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Circular Economy in the Water and Wastewater Sector:

Possibilities for the local production and sale of biogas and biochar to finance municipal treatment plant's operation and maintenance costs and enhance sustainability

Sirkulær økonomi i vann- og avløpssektoren:
Muligheter for lokal produksjon og salg av biogass og biokull for å finansiere kommunalt renseanleggs drifts- og vedlikeholdskostnader og styrke bærekraften

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Specialization: Circular engineering

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MASTER'S THESIS

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"*Our precious treasure, the true self, is hidden in ourselves but can only be retrieved when consciousness is at rest" (Paul Brunton, 1935, "The Secret Path")*.

There has always been a "transparent door" quietly open to protect our planet, but only a few conscious minds were aware of it and inspired to investigate it. It is now time for everyone to go through it. Everyone must follow the path of "directed thought and feeling" to find this entrance that will soothe our environmental awareness. The circular economy's vision and mission today are to create "green incentives" that will allow everyone to move quickly through the "ecological transition door" and achieve the goal of sustainability as defined at its origin. Now is the time for industry players to begin adapting and pooling their resources by "thinking circular" in order to capitalize on the circular economy's future values. We will have answers to the majority of environmental problems that plague us every year once we cross the threshold of the circular economy through the proper use of resources that are currently wasted. We will finally be free of restless desires, uncontrolled environmentally unfriendly thoughts, rash economic actions, and unnecessary material needs when we have completed our journey into the "circular mentality," which was once a "hidden path" in favor of planned obsolescence. Although the effort required may appear to be significant, the rewards will far outweigh the effort. We will regain control of ourselves once we regain "consciousness rest," and this will eventually seep into our daily lives and be felt in all of our actions. This will encourage us to buy sustainably, use wisely, create incentives for less material waste, and sort correctly at the source. As a result, the 3R drivers of the circular economy are being promoted (reduce, reuse, and recycle). Nothing can stop the forces of a circular economy from working without our latent doubts, as the outcome of this cognitive exercise can be scientifically proven. So, let us take what was once a "secret path" for many minds and capitalize on what is already ours in the cycle (Kadibu, 2021).

Exploiting the opportunities offered by local primary and secondary raw materials reduces exaggerated desire and demand for other nations' natural resources, lowering the risk of unnecessary conflicts. I would like to take advantage of this opportunity to dedicate this master's thesis to all the innocent children who are suffering in the eastern Democratic Republic of the Congo (DRC) because of the ongoing conflict over natural resources, while omnipotent instances and nations remain silent on their rights. My modest contribution to the fight for a greener planet is the result of my work, which I hope to pass down to future generations.

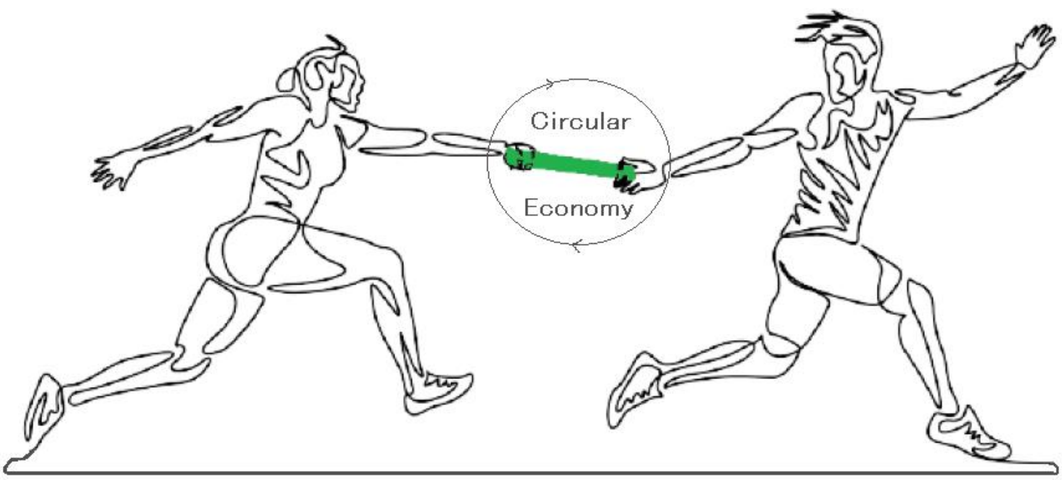


Illustration source: Tresor Kadibu, 2021

PREFACE

This project concludes my Master of Science in Water and Environmental Technology, concentrating in Circular Engineering, at the Faculty of Science and Technology (REALTEK), Norwegian University of Life Sciences (NMBU - campus S) in 2023. This degree leads to the protected title of Civil Engineer in Norway.

