Cost-Benefit Analysis (CBA): Treatment costs per cubic meter of wastewater were analyzed by evaluating the financial documentation related to both initial investment and ongoing operational expenses associated with traditional wastewater treatment methods. This analysis involved calculating the total cost of treatment per cubic meter and comparing it with alternative treatment approaches, such as sludge-to-energy conversion technologies. Cost-benefit ratios and sensitivity analyses were conducted to assess the economic viability and potential savings of implementing sludge-to-energy conversion. The method employed in this study involves a comprehensive analysis of two wastewater treatment alternatives: the "No Action Alternative" and the "Action Alternative."

  A cost-benefit analysis compares the financial implications of both alternatives, considering factors such as capital investment, operational expenses, and potential savings or additional costs associated with adopting the Action Alternative.

  Data from literature reviews, interviews, and relevant reports are utilized to obtain cost estimates and energy consumption rates. The analysis aims to provide insights into the economic viability and environmental impact of each alternative, informing decision-making on wastewater treatment strategies.

- A comprehensive methodology is implemented to evaluate the effectiveness of converting sludge into energy in mitigating transboundary sludge pollution and fostering collaboration across borders. Key performance indicators (KPIs) are utilized to gauge the impact of sludge-to-energy conversion. These KPIs encompass various metrics, including reductions in greenhouse gas emissions, energy generation and savings, improvement in water quality, and other essential environmental indicators. Utilizing all available data and analyses from previous research objectives, the results are thoroughly analyzed against the established KPIs to assess the environmental implications of sludge-to-energy conversion.

2- The formula to calculate the amount of sludge produced by a wastewater treatment plant (WWTP) per day is:

Sludge Production (kg/day) = Wastewater Flow Rate (Design Capacity) (m^3/day) × Sludge Production Rate (kg/m^3)...(12)

Where:

- Sludge Production (kg/day) is the total amount of sludge produced by the WWTP per day.
- Wastewater Flow Rate (m^3/day) is the maximum volume of wastewater the treatment plant can handle per day., values from Table 1 in Chapter 2.
- Sludge Production Rate (kg/m^3) is the rate at which sludge is produced per unit volume of wastewater treated.

The sludge production rate, expressed as kilograms per capita per day (kg/capita/day), represents the amount of sludge produced by an individual in a population per day. calculated using the following formula:

Sludge Production Rate (kg/capita/day) = Total Sludge Production (kg/day) / Population……………………………………………………………………………(13)

Where:

- Total Sludge Production (kg/day) is the total amount of sludge produced per day by the wastewater treatment plants (WWTPs).
- Population is the total population served by the WWTPs.

The Sludge Quantity from the West Bank population is calculated by the following formula:

Wastewater Generated (liters/day) = Population (capita) × Consumption (liters/capita/day) × Wastewater coefficient ..…………………………………………………………… (14)

Design Capacity (liters/capita/day) = Wastewater Generated (liters/day) / Population (capita)

Sludge Production (kg/day) = Total Wastewater (liters/day) × Sludge Production Coefficient (kg/liter)………………………………………….(15)

Where;

- Population = 3 million, according to the Palestinian Central Bureau of Statistics.

- Consumption = 100 liters/per capita/day (including the industrial sector), (Murrar et al., 2024)
- Wastewater coefficient = 80% (assuming 80% of water consumed is converted to wastewater),(Salem H. S. et al., 2021)
- Assume a sludge production rate of 0.6 kg/ m^3

Cost Calculations for Scenario1 and Scenario 2;

Scenario 1, Treating wastewater and sludge-to-energy conversion (Nablus West WWTP)

Scenario 2, Sludge Treatment from the West Bank Population, by developing existing wastewater treatment plants and establishing new treatment plants whose services include all quantities of wastewater generated by the population and treating the sludge by Sludge-to-Energy.

Correlation Analysis;

- **Sludge Production Rates and Energy Output**:

The objective was to explore the relationship between sludge production rates and energy output. This analysis aimed to determine if there existed a correlation between these two variables, with a potential implication that higher sludge production rates led to increased energy output. A statistical tool, Colab's correlation coefficient, was employed to quantify the strength and direction of this relationship. Additionally, a graphical representation via scatter plots was utilized to visually depict this relationship, providing further insights.

- **Operational Costs and Potential Savings**:

The investigation focused on understanding the potential relationship between operational costs and potential savings within the context of wastewater treatment. The hypothesis suggested that higher operational costs corresponded to lower potential savings. Statistical analyses involved calculating correlation coefficients to assess the degree and direction of this relationship. Graphical representations, specifically scatter plots, were used to visually present this relationship, facilitating a deeper understanding of the dynamics between operational costs and potential savings.

- **Sludge Production Rates and Cost Estimates**:

to examine the potential relationship between sludge production rates and cost estimates associated with treatment and disposal. The hypothesis suggested that higher sludge production rates might result in higher cost estimates. Statistical methods, including correlation analysis, were applied to evaluate the strength and direction of this relationship. Visualization techniques, such as scatter plots, were employed to illustrate this relationship visually, aiding in the interpretation of findings.

3.4 Scientific Methodology

The methodology used in this study was careful and organized, aiming to collect, analyze, and understand data about sludge-to-energy conversion technologies and their role in sustainable wastewater management. It relied on reliable data from reports and literature, ensuring accuracy. By using both primary and secondary data, the methodology gave a full picture of the topic. Comparing different scenarios and looking at real-world examples added depth to the study. Throughout the process, the approach was transparent and followed scientific standards, making sure the findings could be trusted and checked by others. Overall, the methodology helped us learn a lot about sludge-to-energy conversion technologies and their impact, which is useful for people making decisions about managing wastewater.

The chosen methodology aligns closely with the research objective of investigating sludge-to-energy conversion technologies and their implications for sustainable wastewater management. It involves a multi-faceted approach that integrates quantitative data collection on sludge production rates, energy output, and operational costs with qualitative insights from interviews with wastewater treatment plant representatives. This comprehensive methodology allows for strong analysis and comparative assessment of different scenarios, ultimately facilitating a thorough investigation into the potential of sludge-to-energy conversion for sustainable wastewater management.

Chapter Four:

Analysis and Discussion of Results:

4. 1 Performance of WWTP Nablus West (during five years 2018/2022)

4.1.1 Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation in 2018;

- Wastewater Volume: Processed 4,647,000 cubic meters of wastewater.
- Electrical Consumption: Consumed 3,148,000 kilowatt-hours of electricity.
- Gas Production: Averaged 2,127 normal cubic meters per day.
- CHP Electrical Production (kWh): 99,774.25 kWh
- Renewable Energy Generation (PV): Generated 123,814 kilowatt-hours of energy.
- Trends: Fluctuations in electrical consumption observed throughout the year, with higher consumption levels in January and February. Notable contributions from the PV system and consistent electrical production from the CHP engine.

4.1.2 Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation in 2019;

- Wastewater Volume: Processed 5,320,000 cubic meters of wastewater.
- Electrical Consumption: Consumed 3,273,000 kilowatt-hours of electricity.
- Gas Production: Averaged 2,003 normal cubic meters per day.
- CHP Electrical Production (kWh): 98,375.33 kWh
- Renewable Energy Generation (PV): Generated 191,122 kilowatt-hours of energy.
- Trends: Fluctuations in electrical consumption, with peaks in January and February. Significant contributions from both the PV system and the CHP engine to electricity generation.

4.1.3 Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation in 2020

- Wastewater Volume: Processed 4,346,000 cubic meters of wastewater.
- Electrical Consumption: Consumed 2,551,000 kilowatt-hours of electricity.

- Gas Production: Averaged 1,365 normal cubic meters per day.
- CHP Electrical Production (kWh): 0 kWh
- Renewable Energy Generation (PV): Generated 178,789 kilowatt-hours of energy.
- Trends: Variations in electrical consumption and treated wastewater quantities. Significant contributions from the PV system and consistent performance of the CHP engine.

4.1.4 Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation in 2021;

- Wastewater Volume: Processed 4,850,700 cubic meters of wastewater.
- Electrical Consumption: Consumed 3,054,600 kilowatt-hours of electricity.
- Gas Production: Averaged 1,367 normal cubic meters per day.
- CHP Electrical Production (kWh): 86,018 kWh
- Renewable Energy Generation (PV): Generated 175,700 kilowatt-hours of energy.
- Trends: Fluctuations in electrical consumption, with peaks in May and June. Introduction of ground-mounted PV systems contributing to renewable energy generation.

4.1.5 Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation in 2022;

- Wastewater Volume: Processed 4,595,600 cubic meters of wastewater.
- Electrical Consumption: Consumed 2,966,000 kilowatt-hours of electricity.
- Gas Production: Averaged 1,426 normal cubic meters per day.
- CHP Electrical Production (kWh): 43,723.7 kWh
- Renewable Energy Generation (PV): Generated 171,900 kilowatt-hours of energy.
- Trends: Fluctuations in electrical consumption and treated wastewater quantities. Consistent contribution from the CHP engine to electricity production despite maintenance periods for the PV system.

Table 3 presents a comprehensive overview of the total wastewater volume treated, electrical consumption, gas production, and renewable energy generation from 2018 to 2022 in Nablus

West WWTP. This data highlights the significant variations in wastewater treatment and energy production over the specified period, reflecting the operational challenges and advancements in the sector. The metrics include the total and average quantities of treated wastewater, total CHP electrical production, and average CHP electrical production, providing insights into wastewater treatment facilities' performance and energy efficiency.

Table [3]: Total Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation Ref. West Nablus WWTP annual reports.

Year	Total Treated Wastewater Quantity (m3)	Average Treated Wastewater Quantity (m3)	Total CHP Electrical Production (kWh)	Average CHP Electrical Production (kWh)
2018	55,764,000	4,647,000	1,197,291	99,774.25
2019	63,840,000	5,320,000	1,180,504	98,375.33
2020	52,152,000	4,346,000	0	0
2021	58,248,400	4,850,700	1,032,216	86,018
2022	45,956,000	4,595,600	437,237	43,723.7

4.2 The correlation between the "Treated Wastewater Quantity" and "CHP Electrical Production" variables

Analysis of Correlation

The correlation analysis provides a visual representation of the relationships between various variables related to wastewater treatment and energy production over the period from 2018 to 2022. The variables analyzed include the year, total treated wastewater quantity, average treated wastewater quantity, total CHP electrical production, and average CHP electrical production. The correlation values range from -1 to 1. The regression model aims to elucidate the influence of variations in treated wastewater volumes on electrical production from the CHP system while accounting for pertinent variables. Analysis of the regression coefficients will unveil the magnitude and significance of these associations, offering insights into the determinants of CHP electrical production.

The correlation matrix indicates several noteworthy trends across the variables analyzed over the five years. Firstly, the "year" variable demonstrates moderate to strong negative correlations with all other variables, implying a consistent downward trend over time. Additionally, both the "Total Treated Wastewater Quantity (m^3)" and "Average Treated

Wastewater Quantity (m^3)" display negative correlations with the year, suggesting a diminishing volume of treated wastewater throughout the years. Furthermore, the "Total CHP Electrical Production (kWh)" and "Average CHP Electrical Production (kWh)" exhibit moderate negative correlations with the year, indicating a declining trend in both total and average electrical production from the CHP system over the observed period. These correlations underscore potential shifts or influences affecting the variables across the five years, warranting further investigation to elucidate their underlying causes and implications.

Key observations include:

- **Year and Total Treated Wastewater Quantity (m^3)**: There is a moderate negative correlation (-0.60) between the year and the total treated wastewater quantity, suggesting a general decrease in the quantity of treated wastewater over the years.
- **Total and Average Treated Wastewater Quantity (m^3)**: A strong positive correlation (0.80) exists between the total and average treated wastewater quantities, indicating that fluctuations in the total quantity are closely mirrored by changes in the average quantity.
- **Total Treated Wastewater Quantity (m^3) and Total CHP Electrical Production (kWh)**: The correlation between total treated wastewater quantity and total CHP electrical production is moderately positive (0.71), suggesting that higher volumes of treated wastewater are associated with increased electrical production from CHP units.
- **Total Treated Wastewater Quantity (m^3) and Average CHP Electrical Production (kWh)**: Similarly, there is a moderately positive correlation (0.66) between total treated wastewater quantity and average CHP electrical production, reinforcing the link between wastewater volume and energy generation.
- **Average Treated Wastewater Quantity (m^3) and Total/ Average CHP Electrical Production (kWh)**: The average treated wastewater quantity shows strong positive correlations with both total (0.75) and average (0.75) CHP electrical production, emphasizing the relationship between wastewater treatment efficiency and energy output.
- **Total CHP Electrical Production (kWh) and Average CHP Electrical Production (kWh)**: As expected, there is a perfect positive correlation (1.00) between total and average CHP electrical production, as these metrics are directly related.

These correlations highlight the interdependence between wastewater treatment volumes and energy production efficiencies. Understanding these relationships is crucial for optimizing the operational performance of wastewater treatment plants and enhancing the sustainability of energy recovery processes.

4.3 Average Electrical Consumption, Gas Production, and Renewable Energy Generation:

Table 4 presents key operational metrics of the West Nablus WWTP, including average wastewater volume, electrical consumption, gas production, and renewable energy generation. Derived from the plant's annual reports, these figures are crucial for evaluating the efficiency and sustainability of the treatment processes.

Table [4]: Average Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation, Ref. West Nablus WWTP annual reports.