This thesis, written in collaboration with the following Lier Municipality's enterprises: Lier Road, Water, and Wastewater (Lier VVA KF), 3. The supervision for decentralized wastewater treatment systems or Supervision Office (“Tilsynet for små avløpsanlegg or Tilsynskontoret), and the Agricultural Office (Landbrukskontoret). The thesis aims to investigate various requirements and limitations, as well as potential effective solutions, for exploiting sludge as a resource from treatment plants.

The theme "Possibilities for the local production and sale of biogas and biochar to finance municipal treatment plant's operation and maintenance costs and enhance sustainability" is broad and complex, with many different solutions depending on various factors such as existing treatment plant technology, financing options, collected sludge quantity, treatment methods, end-product consumption areas, stakeholders' incentives, and legislative action space. This justifies the wide scope and length of this paper.

The expectation of Lier Municipality is to acquire an overall picture of the current situation for exploiting sludge resources and the potential to produce economic advantages for the community. Furthermore, to identify critical criteria and indicators that a producer of sludge-derived biogas and biochar should implement and monitor to meet circular economy requirements in the appropriate sectors. I chose this topic due to its alignment with my previous master's thesis on the circular economy of construction site packaging, as well as my curiosity in gaining a deeper insight into the waste world, specifically sludge, and potential business. This was achieved by examining the lifecycle of sludge and the ability to optimize its value while contributing to sustainable solutions in light of climate change, which presents waste management challenges.

Throughout this task, I gained greatly from in-depth studies in numerous subjects, ranging from water pollution to supply chain management and organizational changes. My personal experience as a division engineer working with decentralized wastewater treatment systems, aware of various challenges and alternative solutions for sludge handling, makes my master’s project distinctive. This experience, together with the inputs of colleagues and industry actors via interviews and field observations, confirmed the findings of this thesis, making it reliable.

As a trained water and environmental civil engineer, innovative business developer, and construction engineer, this master’s thesis offers me an exhaustive overview of multidisciplinary work with environmentally oriented projects. Given the tendency toward considering environmental perspectives in the growth of the water and wastewater sectors, investing in the circular economy is critical to meeting the Paris Agreement's goals.

I would like to thank everyone who helped me with this master’s thesis. Your involvement and insightful feedback profoundly influenced the result of this study. Special thanks to several colleagues, with particular gratitude to Ina Elisabeth Rasmussen (Tilsynskontoret), Nina Alstad Rukke (Tilsynskontoret), Obed Otto Lopes Schacht (Lier VVA KF), Janne Ruud Lykke (Lier VVA KF), Gry Løberg (Landbrukskontoret), and Jessica M. Kadibu (My lovely young sister).

Finally, I want to express my gratitude to my main supervisor, Nazli Pelin Kocatürk Schumacher, Associate Professor at NMBU, and co-supervisor, John Morken, Professor at NMBU, for providing guidance.

Tresor Ngalasele Kadibu　　　　Oslo, 15.07.2023

ABSTRACT - English

This thesis aims to investigate the possibility of optimizing the sludge treatment process in a municipal wastewater treatment plant to produce biogas and biochar from bioresidues. The objective is to maximize the sales of these products to finance the operating and maintenance costs of the treatment plant or reduce the energy bill. The study involves a detailed review of literature and interviews to identify the best practices in sludge treatment and the potential for biogas and biochar production. Furthermore, the thesis considers the economic and environmental benefits of producing biogas and biochar, including their potential as renewable energy sources and soil amendments. The study also evaluates the feasibility of locally using the produced biogas and biochar, including the availability of local markets and the infrastructure required for transportation and distribution. Ultimately, this document provides a comprehensive picture of sludge as an important resource from a municipal water and wastewater treatment plant in terms of sustainability and economic viability.