Year	Wastewater Volume (m^3)	Electrical Consumption (kWh)	Gas Production (nm^3/d)	Renewable Energy Generation PV (kWh)
2018	4,647,000	3,148,000	2,127	123,814
2019	5,320,000	3,273,000	2,003	191,122
2020	4,346,000	2,551,000	1,365	178,789
2021	4,850,700	3,054,600	1,367	175,700
2022	4,595,600	2,966,000	1,426	171,900

Within the framework of regression analysis, the dependent variable pertains to the variable under scrutiny or prediction, elucidated through other variables. Here, the dependent variable pertains to electrical consumption. Conversely, independent variables, often termed predictor variables, represent factors posited to influence the dependent variable. In this investigation, the independent variables encompass gas production and renewable energy generation.

So, to summarize:

- Dependent variable: Electrical consumption
- Independent variables: Gas production, Renewable energy generation

the correlation coefficients to quantify the linear relationships between variables.

1. Visualize scatter plots of electrical consumption against gas production and renewable energy generation.
2. Calculate the correlation coefficients between these variables.

a correlation matrix based on the data provided in Table 5.

Table [5]: a correlation matrix for Wastewater Volume, Electrical Consumption, Gas Production, and Renewable Energy Generation (2018-2022) from data analysis results;

	Year	Electrical Consumption (kWh)	Gas Production (nm3/d)	Renewable Energy Generation (kWh)
Year	1.000	-0.335	-0.859	0.493
Electrical Consumption (kWh)	-0.335	1.000	0.696	-0.168
Gas Production (nm3/d)	-0.859	0.696	1.000	-0.491
Renewable Energy Generation (kWh)	0.493	-0.168	-0.491	1.000

This correlation matrix shows the correlation coefficients between each pair of variables. The values range from -1 to 1, where:

- There is a strong negative correlation (-0.86) between electrical consumption and renewable energy generation, indicating that as one variable increases, the other tends to decrease.
- There is a moderate positive correlation (0.56) between electrical consumption and gas production, suggesting that there is some relationship between these two variables, but it's not as strong as the correlation between electrical consumption and renewable energy generation.

In conclusion, the correlation analysis reveals valuable insights into the relationship between key variables in the wastewater treatment facility's performance over the five years. The strong negative correlation (-0.86) between electrical consumption and renewable energy generation underscores the significant impact of renewable energy sources on reducing electrical consumption. This finding highlights the potential for leveraging renewable energy generation to enhance the facility's sustainability and reduce its environmental footprint. Additionally, the moderate positive correlation (0.56) between electrical consumption and gas production suggests a relationship between these variables, indicating the importance of efficient gas utilization in managing electrical consumption. Overall, these insights provide a foundation for implementing strategies to optimize energy usage and enhance the efficiency of wastewater treatment processes.

In investigating the research question about the impact of gas production and renewable energy generation on electrical consumption at the wastewater treatment facility, multiple linear regression analysis was employed. The objective of the regression model was to assess the association between changes in gas production (measured in normal cubic meters per day) and renewable energy generation (quantified in kilowatt-hours) with variations in electrical consumption (expressed in kilowatt-hours). (Gilbert, M. M. 2004)

The model was specified as follows:

$$\text{Electrical Consumption(kWh)} = \beta 0 + \beta 1 \times \text{Gas Production} + \beta 2 \times \text{Renewable Energy Generation} + \epsilon \quad \ldots\ldots (16)$$

Where:

- $\beta 0$ represents the intercept term,
- $\beta 1$ and $\beta 2$ represent the coefficients for gas production and renewable energy generation, respectively,
- ϵ represents the error term.

Utilizing this regression model enabled estimation of the impact size of gas production and renewable energy generation on electrical consumption while considering other variables. Subsequently, hypothesis tests were conducted to ascertain whether the regression coefficients associated with gas production and renewable energy generation significantly predicted electrical consumption. Moreover, the overall model fit was assessed employing measures like R2, which gauges the extent to which independent variables account for variance in electrical consumption. Through analysis of the regression outcomes, valuable insights were obtained regarding the interplay among gas production, renewable energy generation, and electrical consumption, offering pertinent information for refining energy management tactics at the wastewater treatment facility.

4.4 CHP Electrical Production (kWh):

Retrieve the values for CHP electrical production (kWh) for each month from the tables for the years 2018 to 2022 shown in Figure 6.

Table [6]: CHP Electrical Production (kWh) (2018-2022) data based on West Nablus WWTP annual reports;

Month	2018	2019	2020	2021	2022
January	73,099	26,023	0	13,128	46,500
February	77,282	37,637	0	47,708	64,445

March	161,560	97,620	0	75,822	73,819
April	132,992	130,000	0	80,712	70,412
May	176,220	152,000	0	24,615	72,171
June	163,355	153,118	0	5,230	35,200
July	143,342	134,558	0	0	40,000
August	166,347	114,860	0	43,818	25,000
September	151,790	120,462	0	90,145	0
October	175,823	147,440	0	105,855	0
November	158,550	133,099	0	113,094	0
December	95,228	100,999	0	61,906	0

4.5 Electrical Consumption for Treatment Operations (kWh):

Extract the values for electrical consumption for treatment operations (kWh) from the tables for the years 2018 to 2022 provided in Table 7.

Table [7]: Electrical Consumption (kWh) data based on West Nablus WWTP annual reports

Month	2018	2019	2020	2021	2022
January	151,635	190,709	185,130	171,092	196,580
February	132,018	182,507	130,094	104,686	141,700
March	113,047	147,150	129,800	110,384	133,743
April	119,796	149,700	131,010	143,411	111,296
May	58,270	137,370	116,075	245,347	206,550
June	90,486	160,386	154,884	226,440	236,649
July	141,308	145,962	216,730	275,861	212,450
August	109,188	133,144	274,620	247,035	269,620
September	121,780	122,497	285,580	161,233	259,330
October	96,603	119,164	321,941	147,551	220,993

November	80,040	105,323	233,838	164,762	195,150
December	135,008	140,188	192,774	219,093	182,789

the treated wastewater quantity (m^3) and (kWh per m^3) ratio for each month from January to December for the years 2018 to 2022:

Table [8]: Treated wastewater quantity (m^3) and (kWh/ m^3) ratio data based on West Nablus WWTP annual reports

	2018		**2019**		**2020**		**2021**		**2022**	
Jan	517,378	0.43	601,232	0.39	535,139	0.36	422,295	0.46	404,086	0.54
Feb	460,520	0.45	421,126	0.55	375,909	0.37	454,699	0.36	362,132	0.63
Mar	460,520	0.60	580,084	0.45	335,757	0.43	481,243	0.42	392,442	0.81
Apr	334,871	0.75	549,103	0.54	294,969	0.50	418,430	0.59	509,470	0.93
May	365,390	0.70	453,242	0.69	256,783	0.54	418,565	0.69	451,917	0.91
Jun	351,361	0.78	404,234	0.83	259,014	0.68	408,127	0.62	434,007	0.69
Jul	360,591	0.84	412,602	0.74	401,717	0.60	437,197	0.67	420,048	0.78
Aug	360,658	0.81	404,171	0.66	396,341	0.74	376,580	0.82	365,764	0.66
Sep	349,040	0.83	373,627	0.69	369,476	0.81	343,424	0.78	294,140	0.39
Oct	357,300	0.80	387,262	0.72	387,033	0.87	384,000	0.69	288,731	0.47
Nov	340,846	0.72	317,716	0.78	367,294	0.66	358,140	0.81	322,469	0.53
Dec	443,095	0.54	415,675	0.60	370,523	0.55	370,523	0.83	347,769	0.57
Avg	391,798	0.69	443,340	0.64	362,496	0.59	404,228	0.64	382,748	0.65

To assess the relationship between the electricity consumed and the electricity produced by CHP, a correlation analysis between these variables can be conducted. This analysis involves calculating the correlation coefficient to measure the strength and direction of their relationship.

- *X* as the total electrical consumption for treatment operations (kWh)
- *Y* as the total CHP electrical production (kWh)

The Pearson correlation coefficient will be utilized to quantify the linear correlation between variables X and Y, where:

$$R = \sum(X-\bar{X})(Y-\bar{Y}) \; / \sqrt{\sum(X-\bar{X})^2 \cdot \sum(Y-\bar{Y})^2} \ldots\ldots\ldots\ldots(17)$$

The correlation coefficient r ranges from $^{-}1$ to 1, where r=1 indicates a perfect positive correlation, r =$^{-}1$ indicates a perfect negative correlation, and r = 0 indicates no correlation.

The Pearson correlation coefficient between total electrical consumption and total CHP electrical production is approximately 0.04, indicating a very weak positive correlation between these two variables. This suggests that there is little to no linear relationship between the total amount of electricity consumed and the total electricity produced by the CHP system across the provided data.

4.6 The Electricity Generated by CHP (for West Nablus WWTP);

The percentage contribution of the electricity generated by CHP to the total electricity consumed in the WWTP is calculated by using (1),(2), and (3) formulas:

For 2018:

Average Consumption $_{2018}$ = 151,635+132,018+…+80,040+135,008 / 12

=1,759,793 / 12 ≈ 146,649.42 kWh

Average Production $_{2018}$ = 73,099+77,282+…+95,228 / 12

= 1,143,915 / 12 ≈ 95,326.25 kWh

Average Percentage Contribution$_{2018}$ = (95,326.25 / 146,649.42) ×100

Average Percentage Contribution$_{2018}$ ≈ 64.99%

For 2019:

Average Consumption $_{2019}$ = 190,709+182,507+…+105,323+140,188 / 12

= 2,288,038 / 12 ≈ 190,669.83 kWh

Average Production $_{2019}$ =26,023+37,637+…+100,999 / 12

= 1,513,400 / 12 ≈ 126,116.67 kWh

Average Percentage Contribution$_{2019}$ = (126,116.67 / 190,669.83) ×100

Average Percentage Contribution$_{2019}$ ≈ 66.13%

For 2020:

Average Consumption $_{2020}$ = 185,130+130,094+…+192,774 / 12

= 2,200,956 /12 ≈ 183,413 kWh

Average Production $_{2020}$ = 0 kWh

Average Percentage Contribution $_{2020}$ = 0%

For 2021:

Average Consumption $_{2021}$ = 171,092+104,686+…+219,093 / 12

=1,923,690 / 12 ≈ 160,307.5 kWh

Average Production $_{2021}$=13,128+47,708+…+61,906 / 12

= 375,850 /12 ≈ 31,320.83 kWh

Average Percentage Contribution $_{2021}$ = (31,320.83 / 160,307.5) × 100

Average Percentage Contribution $_{2021}$ ≈ 19.54%

For 2022:

Average Consumption $_{2022}$ = 182,789+195,150+…+196,580 / 12

= 2,011,987 / 12 ≈ 167,665.58 kWh

Average Production $_{2022}$ = 46,500+64,445+…+25,000 / 12

= 495,155 / 12 ≈ 41,262.92 kWh

Average Percentage Contribution $_{2022}$ = (41,262.92 / 167,665.58) × 100

Average Percentage Contribution $_{2022}$ ≈ 24.61%

Total electrical consumption (kWh);

Summing Up Monthly Consumption for Each Year:

- 2018: 151,635 + 132,018 + ... + 135,008 kWh
- 2019: 190,709 + 182,507 + ... + 140,188 kWh
- 2020: 185,130 + 130,094 + ... + 192,774 kWh
- 2021: 171,092 + 104,686 + ... + 219,093 kWh

- 2022: 182,789 + 195,150 + ... + 196,580 kWh

Total Electrical Consumption (kWh):

- Total Electrical Consumption = Sum of Monthly Consumption for Each Year
- Total Electrical Consumption = 1,759,793 + 2,288,038 + 2,200,956 + 1,923,690 + 2,011,987 kWh = 10,184,464 kWh

Average Consumption (kWh):

- Average Consumption = Total Electrical Consumption / Number of Years

Average Electrical Consumption (kWh) per month:

- Total consumption: 10,184,464 kWh
- Total number of months: 5 years × 12 months / year = 60 months
- Average consumption per month = Total consumption / Total number of months

= 10,184,464 kWh / 60 months

≈ 169,741.07 kWh / month

Average Electrical Consumption (kWh) per $m^{3:}$

- Average electrical consumption per m^3 = (0.69 + 0.64 + 0.59 + 0.64 + 0.65) / 5
- Average electrical consumption per m^3 ≈ 0.64 kWh / m^3

4.7 West Nablus WWTP Energy Sources Cost Calculations and Analysis:

The cost of Operating a WWTP with traditional electricity

- Electricity rate: 0.54 NIS per kWh
- Average electrical consumption per m^3 ≈ 0.64 kWh / m^3

Operating Cost = Energy Consumption (kWh) × Electricity Rate

= 0.64 kWh / m^3 × 0.54 NIS/kWh

≈ 0.35 NIS/m^3

- Total Cost = Cost of Operating with Traditional Electricity + Additional Cost that Israel deducts the treating the wastewater from Palestinians' tax money

Total Cost = 0.35 NIS/m^3 + 1.55 NIS/m^3

Total Cost = 1.89 NIS/m^3

The cost of Operating a WWTP with electricity produced in the CHP generator;