SAMMENDRAG - Norsk

Denne masteroppgaven tar sikte på å undersøke muligheten for å optimalisere slambehandlingsprosessen i et kommunalt avløpsrenseanlegg for å produsere biogass og biokull fra biorester. Målet er å maksimere salget av disse produktene for å finansiere drifts- og vedlikeholdskostnadene til renseanlegget eller redusere energiregningen. Studien omfatter en detaljert gjennomgang av litteratur og intervjuer for å identifisere beste praksis innen slambehandling og potensialet for produksjon av biogass og biokull. Videre vurderer oppgaven de økonomiske og miljømessige fordelene ved å produsere biogass og biokull, inkludert potensialet som fornybar energikilde og jordforbedring. Studien evaluerer også muligheten for å bruke den produserte biogassen og biokullet lokalt, inkludert tilgjengeligheten av lokale markeder og infrastrukturen som kreves for transport og distribusjon. Til syvende og sist gir denne masteroppgaven et omfattende bilde av slam som en viktig ressurs fra et kommunalt vann- og avløpsrenseanlegg når det gjelder bærekraft og økonomisk levedyktighet.

RÉSUMÉ - Français

Cette thèse vise à étudier la possibilité d'optimiser le processus de traitement des boues dans une station d'épuration municipale afin de produire du biogaz et du biochar (charbon biologique) à partir des bio-résidus. L'objectif est de maximiser les ventes de ces produits afin de financer les coûts d'exploitation et de maintenance de la station d'épuration ou de réduire la facture énergétique. L'étude comprend une revue détaillée de la littérature et des entretiens afin d'identifier les meilleures pratiques en matière de traitement des boues et le potentiel de production de biogaz et de biochar. En outre, la thèse examine les avantages économiques et environnementaux de la production de biogaz et de biochar, y compris leur potentiel en tant que source d'énergie renouvelable et amendement du sol. L'étude évalue également la faisabilité de l'utilisation locale du biogaz et du biochar produits, y compris la disponibilité des marchés locaux et l'infrastructure nécessaire au transport et à la distribution.

En fin de compte, ce document fournit une image complète des boues en tant que ressource importante provenant d'une station d'épuration municipale en termes de durabilité et de viabilité économique.

TABLE OF CONTENTS

ABBREVIATIONS

WTP = Drinking Water Treatment Plant

WTR = Water Treatment Residual, or drinking water treatment' sludge

WWTP = Wastewater Treatment Plant

DEWATS = Decentralised Wastewater Treatment System

EU = European Union

SDGs = Sustainable Development Goals

LCA = Life Cycle Analysis

LCC = Life Cycle Costing

LCIA = Life Cycle Impact Assessment

LCI = Life Cycle Inventory

TSS = Total Suspended Solids

VS = Volatile Solids

VSS = Volatile Suspended Solids

SS = Suspended Solids

TDS = Total Dissolved Solids

MLSS = Mixed Liquor Suspended Solids

MLVSS = Mixed Liquor Volatile Suspended Solids

COD = Chemical Oxygen Demand

BOD = Biochemical Oxygen Demand

OLR = Organic Loading Rate

SRT = Solids Retention Time

HRT = Hydraulic Retention Time

MCRT = Mean Cell Residence Time

SVI = Sludge Volume Index

CAS = Classical Activated Sludge

GAC = Granular Activated Carbon

SCWO = Supercritical Water Oxidation

HTO = HydroThermal Oxidation

GHG = GreenHouse Gases

OpEX = Operating Expenditure on a recurring annual basis

CapEX = Capital Expenditure investment

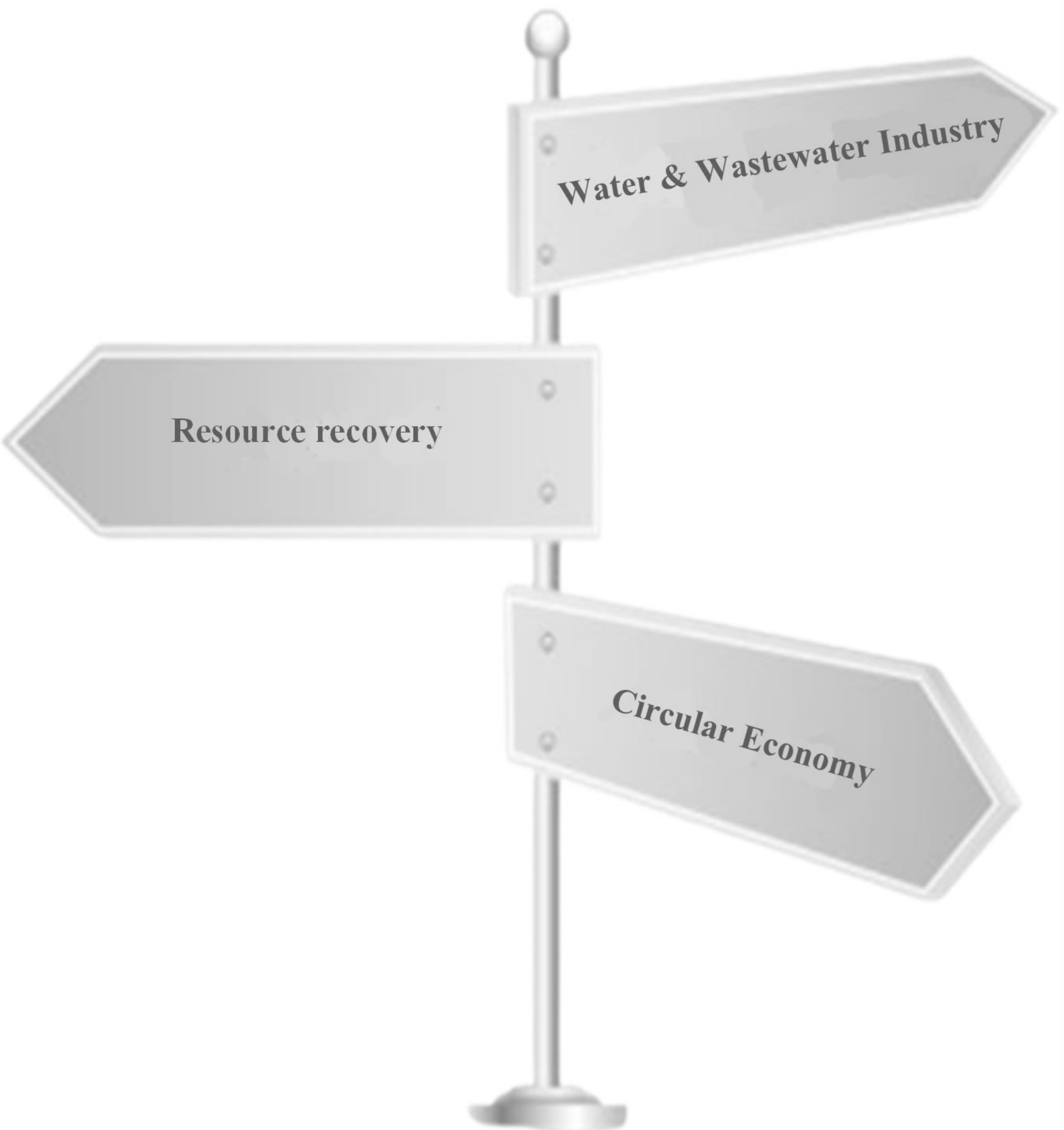
CSR = Corporate Social Responsibility

ESG = Environmental, Social, and Governance

EBC = European Benchmarking Co-operation

PART 1

INTRODUCTION CHAPTER



1 INTRODUCTION

By 2050, the world's population is estimated to increase to 9.9 billion from today's 7.9 billion (United Nations, 2021). Increased population leads to higher food, water, and energy demand, forming a nexus. This leads to higher waste generation volumes and more greenhouse gas emissions (UN Water, 2023; FAO, 2023; European Commission, 2023; World Bank, 2021). Renewable and energy-generating gases such as biogas derived biomethane and hydrogen can be used in existing gas pipelines, while biochar from bioresidue of anaerobic digestion processes can be utilized in agriculture and water treatment processes. These products can play a significant role in reducing greenhouse gas emissions (European Commission, 2021a).