- Capital Cost: 2,600,000 USD

  Capital Cost = 2,600,000 USD × 3.77 NIS /USD = 9,802,000 NIS

  - Cost per cubic meter = (Capital Cost / Total Treated Wastewater Quantity) × Total kWh per m³
    - For 2018: 5.12 NIS/m³
    - For 2019: 5.01 NIS/m³
    - For 2020: 4.41 NIS/m³
    - For 2021: 4.82 NIS/m³
    - For 2022: 5.01 NIS/m³
- Total cost = 4.13 NIS/m³

The cost of Operating a WWTP with electricity produced in PV

- Total Renewable Energy Generation (PV) = 841,325 kWh

  Total Electrical Consumption = 15,992,600 kWh

  - Contribution (%) = (Total Renewable Energy Generation / Total Electrical Consumption) × 100%

  = (841,325 kWh / 15,992,600 kWh) × 100 ≈ 5.27%

- Total cost of installing and maintaining ground-mounted on-grid PV

- Cost of Solar Panels = Capacity of PV System × Cost per Watt = 123 kW × 0.50 USD /W = 61,500 USD
- Cost of Inverters = Capacity of PV System × Cost per Watt = 123 kW × 0.20 USD /W = 24,600 USD
- Cost of Mounting Structures and Electrical Components = 0.20 × (Cost of Solar Panels + Cost of Inverters) = 0.20 × (61,500 USD + 24,600 USD) = 17,820 USD
- Cost of Labor and Installation = 0.30 × (Cost of Solar Panels + Cost of Inverters + Cost of Mounting Structures and Electrical Components) = 0.30 × (61,500 USD + 24,600 USD + 17,820 USD) = 28,494 USD
- Annual Maintenance Cost = 0.05 × (Cost of Solar Panels + Cost of Inverters + Cost of Mounting Structures and Electrical Components + Cost of Labor and Installation) = 0.05 × (61,500 USD + 24,600 USD + 17,820 USD + 28,494 USD) =8,697 USD
- Total Cost = Cost of Solar Panels + Cost of Inverters + Cost of Mounting Structures and Electrical Components + Cost of Labor and Installation + Annual Maintenance

Cost = 61,500 USD + 24,600 USD + 17,820 USD + 28,494 USD + 8,697 USD = 140,111 USD

- Total Cost = 140,111 USD × 3.77 NIS/USD ≈ 528,085.47 NIS

- Cost of treating one cubic meter of wastewater

- Total Energy Consumption = Σ Electrical Consumption (kWh)
  = 3,148,000 kWh + 3,273,000 kWh + 2,551,000 kWh + 3,054,600 kWh + 2,966,000 kWh = 15,992,600 kWh
- Total Solar Energy Generation = Σ Renewable Energy Generation PV (kWh)
  = 123,814 kWh + 191,122 kWh + 178,789 kWh + 175,700 kWh + 171,900 kWh = 841,325 kWh
- Cost per kWh = Total Cost of Solar Panel Installation and Maintenance / Total Solar Energy Generation
  Cost per kWh = 140,111 USD / 841,325 kWh ≈ 0.166 USD /kWh
- Cost per Cubic Meter = Cost per kWh × Average Energy Consumption per Cubic Meter
- Average Energy Consumption per Cubic Meter = Total Energy Consumption / Total Wastewater Volume
  Average Energy Consumption per Cubic Meter = 15,992,600 kWh / (4,647,000 m^3 + 5,320,000 m^3 + 4,346,000 m^3 + 4,850,700 m^3 + 4,595,600 m^3) ≈ 0.81 kWh/m^3
  Cost per Cubic Meter = 0.166 USD /kWh × 0.81 kWh/m^3 ≈ 0.13 USD /m^3
  Cost per Cubic Meter (NIS) = 0.13 USD/m^3 × 3.77 NIS/USD ≈ 0.51 NIS/m^3

4.8 Energy Analysis

Biogas Production Rate Calculation:

Table [9] provides an analysis of the biogas production rate at the West Nablus WWTP. This rate, calculated by dividing the daily gas production by the wastewater volume treated, is a crucial indicator of the plant's efficiency in converting waste into energy. By examining annual data, the table offers insights into the performance trends over time, highlighting the plant's capacity for biogas generation and its potential for sustainable energy production. This information is essential for evaluating the effectiveness of biogas technology in wastewater treatment and identifying opportunities for optimization.

- *Biogas production rate (m^3/m^3) = Gas Production (nm^3/d) / Wastewater Volume (m^3)*……………………………………..………..…….. (18)

Table [9]: Biogas Production Rate data based on West Nablus WWTP annual reports

Year	Gas Production (nm^3/d)	Wastewater Volume (m^3)	Biogas Production Rate (m^3/m^3)
2018	2,127	4,647,000	≈ 4.57×10−4
2019	2,003	5,320,000	≈ 3.76×10−4
2020	1,365	4,346,000	$\approx 3.14\times10^{-4}$
2021	1,367	4,850,700	$\approx 2.82\times10^{-4}$
2022	1,426	4,595,600	$\approx 3.10\times10^{-4}$

- Average Biogas Production Rate (m^3/m^3) = Sum of Biogas Production Rates / Number of Years

Average Biogas Production Rate $\approx 3.50\times10^{-4}$ m^3/m^3

Biogas Produced from Sludge;

the volume of biogas produced from a cup of sludge:

Assume a cup of sludge is approximately 0.25 liters or 0.00025 cubic meters.

- *Biogas Produced from a Cup of Sludge (m^3) = Average Biogas Production Rate (m^3/m^3) × Volume of Sludge (m^3)* …………………………………………….. (19)

Biogas Produced from a Cup of Sludge $\approx 3.50 \times 10^{-4}$ $m^3/m^3 \times 0.00025$ m^3

Biogas Produced from a Cup of Sludge (m^3) $\approx 8.75 \times10^{-8}$ m^3

Average kWh per m³ of Biogas:

- Sum up the total kWh produced for each year: 3,582,971 kWh
- Sum up the total biogas produced for each year: 8,288 m^3

Average kWh per m^3 of biogas ≈ 3,582,971 / 8,288 ≈ 432.03 kWh/m^3

4.9 Electrical Energy Produced from a Cup of Sludge:

The electrical energy produced from a Cup of Sludge (kWh) =

Biogas Produced from a Cup of Sludge × Average kWh per m³ of biogas …………….. (20)

- Electrical energy produced from a Cup of Sludge $\approx 8.75\times10^{-8}$ $m^3 \times 432.03$ kWh/m^3
- Electrical energy produced from a Cup of Sludge (kWh) ≈ 0.0038 kWh

Electrical Energy Produced from a Cup of Sludge in Ideal Conditions:

The quantity of electrical energy generated from sewage treatment plants per unit of sludge may fluctuate due to several factors, including sludge composition, treatment process efficiency, and CHP generator capacity. However, a typical estimation indicates that one cubic meter of sewage sludge can yield approximately 30 to 40 cubic meters of biogas, predominantly methane. Assuming proficient conversion of methane into electrical energy via a CHP generator, an estimate can be derived. consider a hypothetical situation where one cubic meter of sludge generates 35 cubic meters of biogas (mainly methane), with methane possessing an average energy content of about 35.80 megajoules (MJ) per cubic meter. A cup's volume is roughly 0.2366 liters or 0.0002366 cubic meters, factoring in a CHP generator efficiency of approximately 30%, the electrical energy output can be computed using the relevant formula:

- *Energy output (kWh) = Biogas volume (m^3) × Biogas production rate (m^3/m^3) × Energy content of methane (MJ/m^3) × Efficiency of CHP generator* ..……..…… (21)
- Biogas Volume (m^3):Tthe total biogas produced.
- Energy Content of Methane (MJ/m^3): The typical energy content of methane is approximately 35.80 MJ/m^3.
- Efficiency of CHP Generator: This is the efficiency of the combined heat and power (CHP) generator, typically around 35 - 40%. For this calculation, we'll use 30% (0.30)
- Convert MJ to kWh: 1 kWh = 3.6 MJ

Energy output (kWh) = (0.0002366 m^3 × 35 m^3/m^3× 35.80 MJ/m^3 × 0.30) ÷ 3.6

= 0.025 kWh

Electrical Energy Production Analysis

The analysis suggests that sludge-to-energy conversion methods, such as methane production from sewage treatment, hold promise for renewable energy generation. However, it indicates that the energy output per unit of sludge is relatively modest, emphasizing the need for more efficient energy conversion technologies. Additionally, the study highlights variations in the contribution of CHP electrical production to total consumption across different years, underscoring the importance of site-specific considerations in assessing energy generation from wastewater treatment processes.

Several factors can influence the percentage contribution of CHP electrical production to total electrical consumption in a treatment plant, including the size of the plant, its energy efficiency, the type and capacity of CHP systems used, the operational practices, and external factors such as weather conditions and regulatory requirements.

To generalize this relationship to other treatment plants, additional research and analysis would be required to understand the specific characteristics and dynamics of each plant. This could involve collecting data from multiple treatment plants, conducting statistical analyses to identify patterns and trends, and developing models that account for various influencing factors. Additionally, validation studies may be needed to assess the applicability and accuracy of the relationship across different plant settings.

The relationship between CHP electrical production and total electricity consumption can directly impact material costs by reducing energy expenditures and improving overall energy efficiency in the treatment plant. Therefore, optimizing the use of CHP technology can contribute to significant cost savings and enhance the economic sustainability of wastewater treatment operations.

By increasing the proportion of electricity generated from CHP systems, treatment plants can potentially reduce their reliance on grid electricity, leading to cost savings associated with purchasing electricity from external sources. Additionally, CHP systems can often generate electricity more efficiently than traditional power plants, resulting in lower fuel consumption and operating costs.

Moreover, CHP systems can utilize waste heat generated during electricity production for various heating applications within the treatment plant, such as heating process water or space heating. This can further enhance energy efficiency and reduce the need for additional heating equipment, thereby lowering material costs associated with heating systems.

Combined Heat and Power (CHP) systems can greatly benefit from the integration of artificial intelligence (AI) systems to enhance efficiency, optimize energy production, and improve overall performance. Here are several ways AI can contribute to the effectiveness of CHP systems:

1. **Predictive Maintenance**: AI algorithms can analyze real-time data from sensors and equipment within CHP systems to predict potential failures or maintenance needs. By

identifying issues before they occur, AI-driven predictive maintenance can minimize downtime, reduce maintenance costs, and prolong the lifespan of CHP components.

2. **Optimized Operation**: AI-based control systems can dynamically adjust the operation of CHP units based on factors such as energy demand, fuel prices, and weather conditions. These systems can optimize the balance between heat and power generation, ensuring that the CHP system operates at maximum efficiency under varying circumstances.
3. **Load Forecasting**: AI algorithms can analyze historical energy usage data and external factors to forecast future energy demand accurately. By predicting load variations, CHP systems can adjust their output accordingly to meet demand fluctuations efficiently, maximizing electricity production while minimizing waste.
4. **Fault Detection and Diagnosis**: AI-powered analytics can detect anomalies in CHP system performance and diagnose the root causes of inefficiencies or malfunctions. This proactive approach enables operators to address issues promptly, maintain optimal operation, and prevent potential energy losses.
5. **Dynamic Fuel Management**: AI systems can optimize fuel consumption in CHP units by analyzing real-time data on fuel quality, availability, and pricing. By dynamically adjusting fuel usage based on these factors, AI can help CHP systems minimize fuel costs while maximizing electrical and thermal energy output.
6. **Integration with Renewable Energy Sources**: AI algorithms can facilitate the integration of renewable energy sources, such as solar or wind power, with CHP systems. By predicting renewable energy generation patterns and optimizing their combined operation, AI can enhance the overall efficiency and sustainability of CHP-based energy generation.

4.10 Factors to Enhance Efficiency of Methane Production

Modernizing the production of methane from sludge in wastewater treatment plants for use in a Combined Heat and Power (CHP) generator to produce electricity involves several key factors to enhance efficiency and reduce operational costs:

1. **Anaerobic Digestion Efficiency**: Improving the efficiency of anaerobic digestion, the process used to produce methane from sludge, is crucial. Optimizing operating conditions such as temperature, pH levels, retention time, and mixing can increase biogas yield and quality.

2. **Biogas Cleaning and Upgrading**: Proper cleaning and upgrading of biogas to remove impurities such as hydrogen sulfide and moisture are essential to protect CHP equipment and ensure stable electricity generation. Advanced gas purification technologies like scrubbers and membranes can enhance biogas quality.
3. **CHP System Integration**: Integrating the CHP system with the biogas production process and other plant operations is important for efficient energy utilization. Proper system design, including sizing of the generator and heat recovery equipment, ensures optimal energy output and utilization of waste heat.
4. **Energy Management and Optimization**: Implementing advanced energy management and optimization strategies, such as predictive maintenance, load forecasting, and demand-side management, helps maximize energy efficiency and minimize downtime.
5. **Monitoring and Control Systems**: Installing robust monitoring and control systems enables real-time tracking of biogas production, CHP operation, and energy consumption. Data analytics and remote monitoring capabilities facilitate proactive maintenance and performance optimization.
6. **Biogas Storage and Flexibility**: Incorporating biogas storage facilities allows for flexible operation of the CHP system to meet varying electricity demand and grid requirements. Biogas storage tanks or systems enable energy storage during periods of low demand and can supplement electricity generation during peak demand.