The water and wastewater companies in Norway are municipal or regional monopolies. The Norwegian water and wastewater sector is responsible for the supply and treatment of drinking water and the treatment and disposal of wastewater for approximately 5 million people. The sector includes around 1100 municipal drinking water treatment plants and 2250 municipal wastewater treatment plants that vary in size and technology (Berge & Onstad, 2022; Norsk Vann, 2023a; VA-finansiering, 2023). According to Statistics Norway, total emissions from all wastewater treatment plants in Norway, including an estimated leakage on the sewer network, were approximately 1 480 tons of phosphorus and 19 200 tons of nitrogen in 2021. Emissions from overflows on the sewer network are not included in the calculation (Berge & Onstad, 2022). The Norwegian water and wastewater sector faces various challenges related to the cold climate, aging infrastructure, decentralized management, increasing energy costs, climate change, and stricter requirements for wastewater treatment. Municipal treatment plants also face different challenges related to operation and maintenance costs and environmental impact (KLD, 2022; KommunalRapport, 2023; KS, 2018; Miljødirektoratet, 2022; Norsk Vann, 2021b; Norsk Vann, 2023a; VA-finansiering, 2023).

The Norwegian water and wastewater sector's income to cover various projects, operations, and maintenance is based on the full cost principle ("selvkostprinsippet in Norwegian"), which means that water and wastewater charges (fees) must not exceed the cost of making the service possible. This makes it difficult for the sector to quickly adopt new practices (services, innovations, etc.) that can influence or raise the expenses of the treatment facilities since they must first be authorized by local authorities or politicians. (Moen Sofia, 2022; Norsk Vann, 2013a; Norsk Vann, 2015b; Norsk Vann, 2016e; Norsk Vann, 2017b; Norsk Vann, 2019a; Norsk Vann, 2021b, Norsk Vann, 2022; VA-finansiering, 2023). For example, Huseiernes

Landsforbund (The Norwegian National Association of Houseowners) is now warning how new stricter EU requirements on wastewater treatment will again inflate water and wastewater fees, while these have already increased by an average of 20% across the country in 2023 due to inflation (Huseiernes Landsforbund, 2023; KommunalRapport, 2023). The principles of the circular economy can be very useful, as circular thinking and circularity practices can help address this challenge.

1.1 Sustainability relation to circularity

As the title of this report shows, it is important to first understand the difference between sustainability and circularity before introducing the concept of the circular economy, which is the core topic of this report. The terms circularity and sustainability are used together and somewhat interchangeably, which is confusing and dilutes the importance and value of the actions associated with either. Cf. the 'butterfly diagram' by the MacArthur Foundation (2019).

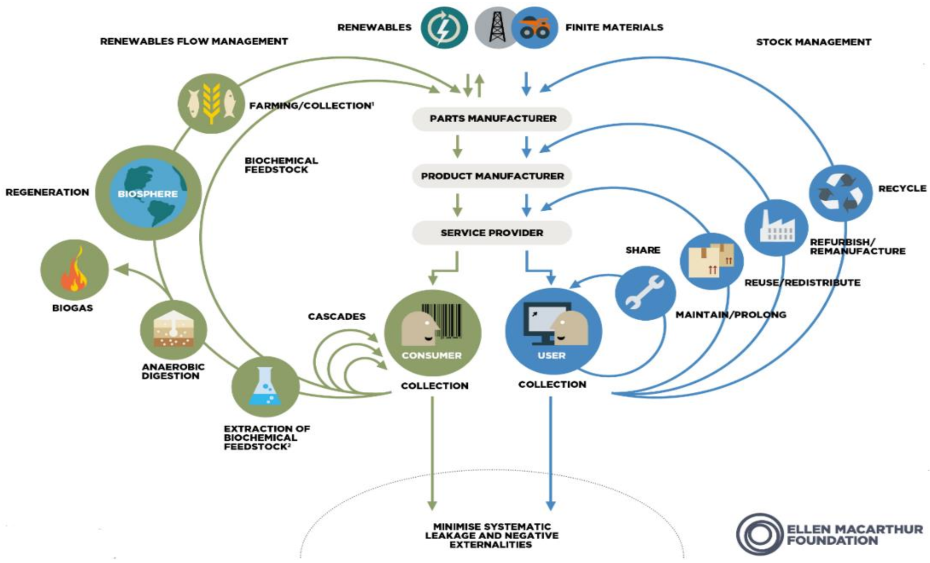


Figure 1: Butterfly diagram (circular economy system diagram), Source: MacArthur foundation, 2019

As defined by the United Nations, sustainability encompasses "sustainable development," progress that satisfies the demands of the current moment without affecting the capacity of future generations to follow in their own footsteps. This overarching concept may apply to any endeavor with the goal of realizing this vision (U.S. Chamber of Commerce, 2020). Circularity is an approach that centers and originates in the "technosphere" (anthroposphere). A human concept developed to encourage the transformation of raw resources for uses beyond those required for subsistence. The key difference between circularity and sustainability lies in the system's intentional design. As material recycling in the technosphere does not occur naturally, it must be accounted for in the design. In response, circularity and the circular economy provide a distinct "umbrella" for rethinking the transition (U.S. Chamber of Commerce, 2020).

1.2 From linear to circular economy system

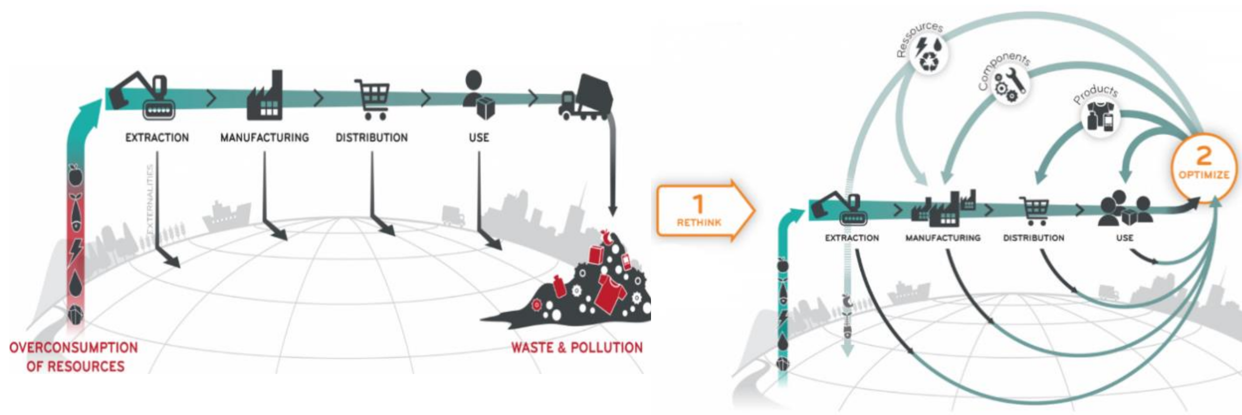


Figure 2: From linear to circular economy. Source: MacArthur, 2019

Linear economic reasoning has facilitated “planned obsolescence”, which has led to overexploitation of natural resources on a national and global scale. This is the basis for several environmental damages and international conflicts, including: industrial pollution (greenhouse gas emissions), excess waste volumes (increasing every year), and high demand for raw materials from industrialized countries, sometimes leading to diplomatic conflicts or war due to limited access or an insufficient amount of core materials locally.

The United Nations Declaration for the Preservation of the Environment, established humankind's dedication to nature and the environment. The dedication was approved during the first United Nations environmental conference in Stockholm in 1972. As a result, the concept of sustainability emerged, from which the circular economic notion grew later (United Nations, 1972; Kadibu, 2021). In contrast to the existing extractive industrial paradigm, the circular economy seeks to reinvent development by concentrating on positive social benefits, as defined by the Ellen MacArthur Foundation (2019). Decoupling economic activity from the use of scarce resources and designing waste out of the system entails converting to renewable energy sources. The 3Rs (reduce - reuse - recycle) serve as a foundation for the circular economy and further expand into more "Rs" (recover, repurpose, remanufacture, refurbish, repair, rethink, and refuse).

As a solution to resource depletion, waste production, and environmental deterioration, the concept of the circular economy has gained traction in recent years. By keeping materials, energy, and information in continuous cycles, as well as generating economic, social, and environmental value from waste and by-products, the circular economy represents a comprehensive and regenerative approach to resource management. The ideas of waste hierarchy, closed loops, and industrial ecology form the foundation of the circular economy. The waste hierarchy is a ranking of waste management strategies from highest to lowest in terms of their impact on the environment, resource efficiency, and economic viability. Waste prevention, reuse, recycling, and recovery are preferred over waste incineration and landfilling (European Commission, 2015). To reduce waste and pollution, closed-loop systems are designed to maximize the re-use of resources. The goal of industrial ecology is to maximize resource use and reduce negative environmental consequences via industry and sector cooperation and synergy (Bocken et al., 2016). The water and wastewater sectors may find new ways to solve old challenges and create profitable revenue streams by using circular economy principles.