By focusing on these factors and leveraging advancements in biogas production and utilization technologies, wastewater treatment plants can modernize their operations, increase energy self-sufficiency, and contribute to sustainable energy generation while reducing operational costs and environmental impact. Moreover, the advancement of methane production from sludge in wastewater treatment plants for utilization in CHP generators through AI integration offers significant opportunities to enhance efficiency, reduce operational costs, and improve overall system performance. By optimizing methane production processes, enabling predictive maintenance, implementing dynamic process control, effectively managing energy, integrating with renewable energy sources, and harnessing data analytics, AI can catalyze transformative enhancements in methane-based CHP generation for wastewater treatment plants.

Similarly, technical issues such as mechanical failures, malfunctioning components, or operational inefficiencies can lead to a decrease in the amount of electricity produced by the

CHP generator. These problems can disrupt the normal operation of the generator, causing downtime and reducing its overall efficiency.

Various factors can contribute to the decrease in efficiency of a CHP generator, including inadequate maintenance, aging equipment, environmental conditions, and insufficient monitoring and control systems. Addressing these issues requires proactive maintenance strategies, regular inspections, prompt troubleshooting of technical problems, and continuous optimization of operational processes to maximize the electrical energy output of the generator.

4.11 Analyzing Financial Impact

4.11.1 Cost-Benefit Analysis:

This section intends to perform a cost-benefit analysis (CBA) for two distinct alternatives:

1. No Action Alternative: This alternative is the wastewater treated without converting sludge into electrical energy,
2. Action Alternative**:** This alternative adopts renewable energy technologies, particularly Combined Heat and Power (CHP) generators converting sludge into electrical energy.

Comparison between Costs and Benefits:

This section provides an initial comparison between the costs and benefits associated with the alternatives.

- **Capital Cost;**

No Action Alternative:

In the scenario where wastewater is treated without converting sludge into electrical energy, the cost of the wastewater treatment plant project in Nablus is estimated at approximately 281,400,000 NIS (Yaqob et al., 2016). This capital expenditure covers a range of costs associated with establishing crucial infrastructure, including the installation of main trunk lines for transporting wastewater to the WWTP, as well as the construction of various components within the WWTP itself, such as process and operational buildings. Additionally, it encompasses the expenses related to conveyance systems required for transporting treated effluent to designated agricultural areas or wadis. In both proposed alternatives, the construction of wastewater treatment plants within Israel is currently borne as an expense by the Palestinian authorities. Thus, there is minimal disparity in capital costs between the two alternatives, as both entail Palestinian investment in WWTP construction and associated infrastructure.

- **Running Costs;**

For the "No Action Alternative," the operating cost of a wastewater treatment plant using traditional electricity is calculated based on the electricity rate and average electrical consumption per cubic meter. The operating cost is approximately 0.35 NIS per cubic meter. Additionally, an additional cost, deducted from Palestinians' tax money by Israel for treating wastewater, amounts to 1.55 NIS per cubic meter. Therefore, the total operating cost for this alternative is approximately 1.89 NIS per cubic meter.

In contrast, for the "Action Alternative," the operating cost involves both the capital cost and the cost per cubic meter of treated wastewater. The cost per cubic meter is 4.12 NIS.

Action Alternative:

The action alternative involves the adoption of Combined Heat and Power (CHP) generators for energy production from biogas. The total cost for this alternative includes the capital cost of constructing the wastewater treatment plant, along with an additional 9,802,000 NIS. By implementing processes to treat sludge and extract methane, efforts are made to reduce the volume of wastewater flowing into Wadi Zomar. This strategic shift aims to alleviate financial burdens on the Palestinian Authority. Notably, Israeli authorities have historically deducted 30 M NIS from Palestinian tax revenues to finance the construction of treatment plant Yad Hana Waste Water Treatment Plant (WWTP) in Emek Hefer. Additionally, annual deductions, ranging from 17 million to 25 million NIS, have been attributed to sewage treatment, environmental penalties, and compensations, which is equivalent to approximately 115 million NIS. The annual payment rate is estimated at 90 million NIS to 120 million NIS, presenting a significant challenge for the Palestinian government (PWA, 2022).

- **Positive Impacts;**

Environmental Benefits: Reduced Greenhouse Gas Emissions: Converting sludge into electrical energy through methods like anaerobic digestion or thermal treatment helps decrease greenhouse gas emissions. By capturing methane released during sludge decomposition and using it for energy production, the overall carbon footprint of wastewater treatment facilities is lowered, aiding global climate change mitigation efforts.

Water Quality Enhancement: The treated wastewater resulting from sludge-to-energy conversion undergoes tertiary treatment processes, such as sand filtration, UV disinfection, and chlorination. These processes ensure the removal of contaminants and pathogens, resulting in high-quality water suitable for irrigation purposes. Consequently, the use of treated wastewater for irrigation helps maintain soil moisture and sustains agricultural productivity while minimizing the risk of waterborne diseases.

Groundwater Protection: Converting sludge into electrical energy helps mitigate groundwater contamination risks by reducing untreated sludge volume. Effective sludge treatment minimizes environmental impacts on groundwater quality, contributing to enhanced groundwater protection.

Improved Waste Management Practices: Converting sludge into electrical energy promotes better waste management practices within wastewater treatment facilities. By extracting energy from sludge, the volume of waste needing disposal is reduced, minimizing the need for landfilling or incineration. This helps mitigate environmental pollution and preserves valuable land resources.

Resource Recovery and Circular Economy: Converting sludge into electrical energy supports resource recovery and circular economy principles. Instead of treating sludge as waste, it's repurposed into a valuable energy resource, minimizing waste generation and maximizing resource utilization. This recovered energy can power various processes, fostering a more sustainable resource management system.

Technological Innovation and Knowledge Transfer: The development of sludge-to-energy technologies fosters innovation and knowledge transfer within the renewable energy sector. Research and investment in innovative processes drive advancements in energy efficiency, waste utilization, and environmental protection, promoting continuous improvement in sludge management and energy production techniques.

Agricultural Impact: Improved Crop Quality: The organic fertilizer derived from sludge contains essential nutrients that enhance soil fertility and improve crop yields. By supplying crops with nutrient-rich organic matter, the quality and nutritional value of agricultural produce are enhanced, leading to healthier and more resilient crops.

Alternative to Chemical Fertilizers: The organic fertilizer obtained from sludge provides a sustainable alternative to chemical fertilizers, reducing reliance on synthetic inputs that may have adverse environmental impacts. This promotes environmentally friendly agricultural practices and reduces the risk of soil degradation and water contamination associated with chemical fertilizers.

Sustainable Agricultural Practices: The availability of high-quality organic fertilizer and treated wastewater encourages the adoption of sustainable agricultural practices. Farmers can utilize these resources to maintain soil health, conserve water resources, and enhance crop productivity in an environmentally sustainable manner. Additionally, the promotion of sustainable agriculture contributes to long-term food security and resilience to climate change impacts.

Impact on Agriculture: Converting sludge into electrical energy positively impacts agriculture by providing sustainable energy sources and addressing waste management challenges. Reduced sludge volume preserves agricultural land and minimizes soil and water contamination risks, fostering a healthier environment for farming activities.

Promotion of Reuse Projects: Initiatives such as the Nablus Tertiary Treatment project demonstrate the practical implementation of wastewater reuse for agricultural irrigation. By establishing tertiary treatment systems funded by organizations like KfW and USAID, treated wastewater can be safely utilized for irrigation purposes, benefiting farmers and communities while reducing dependence on freshwater resources.

Energy and Resilience: Utilizing sludge as a renewable energy source enhances community energy security and resilience. Diversifying the energy mix and reducing reliance on finite fossil fuels make communities less vulnerable to supply disruptions and price fluctuations in the global energy market. Decentralized sludge-to-energy facilities also bolster resilience by providing localized energy generation.

Health and Well-being: Converting sludge into electrical energy benefits public health by minimizing environmental and health risks associated with untreated sludge. Effective sludge treatment reduces the release of harmful pathogens and contaminants into the environment, lowering the incidence of waterborne diseases and improving overall community health.

Socio-Economic Impact: The integration of sludge-to-energy conversion and wastewater reuse projects creates economic opportunities for local communities. By maximizing the use of reclaimed water and organic fertilizers, agricultural productivity is enhanced, leading to increased income for farmers and improved livelihoods. Moreover, the reduction in wastewater treatment costs and the generation of renewable energy contribute to overall economic growth and sustainability. Converting sludge into electrical energy generates socio-economic benefits by creating jobs, fostering economic growth, and promoting energy independence.

Water Management: Converting sludge into electrical energy enhances water management by reducing wastewater sludge volume requiring treatment and disposal. This lowers water consumption for treatment processes and alleviates pressure on wastewater treatment facilities, promoting more sustainable water management practices.

Considering the long-term benefits and potential positive impacts on various aspects, including environmental sustainability, agricultural productivity, energy efficiency, public health, and socio-economic development, the action alternative of adopting sludge-to-energy conversion technologies appears to be a favorable option. Despite the initial higher capital and operating costs associated with the action alternative, the long-term benefits outweigh the upfront investments. Therefore, implementing renewable energy technologies for sludge-to-energy conversion would likely yield greater overall value and contribute to the sustainable development of wastewater treatment practices in Nablus.

4.11.2 Sludge to Energy at the West Nablus WWTP:

The implementation of sludge treatment at the West Nablus WWTP directly addresses several key points concerning the financial burden incurred by the Palestinian Authority (PA) due to transboundary pollution and wastewater management along the border between Palestine and Israel:

1. **Reduction of Treatment Tariffs**: Sludge treatment at West Nablus WWTP helps reduce the volume of wastewater requiring treatment in Israeli facilities. By effectively treating sludge locally, the PA can minimize the amount of wastewater discharged into Israeli territories, thereby reducing the tariffs imposed by Israel for treating Palestinian wastewater. This reduction in treatment tariffs alleviates the financial burden on the PA by lowering the costs associated with cross-border wastewater management.
2. **Decrease in Deductions from Tax Revenues**: The implementation of sludge treatment at West Nablus WWTP station mitigates the need for extensive wastewater treatment infrastructure in Israeli territories, thereby reducing the expenses deducted from Palestinian tax revenues by Israel. By treating sludge locally and minimizing the reliance on Israeli treatment facilities, the PA can reduce the amount withheld from its tax revenues, freeing up financial resources for investment in other priority sectors and development projects.
3. **Mitigation of Dispute Resolution Costs**: Sludge treatment at West Nablus WWTP contributes to mitigating disputes and negotiations with Israeli authorities over wastewater

management issues. By enhancing the capacity for local wastewater treatment, the PA can demonstrate proactive measures to address transboundary pollution, fostering constructive dialogue and cooperation with Israeli counterparts. This reduces the administrative expenses and resource mobilization required for resolving disputes, allowing the PA to allocate resources more efficiently towards sustainable development initiatives.

4. **Environmental Remediation Savings**: The effective treatment of sludge at West Nablus WWTP helps prevent environmental degradation and contamination of natural resources along the border between Palestine and Israel. By reducing the discharge of untreated or inadequately treated wastewater into transboundary streams, sludge treatment minimizes the need for costly environmental remediation and restoration activities. This results in savings for the PA in terms of cleanup operations and ecosystem rehabilitation efforts, preserving public health and environmental quality in the region.
5. **Opportunity for Sustainable Development**: Sludge treatment at West Nablus WWTP creates opportunities for sustainable development and investment in Palestinian communities. By promoting local capacity building and technological innovation in wastewater management, the PA can leverage sludge treatment as a catalyst for socioeconomic growth and resilience. The financial resources saved from reduced treatment tariffs, tax revenue deductions, and dispute resolution costs can be redirected towards priority sectors such as education, healthcare, infrastructure, and economic empowerment, fostering long-term prosperity and well-being for Palestinian citizens.

The implementation of sludge treatment at the West Nablus WWTP not only addresses the financial burdens associated with transboundary pollution for the Palestinian Authority but also contributes significantly to the WEF Nexus and the achievement of SDGs:

1. **WEF Nexus**: Sludge treatment at the West Nablus WWTP aligns with the principles of the WEF Nexus by recognizing the interconnectedness of water, energy, and food systems. The process involves the conversion of sludge into electrical energy through methane production, highlighting the intricate relationships between these resources. By optimizing energy resources and minimizing water usage in the treatment process, the solution exemplifies a holistic approach to wastewater management that considers the interdependencies of the WEF Nexus.

2. **Sustainable Development Goals (SDGs)**:

- **Goal 6: Clean Water and Sanitation**: The sludge treatment process directly contributes to Goal 6 by addressing wastewater management challenges and minimizing water pollution. By efficiently treating sludge, the solution promotes the availability of clean water resources, supporting sustainable water and sanitation practices.
- **Goal 7: Affordable and Clean Energy**: Sludge-to-energy conversion significantly aligns with Goal 7 by harnessing methane for electrical energy production. This offers a sustainable and clean energy source, reducing reliance on conventional energy production methods and promoting affordable access to clean energy.
- **Goal 11: Sustainable Cities and Communities**: The proposed approach resonates with Goal 11 by addressing challenges in wastewater management and contributing to the creation of sustainable urban communities. By promoting environmentally friendly practices, such as sludge treatment, the solution supports the development of resilient and sustainable cities.
- **Goal 13: Climate Action**: The sludge conversion process is a climate-friendly initiative that aligns with Goal 13. By mitigating environmental repercussions associated with traditional disposal methods, such as methane emissions, the solution contributes to climate resilience and supports efforts to combat climate change.
- **Goal 15: Life on Land**: Indirectly, the sludge-to-energy conversion process addresses Goal 15 by minimizing potential environmental repercussions on soil quality. Sustainable sludge management practices contribute to the preservation of terrestrial biodiversity and support the maintenance of healthy ecosystems.

Expanding the application of sludge-to-energy conversion across all wastewater treatment plants in Palestine, including West Nablus WWTP, offers a comprehensive solution to the challenges posed by transboundary pollution and wastewater management. This approach not only reduces the financial burden on the Palestinian Authority by minimizing expenses associated with wastewater treatment tariffs and environmental remediation but also enhances wastewater management capabilities. By treating sludge on-site and converting it into energy, the process mitigates the risk of transboundary pollution, particularly in valleys like Wadi Zomar and Wadi Al-Moqatta, which flow into Israeli territories. Moreover, by promoting resource efficiency, environmental sustainability, and regional cooperation, Palestine can foster a more resilient and environmentally responsible future while addressing common transboundary environmental challenges.

4.12 Assessing Effectiveness and Environmental Impact

The data presented in this chapter underscores various aspects of sludge production, energy output, potential expansion scenarios for wastewater treatment operations, and associated costs. This highlights the necessity for a comprehensive analysis, particularly considering the financial implications. Considering the adverse effects of cross-border sludge pollution, there is a critical need to evaluate the implications of converting sludge into energy, taking into account both the environmental benefits and the economic feasibility. This analysis seeks to uncover the potential advantages of such a strategy, particularly in promoting cross-border collaboration. Through this investigation, valuable insights will be provided into the feasibility and importance of adopting sludge-to-energy conversion as a means to mitigate environmental pollution and enhance regional cooperation.

To evaluate the effectiveness of converting sludge into energy in mitigating transboundary sludge pollution and promoting collaboration across borders, several steps can be taken:

4.12.1 Assessment of Environmental Impact

To evaluate the environmental impact of traditional sludge disposal methods in contrast to sludge-to-energy conversion, it is essential to examine factors including greenhouse gas emissions, risks of soil and water contamination, and air pollution.

1. **Greenhouse Gas Emissions:** Traditional sludge disposal methods, such as landfilling or open-air drying, can contribute to greenhouse gas emissions, particularly methane (CH_4) and carbon dioxide (CO_2). Landfilling, for example, can lead to anaerobic decomposition of organic matter in the sludge, resulting in methane emissions, which are potent greenhouse gases. Open-air drying may also release methane and CO_2 as the sludge undergoes decomposition. On the other hand, sludge-to-energy conversion methods, such as anaerobic digestion for methane production, capture methane emissions and utilize them as a fuel source for energy generation. This process effectively reduces methane emissions that would otherwise be released into the atmosphere, thus mitigating greenhouse gas emissions.
2. **Soil and Water Contamination Risks:** Traditional sludge disposal methods pose risks of soil and water contamination, especially if the sludge contains harmful substances or

pathogens. Landfilling can potentially lead to leachate production, where contaminants from the sludge can seep into the soil and groundwater, posing risks to environmental and human health. Similarly, open-air drying may result in runoff of contaminants into nearby water bodies during rainfall events. In contrast, sludge-to-energy conversion methods typically involve pre-treatment processes, such as anaerobic digestion, which can reduce the concentration of harmful substances and pathogens in the sludge. Furthermore, the conversion of sludge into energy reduces the volume of sludge requiring disposal, thereby minimizing the potential for soil and water contamination.

3. **Air Pollution**: Traditional sludge disposal methods, particularly open-air drying, can contribute to air pollution through the release of volatile organic compounds (VOCs), ammonia (NH_3), and particulate matter (PM) during decomposition and drying processes. These pollutants can have adverse effects on air quality and human health, especially in nearby communities. Sludge-to-energy conversion methods, however, typically involve combustion or digestion processes that are conducted in controlled environments, minimizing the release of pollutants into the atmosphere. Moreover, the utilization of biogas or syngas produced from sludge conversion as a fuel source for energy generation can further reduce reliance on fossil fuels, thereby indirectly mitigating air pollution.

By comparing the environmental impact of traditional sludge disposal methods to sludge-to-energy conversion, it becomes evident that the latter offers several environmental benefits. Not only does it reduce greenhouse gas emissions, but it also minimizes soil and water contamination risks while mitigating air pollution. These findings underscore the importance of adopting sustainable waste management practices, such as sludge-to-energy conversion, to address environmental challenges effectively and promote sustainable development.

4.12.2 Comparison of Economic and Environmental Costs:

To conduct a cost-benefit analysis comparing the economic and environmental costs of traditional sludge disposal methods to sludge-to-energy conversion, it's essential to consider expenses associated with pollution mitigation, environmental remediation, and cross-border collaboration efforts, utilizing data from the thesis.

Economic Costs;

Traditional Sludge Disposal Methods:

- Pollution Mitigation Expenses: These include investments in wastewater treatment infrastructure, pollution control measures, and environmental monitoring.
- Environmental Remediation Costs: Addressing soil and water contamination involves expenses related to cleanup operations, soil remediation, and ecosystem restoration.
- Cross-Border Collaboration Expenses: Collaboration efforts between relevant authorities may be necessary to address shared environmental concerns, leading to additional economic costs.

Sludge-to-Energy Conversion

- Initial Investment Costs: Implementing conversion technologies requires upfront capital investment in infrastructure and equipment.
- Operational Expenses: Operating and maintaining conversion facilities entail ongoing expenses, including labor, energy consumption, and maintenance.
- Cross-Border Collaboration Expenses: Similar to traditional methods, conversion projects may involve collaboration efforts, focusing on technology transfer and joint investment.

Environmental Costs;

Traditional Sludge Disposal Methods

- Pollution Footprint: These methods contribute to environmental degradation through soil, water, and air pollution.
- Environmental Remediation: Addressing impacts requires extensive remediation efforts, including habitat restoration and pollution control measures.

Sludge-to-Energy Conversion

- Pollution Reduction: Conversion technologies mitigate pollution by reducing contaminants and greenhouse gas emissions.
- Resource Recovery: They promote resource recovery by harnessing energy and producing valuable byproducts.

In summary, while traditional methods may have lower initial costs, they impose significant economic and environmental burdens. Conversely, sludge-to-energy conversion offers economic benefits through energy generation and resource recovery while mitigating pollution.

Therefore, considering both economic and environmental factors, conversion emerges as a more favorable option for addressing sludge disposal challenges.

4.13 Estimation of Sludge Generation

4.13.1 The current amount of sludge produced by Nablus West WWTP:

sludge production rate of 0.06 kg/capita/day

- Nablus West WWTP:
  - Design Capacity: 110,000 capita/day
  - Sludge Production: 110,000 capita/day × 0.06 kg/capita/day = 6,600 kg/day

4.13.2 Amount of electrical energy that could be produced from sludge to energy technique:

The energy content of methane: 35.80 MJ/m^3

The methane production coefficient is typically around: 0.20 m^3/kg.

The total volume of methane produced (m^3/day) = Sludge production (kg/day) × Methane production coefficient (m^3/kg)

= 6,60 kg/day × 0.20 m^3/kg = 1,32 m^3/day

- Total energy content (MJ/day) = Total volume of methane produced (m^3/day) × Energy content of methane (MJ/$m^{3)}$

= 1,32 m^3/day × 35.8 MJ/m^3 = 47,26 MJ/day

Conversion efficiency using CHP generator: 30%

- Energy Produced (MJ/day) = Energy Content of Methane (MJ/day) × Efficiency

= 47,26 MJ/day × 0.30 ≈ 14,176.80 MJ/day

1 MJ = 0.28 kWh

The electrical energy produced (kWh) ≈ 14,176.80 MJ/day × 0.28 kWh/MJ

≈ 3,938.32 kWh/day

4.13.3 Sludge Quantity from all the West Bank population (As a part of Palestine):

Sludge Treatment from the West Bank Population, by developing existing wastewater treatment plants and establishing new treatment plants whose services include all quantities of wastewater generated by the population and treating the sludge by Sludge-to-Energy.

Population = 3 million

Consumption = 100 liters/capita/day (including industrial sector)

Wastewater coefficient = 80% (assuming 80% of water consumed is converted to wastewater)

- Wastewater Generated (liters/day) = Population (capita) × Consumption (liters/capita/day) × Wastewater coefficient

= 3,000,000 capita × 100 liters/capita/day × 0.8 = 240,000,000 liters/day

- Design Capacity per capita/day (liters/capita/day) = Wastewater Generated (liters/day) / Population (capita)

= 240,000,000 liters/day / 3,000,000 capita = 80 liters/capita/day

Design Capacity per capita/day = 80 liters/person/day

- Sludge Production (kg/day) = Total Wastewater (liters/day) × Sludge Production Coefficient (kg/liter)

= 240,000,000 liters/day × 0.06 kg/liter =14,400,000 kg/day=14,400,000 kg/day

Amount of electrical energy that could be produced from sludge to energy technique

The energy content of methane: 35.8 MJ/m^3

The methane production coefficient is typically around: 0.2 m^3/kg.

- The total volume of methane produced = Sludge production × Methane production coefficient

= 14,400,000 kg/day × 0.2 m^3/kg = 2,880,000 m^3/day

- Total energy content = Total volume of methane produced × Energy content of methane

= 2,880,000 m^3/day × 35.8 MJ/m^3 = 103,104,000 MJ/day

Conversion efficiency using CHP generator: 30%

- Energy Produced = Energy Content of Methane × Efficiency

= 103,104,000 MJ/day × 0.30 ≈ 30,931,200 MJ/day

1 MJ = 0.28 kWh

Electrical energy produced (kWh) ≈ 30,931,200 MJ/day × 0.28 kWh/MJ

≈ 8,588,761.60 kWh/day

Cost Calculations:

Scenario 1, Nablus West WWTP sludge-to-energy, Scenario 2, West Bank Population sludge-to-energy

- Operational costs including energy consumption, maintenance, labor, and sludge handling: 0.78 NIS/m³ (PWA, 2024)
- Additional costs for sludge treatment and disposal: 0.44 NIS/m³ (PWA, 2024)

Treating sludge and converting it into energy has the potential to significantly reduce treatment costs within Israel. According to the Palestinian Water Authority (PWA, 2024), the operational costs associated with energy consumption, maintenance, labor, and sludge handling are estimated at 0.78 NIS/m³, while additional costs for sludge treatment and disposal amount to 0.44 NIS/m³. By addressing sludge treatment and energy conversion at the source, within Palestinian Authority treatment plants, a substantial reduction in the volume of pollutants reaching the valley stream can be achieved. This proactive approach will not only lower the treatment burden on facilities in Israel but also enhance environmental quality and resource efficiency. The larger the quantities of sludge treated before they reach transboundary water bodies, the more significant the cost savings and environmental benefits will be. This strategy underscores the importance of robust sludge management and energy recovery systems to mitigate pollution and promote sustainable development in the region.

Treating sludge and converting it into energy offers substantial economic benefits for local and regional stakeholders. By transforming sludge into a valuable energy resource, wastewater treatment plants can reduce operational expenses and generate additional revenue streams. Producing biogas from sludge allows treatment plants to generate their electricity and heat, significantly cutting down on energy bills. Furthermore, converting sludge into energy reduces the volume of waste requiring disposal, thereby lowering handling and transportation. Excess electricity generated from biogas can be sold back to the grid, creating an additional income stream for these plants. Additionally, treating sludge within the Palestinian Authority before it reaches Israeli territories can result in cost savings for Israeli treatment facilities by reducing the pollutant load in transboundary water bodies.

Implementing sludge-to-energy systems also creates new job opportunities in renewable energy, waste management, and environmental engineering, stimulating local economies and promoting skill development. Moreover, this approach reduces environmental degradation and public health costs associated with contaminated water and soil, leading to long-term economic benefits by preserving natural resources and reducing healthcare expenditures. The use of treated sludge as a fertilizer can benefit agriculture by improving soil quality and crop yields, boosting agricultural productivity, and supporting local food industries. Overall, sludge-to-energy conversion enhances the financial sustainability of wastewater treatment operations and contributes to regional economic development and environmental conservation.

The analysis reveals significant potential savings from efficiently managing sludge production. The first scenario, focusing on wastewater treatment plants (WWTPs), shows moderate annual savings. In contrast, the second scenario, which encompasses the entire West Bank population, highlights the substantial economic benefits achievable through comprehensive sludge management practices. These savings underscore the importance of investing in efficient wastewater treatment and sludge management systems to reduce costs and enhance financial sustainability in the region.

4.13.4 Correlation Analysis:

Sludge Production Rates and Energy Output:

- The objective is to explore the relationship between sludge production rates and energy output. This analysis aims to determine if there exists a correlation between these two variables, with a potential implication that higher sludge production rates lead to increased energy output.

Operational Costs and Potential Cost Differential:

- This investigation focuses on understanding the potential relationship between operational costs and potential Differences within the context of wastewater treatment. The hypothesis suggests that higher operational costs may correspond to lower potential savings.

Sludge Production Rates and Cost Estimates:

- This section aims to examine the potential relationship between sludge production rates and cost estimates associated with treatment and disposal. It is hypothesized that higher sludge production rates might result in higher cost estimates.

The analysis demonstrates clear relationships between sludge production rates, energy output, operational costs, and potential savings in wastewater treatment. A positive linear correlation between sludge production rates and energy output indicates that increased sludge production enhances energy generation, making it a valuable resource. Conversely, a negative correlation between operational costs and potential savings highlights that higher expenses reduce financial efficiency, emphasizing the need for cost-effective management. Additionally, the positive correlation between sludge production rates and cost estimates suggests that higher production rates increase treatment and disposal costs, underscoring the importance of efficient sludge management strategies to control financial impacts.

4.13.5 Comparative Analysis:

Table 10 below shows the key findings from the sludge-to-energy analysis for Nablus West WWTP and the West Bank population. It clearly shows the potential energy outputs and the corresponding financial savings from treating sludge, emphasizing the significant economic and energy benefits of implementing sludge-to-energy technologies on both local and regional scales.

Table 10: Summary Table of Sludge-to-Energy Potential and Cost Analysis Results

Parameter	Nablus West WWTP	West Bank Population
Population Served	110,000 capita	3,000,000 capita

Total Sludge Production	6,600 kg/day	14,400,000 kg/day
Total Volume of Methane Produced	1,32 m^3/day	2,880,000 m^3/day
Energy Produced	14,176.80 MJ/day	30,931,200 MJ/day
Electrical Energy Produced	3,938.85 kWh/day	8,599,385.60 kWh/day

The comparative analysis involves assessing the results obtained from different scenarios, specifically comparing sludge production from wastewater treatment plants (WWTPs) with sludge production from the West Bank population with sludge-to-energy conversion. This comparison aims to evaluate the effectiveness and economic feasibility of these two approaches to sludge management and energy generation. This analysis clearly shows that larger-scale operations like those in the West Bank can achieve significantly higher energy production and greater financial benefits, making a strong case for expanding sludge-to-energy initiatives.

4.13.6 Scenario's Cost Analysis:

The analysis demonstrates that implementing sludge treatment locally for the West Bank population offers significant financial benefits compared to the current practice of relying on Israeli treatment facilities. This highlights the economic benefits of expanding sludge-to-energy initiatives across larger populations, showcasing the potential for both energy production and substantial cost savings.

The significant amount of energy generated in both scenarios has a profound effect on the overall cost dynamics. With substantial energy production from sludge treatment, There is an excess of energy generated in both scenarios, leading to a reduction in operational expenses, particularly in Scenario 2 where energy output is notably higher due to the larger sludge volume from the West Bank population. This excess energy can potentially be harnessed to power various aspects of the treatment process, reducing reliance on external energy sources and consequently lowering operational costs. Additionally, excess energy can be fed back into the grid, allowing for revenue generation or energy credits that further mitigate the financial burden associated with sludge treatment. Therefore, the substantial energy yield acts as a crucial factor in shaping the cost-effectiveness of each scenario, contributing to overall financial sustainability and resilience in waste management practices.

In examining the current situation, it's evident that wastewater treatment plants in Palestine operate without utilizing sludge for energy production, leading to environmental pollution and dependence on non-renewable energy sources. Converting sludge into energy presents a compelling opportunity to enhance sustainability, mitigate environmental impact, and promote renewable energy. However, realizing this potential requires optimizing technological efficiency, implementing supportive policies, fostering cross-sectoral collaboration, and ensuring long-term sustainability through proactive measures. By converting all sludge into energy, a transformative approach to wastewater management can be achieved, ensuring cleaner waterways, soil, and air while advancing toward a low-carbon economy and fostering stronger transboundary cooperation.

4.14 Stakeholder Engagement:

Engaging with pertinent stakeholders is vital for eliciting perspectives on the potential benefits and obstacles associated with implementing sludge-to-energy conversion technologies, thereby augmenting cross-border collaboration. Here's how to engage with various stakeholders:

Wastewater Treatment Plant Operators:

- Conduct interviews or focus group discussions to glean insights into prevailing sludge management practices and operational hurdles.
- Solicit feedback on the viability and scalability of integrating sludge-to-energy conversion technologies into existing wastewater treatment infrastructures.
- Discuss potential technical requirements, operational considerations, and regulatory impediments related to transitioning to sludge-to-energy systems.
- Explore prospects for collaboration among wastewater treatment plants aimed at sharing best practices and technological solutions.

Government Agencies:

- Organize meetings or workshops involving representatives from pertinent government bodies tasked with environmental regulation and energy policy.
- Present research findings on sludge-to-energy conversion, emphasizing its alignment with national energy objectives and environmental sustainability mandates.

- Seek endorsement for policy reforms, funding opportunities, and incentive programs geared towards promoting the adoption of sludge-to-energy technologies and facilitating cross-border collaboration.
- Address regulatory hurdles and permitting processes that might impede the implementation of sludge-to-energy projects.

Environmental Organizations:

- Collaborate with environmental NGOs and advocacy groups to raise awareness about the environmental advantages of sludge-to-energy conversion.
- Jointly conduct outreach campaigns and educational initiatives aimed at fostering sustainable wastewater management practices.
- Explore avenues for partnership in research endeavors and capacity-building activities geared towards advancing sludge-to-energy conversion and environmental stewardship.

Community Representatives:

- Arrange community meetings or public forums to elicit feedback from local residents and community leaders.
- Listen attentively to community concerns and aspirations regarding wastewater management and environmental conservation.
- Disseminate information regarding the potential benefits of sludge-to-energy conversion, particularly with regard to job creation, environmental sustainability, and public health enhancement.
- Encourage community involvement in decision-making processes and project implementation endeavors to ensure their perspectives are duly considered and represented.

Engaging with a diverse array of stakeholders empowers us to amass valuable insights, foster consensus, and catalyze collaboration toward the effective implementation of sludge-to-energy conversion technologies. This, in turn, serves to bolster cross-border cooperation endeavors aimed at mitigating pollution and fostering sustainable development.

4.15 Policy Recommendations:

Policy recommendations aimed at incentivizing the adoption of sludge-to-energy conversion technologies and facilitating cross-border collaboration on wastewater management could include the following:

- Regulatory Frameworks:
    - Develop comprehensive regulations and standards for sludge management, including guidelines for the implementation of sludge-to-energy conversion technologies.
    - Streamline permitting processes for the construction and operation of sludge-to-energy facilities to reduce administrative barriers and expedite project development.
    - Establish environmental performance standards to ensure that sludge-to-energy projects meet emissions criteria and do not pose risks to public health or the environment.
    - Encourage regulatory harmonization and information sharing among neighboring countries to facilitate cross-border cooperation and alignment of policies.
- Financial Incentives:
    - Provide financial incentives, such as grants, subsidies, tax credits, or low-interest loans, to support the adoption of sludge-to-energy technologies and infrastructure investments.
    - Establish revolving funds or investment programs to finance sludge-to-energy projects, particularly in underserved communities or regions with limited access to capital.
    - Create innovative financing mechanisms, such as carbon offset credits or renewable energy certificates, to monetize the environmental benefits of sludge-to-energy conversion and attract private sector investment.

    - Allocate public funding for research and development initiatives focused on advancing sludge-to-energy technologies, improving efficiency, and reducing costs.

- Capacity-Building Initiatives:
    - Implement training programs, workshops, and knowledge exchange platforms to build the capacity of wastewater treatment plant operators, government officials, and other stakeholders in sludge-to-energy conversion technologies and best practices.
    - Foster partnerships between academic institutions, research organizations, and industry stakeholders to conduct research, pilot projects, and technology demonstrations related to sludge-to-energy conversion.
    - Establish technical assistance programs to provide technical support, feasibility studies, and project development assistance to communities interested in implementing sludge-to-energy projects.
    - Promote technology transfer and knowledge sharing through international cooperation initiatives, collaborative research projects, and joint ventures between countries with expertise in sludge management and energy production.
- Cross-Border Collaboration:
    - Facilitate cross-border dialogue, information exchange, and cooperation on wastewater management issues through regional forums, bilateral agreements, and joint working groups.
    - Encourage the establishment of transboundary partnerships and consortia to address shared challenges, leverage resources, and implement collaborative projects for sludge management and energy recovery.
    - Develop protocols for data sharing, monitoring, and joint assessment of environmental impacts to enhance transparency, accountability, and trust among neighboring countries.
    - Support cross-border research initiatives, pilot projects, and demonstration sites to showcase the benefits of sludge-to-energy conversion and promote regional integration in wastewater management practices.

By implementing these policy recommendations, governments can create an enabling environment for the widespread adoption of sludge-to-energy conversion technologies, foster cross-border collaboration on wastewater management, and contribute to the achievement of sustainable development goals related to clean water, affordable and clean energy, and environmental protection. Moreover Creating effective monitoring and evaluation systems is essential to track the impact of sludge-to-energy conversion on mitigating transboundary pollution and enhancing collaboration. Alongside this, encouraging knowledge exchange, capacity-building initiatives, and pilot projects can help stakeholders evaluate the effectiveness of this approach in tackling pollution and promoting cooperation, ultimately advancing sustainable wastewater management practices.

4.16 Summary of Results

1. Wastewater Volume and Electrical Consumption:

- Total treated wastewater ranged from 45,956,000 to 63,840,000 cubic meters.
- Electrical consumption varied from 2,551,000 to 3,273,000 kilowatt-hours.
- Fluctuations were observed, with peaks in electrical consumption during certain months.

2. Gas Production and Renewable Energy Generation:

- Gas production averaged between 1,365 and 2,127 normal cubic meters per day.
- Renewable energy generation ranged from 123,814 to 191,122 kilowatt-hours.
- Combined Heat and Power (CHP) electrical production varied monthly but consistently contributed to electricity generation.

4. Regression Analysis:

- Multiple linear regression model assessed the impact of gas production and renewable energy generation on electrical consumption, revealing significant predictors.

5. Percentage Contribution of CHP Electricity:

- CHP electricity contributed significantly to total consumption, varying from approximately 19.54% to 66.13% across the years.

6. Total Electrical Consumption and Operating Costs:

- Total electrical consumption over five years was 10,184,464 kWh.
- Operating costs varied depending on the energy source, with PV electricity offering the lowest cost per cubic meter of wastewater treated.

Cost-Benefit Analysis:

- No Action Alternative:
  - Capital Cost: Approximately 281,400,000 NIS.
  - Running Cost: Operating cost of approximately 1.89 NIS per cubic meter.
- Action Alternative (CHP generators for energy production from biogas):
  - Capital Cost: Includes the construction cost of the WWTP plus an additional 9,802,000 NIS.
  - Running Cost: Operating cost of approximately 4.12 NIS per cubic meter.
- Comparison:
  - Minimal disparity in capital costs; lower operating costs in the No Action Alternative.

Positive Impacts:

- Environmental Benefits:
  - Reduced Greenhouse Gas Emissions.
  - Water Quality Enhancement.
  - Groundwater Protection.
  - Improved Waste Management Practices.
- Agricultural Impact:
  - Improved Crop Quality.
  - Sustainable Agricultural Practices.
- Energy and Resilience:

    - Diversified Energy Mix.
    - Health and Well-being.
- Socio-Economic Impact:
    - Economic Opportunities.
    - Water Management.

Assessment of Environmental Impact:

- Greenhouse Gas Emissions: Sludge-to-energy conversion mitigates emissions by capturing methane.
- Soil and Water Contamination Risks: Pre-treatment reduces contamination risks.
- Air Pollution: Controlled processes minimize air pollution.

Comparison of Economic and Environmental Costs:

- Sludge-to-energy conversion offers economic benefits through energy generation and resource recovery.
- Traditional methods impose significant economic and environmental burdens, while sludge-to-energy conversion promotes sustainability and pollution mitigation.

In conclusion, the implementation of sludge-to-energy conversion at the West Nablus WWTP offers a comprehensive solution to the challenges of transboundary pollution and wastewater management. It reduces financial burden, promotes environmental sustainability, and contributes to achieving sustainable development goals.

Chapter Five:

Conclusion Remarks:

5.1 Recommendations

Based on the research objectives and findings, the following recommendations are proposed:

1. **Investment in Sludge-to-Energy Infrastructure:** Governments and relevant stakeholders should prioritize investments in sludge-to-energy infrastructure, including anaerobic digestion facilities and combined heat and power (CHP) generators. These investments should focus on enhancing the efficiency and capacity of wastewater treatment plants to convert sludge into renewable energy.

2. **Policy Support and Incentives:** Policymakers should develop supportive regulatory frameworks and provide financial incentives to encourage the adoption of sludge-to-energy technologies. This may include subsidies, tax incentives, and grants to offset initial capital costs and promote the economic viability of sludge-to-energy projects.

3. **Capacity Building and Knowledge Transfer**: Capacity-building initiatives should be implemented to enhance the technical expertise of wastewater treatment plant operators and personnel involved in sludge-to-energy conversion. Training programs, workshops, and knowledge-sharing platforms can facilitate the dissemination of best practices and innovative technologies in sludge management and renewable energy production.

4. **Cross-Border Collaboration:** Given the transboundary nature of wastewater management challenges, cross-border collaboration and cooperation between neighboring countries are essential. Governments should engage in dialogue, information sharing, and joint initiatives to address common environmental concerns, promote resource sharing, and enhance regional resilience in wastewater management.

5. **Public Awareness and Engagement**: Efforts should be made to raise public awareness about the environmental and socio-economic benefits of sludge-to-energy conversion.

Public education campaigns, community outreach programs, and stakeholder consultations can empower local communities to actively participate in and support sustainable waste management practices.

6. **Research and Innovation:** Continued research and innovation are critical for advancing sludge-to-energy technologies and overcoming technical challenges. Funding should be allocated to research institutions, universities, and technology developers to drive innovation, improve process efficiency, and develop cost-effective solutions for sludge management and energy production.

7. **Involving the private sector in sludge-to-energy projects**: it is essential to enhance these initiatives' financial viability, technological innovation, and operational efficiency. Private companies can provide the necessary capital investment, advanced technologies, and expertise required for large-scale implementation. Their involvement can lead to more efficient project management, cost control, and market development, ultimately contributing to the successful commercialization and scalability of sludge-to-energy solutions. Encouraging public-private partnerships can leverage the strengths of both sectors, ensuring long-term sustainability and significant environmental benefits.

5.2 Conclusion

In conclusion, this research has provided valuable insights into the feasibility and potential benefits of implementing sludge-to-energy conversion technologies in wastewater treatment practices, particularly in the context of the West Bank region. Through analysis and evaluation, it has been revealed that biogas production from sludge holds significant promise as a renewable energy source for electricity generation. Despite the initial investment costs associated with sludge-to-energy infrastructure, the long-term benefits, including reduced operational expenses, environmental remediation savings, and socio-economic development opportunities, outweigh these upfront investments. Moreover, supportive policy frameworks, incentives, and cross-border collaboration are essential in facilitating the adoption of sludge-to-energy technologies. Moving forward, it is recommended that stakeholders prioritize investment in infrastructure, implement supportive policies, engage in capacity-building initiatives, foster cross-border collaboration, conduct public awareness campaigns, and continue research and innovation efforts. By following these recommendations, governments, policymakers, and stakeholders can drive the transition towards more sustainable waste management practices, ultimately contributing to the achievement of sustainable development goals and the creation of a more resilient future.

References:

Abusharbak, N., & Al-Sa'ed, R. (2000). *Development of Wastewater Treatment Tariff System: A Case Study of Al-Bireh Wastewater Treatment Plant*. Master Thesis, Birzeit University.

Alary, R., Fattah, A., Hasan, R., & Alimari, A. (2019). *Performance Assessment of Hybrid Constructed Wetlands for Wastewater Treatment in The West Bank*. PhD Thesis, Al-Najah University.

Al-Joulani, N. M. A. (2019). Effect of using tertiary treated wastewater from nablus wastewater treatment plant (NWWTP), on some properties of concrete. *International Journal of Innovative Technology and Exploring Engineering (IJITEE), ISSN*, 2278–3075.

Alonso, A. C., van Maren, D. S., Albert, P. O., Esselink, P., Hagen, R., Kösters, F., Bartholdy, J., Bijleveld, A., & Wang, Z. B. (2023). *A cross-border mud budget for future sediment management*.

Al-Sa' ed, R. (2010). A policy framework for trans-boundary wastewater issues along the Green Line, the Israeli–Palestinian border. *International Journal of Environmental Studies*, *67*(6), 937–954.

Al-Sa'ed, R., & Al-Hindi, A. (2012). *Challenges of transboundary wastewater management for Palestinian communities along the Green Line, the Israeli-Palestinian border*. CRC Press, Taylor & Francis Group.

Al-Saidi, M., Al Manji, S., Ayoub, J., Fuad, |, Muna, B. |, Rebhy, D. |, Sheikh, E., Musa, S. El, Mohammed, |, Zeinab Shuker, M. |, & Zawahri, N. (2024). *Troubled Waters in Conflict and a Changing Climate: Transboundary Basins Across the Middle East and North Africa Marwa Daoudy, editor*.

Atawneh, H. A. (2020). *Impact of Geopolitical Factors on Water Supply Management in Area C, South of Palestine*. Master Thesis, Al-Quds University.

Attili, O. A., & Alsàed, R. M. (2020). *Efficacy of Natural Wetlands along Wadi Zomer as a Sustainable Phytoremediation Alternative for Industrial Effluents from Nablus West, Palestine*. https://doi.org/10.20944/preprints202012.0816.v1

Bacenetti, J., Fusi, A., & Azapagic, A. (2019). Environmental sustainability of integrating the organic Rankin cycle with anaerobic digestion and combined heat and power generation. *Science of the Total Environment*, *658*, 684–696.

Escap, U. N. (2013). *Water security & the global water agenda: A UN-water analytical brief*. United Nations University (UNU).

Brooks, D. B., Trottier, J., & Giordano, G. (2011). *Transboundary Water Issues in Israel, Palestine, and the Jordan River Basin*. http://www.springer.com/series/11889

Buge, Antoine, (2023) Palestine water sector and reforms-AFD. https://www.pseau.org/outils/ouvrages/ps_eau_rencontre_du_reseau_palestine_2023_presentation_afd_2023.pdf

Büttner, O., Jawitz, J. W., Birk, S., & Borchardt, D. (2022). Why wastewater treatment fails to protect stream ecosystems in Europe. *Water Research*, *217*, 118382.

Capodaglio, A. G., & Olsson, G. (2019). Energy issues in sustainable urban wastewater management: Use, demand reduction and recovery in the urban water cycle. *Sustainability*, *12*(1), 266.

Castellanos, H. G., Aryanfar, Y., Keçebaş, A., Assad, M. E. H., Islam, S., Naveed, Q. N., & Lasisi, A. (2024). A new paradigm for mining energy from industrial sludge: A low-cost fuel. *Journal of Water Process Engineering*, *59*, 104987.

Chrispim, M. C., Scholz, M., & Nolasco, M. A. (2019). Phosphorus recovery from municipal wastewater treatment: Critical review of challenges and opportunities for developing countries. *Journal of Environmental Management*, *248*, 109268.

Commission for Western Asia, S. (2017). *Developing the Capacity of ESCWA Member Countries to Address the Water and Energy Nexus for Achieving Sustainable Development Goals Water-Energy Nexus Operational Toolkit Resource Efficiency Module Economic and Social Commission for Western Asia*. www.unescwa.org

Cremonez, P. A., Teleken, J. G., Weiser Meier, T. R., & Alves, H. J. (2021). Two-Stage anaerobic digestion in agroindustrial waste treatment: A review. *Journal of Environmental Management*, *281*, 111854. https://doi.org/https://doi.org/10.1016/j.jenvman.2020.111854

Dai, L. (2021). Implementation constraints on Israel–Palestine water cooperation: An analysis using the water governance assessment framework. *Water*, *13*(5), 620.

Delibacak, S., Voronina, L., & Morachevskaya, E. (2020). Use of sewage sludge in agricultural soils: Useful or harmful. *Eurasian Journal of Soil Science*, *9*(2), 126–139.

Di Fraia, S., Massarotti, N., Uddin, M. R., & Vanoli, L. (2022). Conversion of Sewage Sludge to combined heat and power: Modeling and optimization. *Smart Energy*, *5*. https://doi.org/10.1016/j.segy.2021.100061

Dregulo, A. M., & Bobylev, N. G. (2021). Integrated assessment of groundwater pollution from the landfill of sewage sludge. *Journal of Ecological Engineering*, *22*(1), 68–75.

Jazi, D. A., Takrouri, R. K., Mineh, S. R. F. B., & Hamadneh, S. M. (2022). Removal of H2S from biogas by activated carbon: Nablus Western Wastewater Treatment Plant as a Case Study. Graduation Project, Al Najah University.

EIB Advisory Services. (2017). *Feasibility Study For North East Ramallah Villages Wastewater Collection And Treatment System*.

Fresquez, P. R., Francis, R. E., & Dennis, G. L. (1990). *Sewage sludge effects on soil and plant quality in a degraded, semiarid grassland*. Wiley Online Library.

Gao, N., Kamran, K., Quan, C., & Williams, P. T. (2020). Thermochemical conversion of sewage sludge: A critical review. *Progress in Energy and Combustion Science*, *79*, 100843.

Yerousis, G. P. (2011). *Technical and economic feasibility of biosolids-amended brick production* (Doctoral dissertation, M. Sc. Thesis, Birzeit University, Palestine).

Georgeson, L., Maslin, M., Poessinouw, M., & Howard, S. (2016). Adaptation responses to climate change differ between global megacities. *Nature Climate Change*, *6*(6), 584–588. https://doi.org/10.1038/nclimate2944

Masters, G. M. (2013). *Renewable and efficient electric power systems*. John Wiley & Sons.

Godoi, A. F. L., Grasel, A. M., Polezer, G., Brown, A., Potgieter-Vermaak, S., Scremim, D. C., Yamamoto, C. I., & Godoi, R. H. M. (2018). Human exposure to hydrogen sulphide concentrations near wastewater treatment plants. *Science of the Total Environment*, *610*, 583–590.

Goh, P. S., Wong, K. C., & Ismail, A. F. (2022). Membrane technology: A versatile tool for saline wastewater treatment and resource recovery. *Desalination*, *521*, 115377.

Guo, S., Zhou, X., Simha, P., Mercado, L. F. P., Lv, Y., & Li, Z. (2021). Poor awareness and attitudes to sanitation servicing can impede China’s Rural Toilet Revolution: Evidence from Western China. *Science of the Total Environment, 794,* 148660.

House of Water & Environment. (2012). *Understanding and Analyzing the Current Israeli Wastewater. Practices for Transboundary Wastewater Management from Palestinian*. Report, https://procurement-notices.undp.org/view_file.cfm?doc_id=27195

Hák, T., Janoušková, S., & Moldan, B. (2016). Sustainable Development Goals: A need for relevant indicators. *Ecological Indicators*, *60*, 565–573. https://doi.org/10.1016/j.ecolind.2015.08.003

Hao, X., Chen, Q., van Loosdrecht, M. C. M., Li, J., & Jiang, H. (2020). Sustainable disposal of excess sludge: Incineration without anaerobic digestion. *Water Research*, *170*, 115298.

Hareuveni, E. (2009). *Foul Play Neglect of Wastewater Treatment in the West Bank B’TSELEM-The Israeli Information Center for Human Rights in the Occupied Territories*. www.btselem.org•mail@btselem.org

Hasan, A. R., Hussein, M. A., Jafar, H. A., & Hussein, A. I. A. (2021). Septage Characterization and Sustainable Fecal Sludge Management in Rural Nablus–Palestine. *Sustainable Solutions for Environmental Pollution: Waste Management and Value-Added Products*, *1*, 375–416.

Hellegers, P. (2023). *WASTEWATER WITHOUT BORDERS A socio-technical investigation of the management of transboundary olive oil wastewater pollution in Wadi Zomer area, West Bank, Palestine*.

Hu, G., Feng, H., He, P., Li, J., Hewage, K., & Sadiq, R. (2020). Comparative life-cycle assessment of traditional and emerging oily sludge treatment approaches. *Journal of Cleaner Production*, *251*, 119594. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.119594

Jimenez, J., Lei, H., Steyer, J.-P., HOUOT, S., & Patureau, D. (2017). Methane production and fertilizing value of organic waste: Organic matter characterization for a better prediction of valorization pathways. *Bioresource Technology*, *241*. https://doi.org/10.1016/j.biortech.2017.05.176

Jovarauskaitė, L., & Balundė, A. (2021). A Systematic Review of Drivers of Sustainable Wastewater Treatment Technology Adoption. *Sustainability*, *13*(15), 8584.

Lalawmpuii, & Rai, P. K. (2023). Role of water-energy-food nexus in environmental management and climate action. In *Energy Nexus* (Vol. 11). Elsevier Ltd. https://doi.org/10.1016/j.nexus.2023.100230

Larsen, T. A., Hoffmann, S., Lüthi, C., Truffer, B., & Maurer, M. (2016). Emerging solutions to the water challenges of an urbanizing world. *Science*, *352*(6288), 928–933.

Lavee, D. (2014). Is the Upgrading of Wastewater Treatment Facilities to Meet More Stringent Standards Economically Justified: The Case of Israel. *Water Resources*, *41*, 564–573. https://doi.org/10.1134/S0097807814050042

Loch, R. J., Costantini, A., Barry, G. A., & Best, E. K. (1995). Evaluation of the potential to dispose of sewage-sludge. 2. Potential for off-site movements of solids and solutes. *Soil Research*, *33*(6), 1053-1062.

Lipchin, C. (2013). *Transboundary Management of the Hebron/Besor Watershed in Israel and the Palestinian Authority*.

Man, R. D. (2016). *Transboundary wastewater governance-Options based on an uncertainty perspective Transboundary wastewater governance-Options based on an uncertainty perspective Acknowledgements About The Hague Institute for Global Justice About The Hague Institute Working Paper Series*.

Marks, D., Miller, M. A., & Vassanadumrongdee, S. (2020). The geopolitical economy of Thailand's marine plastic pollution crisis. *Asia Pacific Viewpoint*, *61*(2), 266–282.

Mays Shadeed, B., Taradi, M., Abu ali, H., EL-Hamouz, A., Ellari, Y., & Baniodeh, N. (2017). *The Potential of Utilizing the Sewage Sludge Produced from Nablus West Wastewater Treatment Plant as an Energy Source and or a Fertilizer*.

Mechaliz. (2019). *Effluent Recovery and Reuse System and Remediation works*. Report, https://environment.ps/wp-content/uploads/2022/06/f1.pdf

Mills, N., Pearce, P., Farrow, J., Thorpe, R. B., & Kirkby, N. F. (2014). Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. *Waste Management*, *34*(1), 185–195. https://doi.org/10.1016/j.wasman.2013.08.024

Murrar, A., Paz, V., Batra, M., & Yerger, D. (2024). Perceived customer value and willingness to pay: strategies for improving and sustaining water service quality. *The TQM Journal*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/TQM-07-2023-0218

Nabaterega, R., Kumar, V., Khoei, S., & Eskicioglu, C. (2021). A review on two-stage anaerobic digestion options for optimizing municipal wastewater sludge treatment process. *Journal of Environmental Chemical Engineering*, *9*(4), 105502. https://doi.org/https://doi.org/10.1016/j.jece.2021.105502

Nash, K. L., Blythe, J. L., Cvitanovic, C., Fulton, E. A., Halpern, B. S., Milner-Gulland, E. J., Addison, P. F. E., Pecl, G. T., Watson, R. A., & Blanchard, J. L. (2020). To Achieve a Sustainable Blue Future, Progress Assessments Must Include Interdependencies between the Sustainable Development Goals. *One Earth*, *2*(2), 161–173. https://doi.org/10.1016/j.oneear.2020.01.008

Nassar, A. (2015). Strategies of sludge management in the Gaza Strip. *J. Sci. Res. Rep*, 419–426.

Palestinian Central Bureau of Statistics. (2021a). *Palestine in Figures 2020*. http://www.pcbs.gov.ps

Palestinian Central Bureau of Statistics. (2021b). *Performance of the Palestinian Economy*.

Palestinian Water Authority. (2013). *Annual Water Resources Status Report*.

Palestinian Water Authority. (2019). *Annual Water Resources Executive Summary Report*.

Palestinian Water Authority. (2022). *Annual Water Resources Status Report*.

Palestinian Water Authority (PWA). (2013). *Transboundary Water Resources Strategy*.

Palestinian Water Authority (PWA). (2024). *Transboundary Water Resources Strategy*.

Petroody, S. S. A., Hashemi, S. H., & van Gestel, C. A. M. (2021). Transport and accumulation of microplastics through wastewater treatment sludge processes. *Chemosphere*, *278*, 130471.

Rao Meda, S., Kumar Sharma, S., & Tyagi, G. D. (2021). Utilization of Waste Sludge as a Construction Material -A Review. *Materials Today: Proceedings*, *46*, 4195– 4202. https://doi.org/https://doi.org/10.1016/j.matpr.2021.02.762

Mohammad Sobhe Samha, Jawad Hasan Shoqeir (2024). Special Distribution of Pharmaceutical Residue from Wastewater Treatment Plant (WWTP), Master thesis, Al Quds University.

Salem, H. S., Yihdego, Y., & Hamaaziz Muhammed, H. (2021). The status of freshwater and reused treated wastewater for agricultural irrigation in the Occupied Palestinian Territories. *Journal of Water and Health*, *19*(1), 120–158. https://doi.org/10.2166/WH.2020.216

Sallam, M., Yaseen, A., Refai, L., & El-Qanni, A. (2024). Conceptual Feasibility of a Portable Containerized and Decentralized Wastewater Treatment System for Rural Regions: A Case Study in Palestine. *An-Najah University Journal for Research - A (Natural Sciences)*, *38*(1), 42–47. https://doi.org/10.35552/anujr.a.38.1.2149

Sathya, R., Arasu, M. V., Al-Dhabi, N. A., Vijayaraghavan, P., Ilavenil, S., & Rejiniemon, T. S. (2023). Towards sustainable wastewater treatment by biological methods–A challenges and advantages of recent technologies. *Urban Climate*, *47*, 101378.

Scoullos, M., Malotidi, • V, Spirou, • S, & Constantianos, • V. (2002). *Integrated Water Resources Management in the Mediterranean*. www.mio-ecsde.org

Sharifi, A., & Simangan, D. (2021). Environmental sustainability: the missing pillar of positive peace. *The Palgrave Handbook of Positive Peace*, 1–19.

Sharma, M., Yadav, A., Mandal, M. K., Pandey, S., Pal, S., Chaudhuri, H., Chakrabarti, S., & Dubey, K. K. (2022). Chapter 7 - Wastewater treatment and sludge management strategies for environmental sustainability. In A. Stefanakis & I. Nikolaou (Eds.), *Circular Economy and Sustainability* (pp. 97–112). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-821664-4.00027-3

Singh, S., Hariteja, N., Prasad, T. J. R., Raju, N. J., & Ramakrishna, C. (2020). Impact assessment of faecal sludge on groundwater and river water quality in Lucknow environs, Uttar Pradesh, India. *Groundwater for Sustainable Development*, *11*, 100461.

Singh, S., Kumar, V., Dhanjal, D. S., Datta, S., Bhatia, D., Dhiman, J., Samuel, J., Prasad, R., & Singh, J. (2020). A sustainable paradigm of sewage sludge biochar: valorization, opportunities, challenges and future prospects. *Journal of Cleaner Production*, *269*, 122259.

Soares, A. (2020). Wastewater treatment in 2050: Challenges ahead and future vision in a European context. *Environmental Science and Ecotechnology*, *2*, 100030.

Spatolisano, E., De Guido, G., Pellegrini, L. A., Calemma, V., de Angelis, A. R., & Nali, M. (2022). Process sensitivity analysis and techno-economic assessment of hydrogen sulphide to hydrogen via H2S methane reformation. *Journal of Cleaner Production*, *330*, 129889.

Stamatopoulou-Robbins, S. C. (2021). Failure to build: Sewage and the choppy temporality of infrastructure in Palestine. *Environment and Planning E: Nature and Space*, *4*(1), 28–42.

Taha, M., & Al-Sa’ed, R. (2017). Potential application of renewable energy sources at urban wastewater treatment facilities in Palestine – three case studies. *Desalination and Water Treatment*, *94*, 64–71. https://doi.org/10.5004/dwt.2017.21591

Tal, A., Al Khateeb, N., Asaf, L., Assi, A., Nassar, A., Sadah, M. A., Gasith, A., Laronne, J., Hirshkowitz, Y., Halawani, D., Nagouker, N., Angel, R., Akerman, H., Abramson, A., & Diabat, M. (2010). *Monitoring Transboundary Palestinian-Israeli Streams: Implications for Cooperative Management Strategies*, Report. https://arava.org/wp-content/uploads/2013/05/MERC_final_streams-report.pdf

The World Bank. (2009). *WEST BANK AND GAZA ASSESSMENT OF RESTRICTIONS ON PALESTINIAN WATER SECTOR DEVELOPMENT Middle East and North Africa Region Sustainable Development The World Bank*. www.worldbank.org , https://documents1.worldbank.org/curated/en/775491468139782240/pdf/476570SR0P11511nsReport18Apr2009111.pdf

Um, N., Soo Park, Y., Kang, Y.-Y., & Jeon, T.-W. (2022). *Improved strategy for effective management system on transboundary movement of wastes*. Available at SSRN: https://ssrn.com/abstract=4119756 or http://dx.doi.org/10.2139/ssrn.4119756

UNDP. (2020). *Transboundary Wastewater Pollution Control Project*. https://erc.undp.org/evaluation/evaluations/detail/11139

UNDP. (2024). *What are the Sustainable Development Goals? https://www.undp.org/sustainable-development-goals*

USAID Infrastructure Needs Program II. (2012). *Packaged Wastewater Treatment Plants Feasibility Study*.

Varady, R. G., Albrecht, T. R., Modak, S., Wilder, M. O., & Gerlak, A. K. (2023). Transboundary Water Governance Scholarship: A Critical Review. *Environments*, *10*(2), 27.

Water, P. (2012). *National Water Strategy for Palestine Toward Building a Palestinian State from Water Perspective*.

Water, P. (2013). *National Water Policy and Strategy-Full report + Annexes-version 12 30/06/2013 1 National Water and Wastewater Strategy for Palestine Toward Building a Palestinian State from Water Perspective*.

West, N., Suleiman, E., Ghosh, A., Yousef, E., Jaffal, A., Mohammad, E., Rola, H., Salama, A., & Sameh Bitar, M. (2021). *Wastewater Treatment Plant*. https://wwtp.nablus.org/wp-content/uploads/2024/03/Final-2021-report.pdf

West, N., & Yousef Abu Jaffal, S. B. ,Eng M. H. E. O. R. A. S. E. (2022). *Wastewater Treatment Plant*. https://wwtp.nablus.org/wp-content/uploads/2023/06/annual-report-2022-1.pdf

Whiting, A., & Azapagic, A. (2014). Life cycle environmental impacts of generating electricity and heat from biogas produced by anaerobic digestion. *Energy*, *70*, 181–193. https://doi.org/10.1016/j.energy.2014.03.103

World Bank, W. DC. (2018). *Securing Water for Development in West Bank and Gaza*. www.worldbank.org/water

Xiao, S., Dong, H., Geng, Y., Tian, X., Liu, C., & Li, H. (2020). Policy impacts on Municipal Solid Waste management in Shanghai: A system dynamics model analysis. *Journal of Cleaner Production*, *262,* 121366.

Yaqob, E. Y., Alsàed, R., Sorial, G., & Sudian, M. (2014). Situation Analysis and Perspectives of Transboundary Wastewater Management Along Israel/Palestine borders. In *Asian Journal of Applied Science and Engineering* (Vol. 3, Issue 2).

Yaqob, E. Y., Suidan, M., Kupferle, M., & Saleh, H. (2016). *"Prospects for a Shared Management of Transboundary Wastewater: Israel-Palestine Case."*

Yasin, A. (2022). *PWA , Data Bank 2022.* Ramallah: Eng. Adel Yasin.

Zhang, Z., & Chen, Y. (2020). Effects of microplastics on wastewater and sewage sludge treatment and their removal: A review. *Chemical Engineering Journal*, *382*, 122955. https://doi.org/https://doi.org/10.1016/j.cej.2019.122955

تقييم التلوث بالحمأة العابرة للحدود وتحويله إلى طاقة
دراسة حالة: محطة غرب نابلس لمعالجة مياه الصرف الصحي

اعداد: ايمان عمر مرشد منصور

اشراف: ا.د. جواد شقير و د. حسين السمامرة

الملخص

تستكشف هذه الأطروحة إمكانية تحويل الحمأة إلى طاقة لمعالجة التلوث العابر للحدود في منطقة الضفة الغربية، مع اعتماد محطة معالجة مياه الصرف الصحي في غرب نابلس كدراسة حالة. وتدرس مدى فعالية هذا النهج في التخفيف من التلوث البيئي وتعزيز الاستدامة. وعلى وجه التحديد، تبحث الدراسة تأثير تحويل الحمأة إلى طاقة على تكاليف المعالجة لكل متر مكعب من مياه الصرف الصحي وتقيم إنتاج الطاقة لكل وحدة من الحمأة المتولدة. من خلال التحليل الشامل، بما في ذلك تقييم التكلفة والفوائد وتقييم الأثر البيئي، يقدم البحث رؤى قيمة حول جدوى وفوائد حل الطاقة المتجددة هذا. وتؤكد النتائج على إمكانات توليد الطاقة الكبيرة من كل من محطات معالجة مياه الصرف الصحي المحلية وسكان الضفة الغربية الأوسع. إنتاج الحمأة. ومن خلال الاستثمار في تحويل الحمأة إلى طاقة، يمكن استخدام هذه الموارد لمعالجة مشكلة الطاقة في فلسطين مع تخفيف الأعباء البيئية والمالية المرتبطة بالتلوث العابر للحدود. ومن خلال تعزيز ممارسات إدارة النفايات المستدامة واستخدام الطاقة المتجددة، يساهم البحث في تعزيز الاستدامة البيئية ومعالجة التحديات البيئية العابرة للحدود، مما يعود بالنفع في نهاية المطاف على جميع أصحاب المصلحة. وتؤكد البيانات المستمدة من عمليات معالجة الحمأة في محطة معالجة مياه الصرف الصحي غرب نابلس والأرقام المتوقعة لجميع سكان الضفة الغربية على الإنتاج الكبير للطاقة وإمكانية توفير التكاليف الكامنة في تحويل الحمأة إلى طاقة. في محطة معالجة مياه الصرف الصحي غرب نابلس وحدها، بمعدل إنتاج الحمأة 6,600 كجم/يوم، وإنتاج الميثان 1,320 متر مكعب/يوم، وإنتاج الطاقة 3,938.32 كيلووات ساعة/يوم. وباستقراء هذه الأرقام لجميع سكان الضفة الغربية، حيث يصل معدل إنتاج الحمأة إلى 14,400,000 كجم/يوم، ويبلغ إنتاج الميثان 2,880,000 متر مكعب/يوم، ويصل إنتاج الطاقة إلى 8,588,761.60 كيلوواط ساعة/يوم. تسلط هذه المقارنة الضوء على قابلية التوسع وكفاءة تحويل الحمأة إلى طاقة، مع فوائد كبيرة على مستوى محطات معالجة مياه الصرف الصحي الفردية وعلى نطاق أوسع عبر جميع السكان. تسلط الدراسة الضوء على الفوائد الكبيرة لتحويل الحمأة إلى طاقة لمعالجة التلوث البيئي وتعزيز التنمية المستدامة في المناطق المتضررة من تلوث الحمأة العابر للحدود. ويكشف التحليل الشامل عن انخفاض انبعاثات الغازات الدفيئة، وتوفير كبير في تكاليف عمليات معالجة مياه الصرف الصحي، وزيادة كفاءة إنتاج الطاقة. تدعم هذه النتائج الاعتماد الواسع النطاق لتقنيات تحويل الحمأة إلى طاقة في مرافق معالجة مياه الصرف الصحي لتعزيز الاستدامة البيئية والكفاءة الاقتصادية.