The shift to a circular economy system is not just a one-man affair; it requires an engaged and active state that provides favorable framework conditions for green employment. That is, new forms of collaboration between authorities (government), businesses (commercial), researchers (academic), and the voluntary (nonprofit) sector. This necessitates the reconfiguration of actual management systems, the development of new innovative and circular business models (Kadibu, 2021). Policymakers in the European Union (hereinafter EU) and Norway have adopted sector-specific waste management legislation, including for the water and wastewater sector and sludge from treatment plants, in line with the circular economy ideology (European Commission, 2021b).

1.3 Circular economy relation to bioeconomy

It is crucial to clear up any confusion that may arise when comparing the circular economy with the bioeconomy. While they have some of the same goals, bioeconomy and circular economy are not the same concept. The European Union defines the bioeconomy as "the production of food, feed, materials, ingredients, chemicals, pharmaceutical products, and bioenergy from renewable biological resources such as forests, soil, livestock, and plants" (Knarrum, 2015). In a circular economy, waste is recycled into new products. The concept of "circular economy" explains how resources or products might continue to contribute to economic growth long after their initial functions are fulfilled. The circular economy makes material recovery possible and leads to better use of resources and less pollution. It helps the economy expand, creates jobs, and moves us closer to our climate targets (Kadibu, 2021; Knarrum, 2015).

There are distinctions and similarities that are often confused. Both concepts are in their early stages and are much more robust on paper than in practical usage. Nonetheless, they are essential to achieving a more sustainable world and hold a promising future for doing so. The circular economy encompasses a wide range of material flows with a variety of end-use applications. Biodegradable organic waste recycling and carbon dioxide (CO2) recycling from industry or the atmosphere are both covered (Carus, 2017). The "biologization" of value production in the industry lies at the heart of the bioeconomy. In contrast to minerals and metals, it supplies renewable carbon to industry and can replace fossil carbon in practically all uses. As a result, the metals and minerals sector lead the circular economy. As compared to the other materials, biomass is relatively scarce. The bioeconomy expands the circular economy by providing an alternative, organic recycling route (Carus, 2017).

Creating a world that is more sustainable, resource-efficient, and has minimal carbon emissions is a shared objective of both the bioeconomy and the circular economy. The bioeconomy and the circular economy both help reach climate targets without adding to fossil carbon emissions. Through increased eco-efficiency and recycled carbon utilization, the circular economy may help cut down on the burning of fossil fuels. Biomass from agricultural, forestry, and marine ecosystems is used to replace fossil carbon in the bioeconomy. These approaches are distinct, yet they complement one another. Both concepts are founded on more eco-efficient and less carbon-intensive usage (GreenHouse Gas - GHG) of existing resources. These result in less need for fossil carbon and a greater appreciation for byproducts (Carus, 2017).

Creating a genuinely sustainable economy requires incorporating the vast organic byproducts and waste streams generated by agriculture, forestry, fisheries, food and feed production, and organic processing into the circular economy, which is only possible via a bioeconomy approach (Carus, 2017). Biotechnology, algae, and insects are only a few examples of knowledge-based processes that might be used, as are novel applications and connections between the bioeconomy and other industries. The bioeconomy's natural cycles, such as the nutrient cycle, make significant contributions to the circular economy. In addition to the processes already stated, the bioeconomy may contribute to the circular economy in other ways, such as by facilitating the recycling of biodegradable products and the reuse of organic materials. Innovative additives derived from “oleochemicals” may also be used to boost the recyclable quality of other products. The bioeconomy concept's strength lies in its ability to bring distinct business sectors and industries together. As a result, numerous innovative products, and procedures (technologies) may be created to make the planet more sustainable.

The shift to and use of concepts such as circular economy and bioeconomy may be difficult for many well-established organizations (businesses) and may be seen as a "risk", leading those to consider it a "problem". This is because of the need for reorganization and more circular business models, including new players in the value chain. As a holistic comprehension of all appropriate behavior and responses is essential in such circumstances, "Sensemaking theory" may play a pivotal role. In the chap. 3 of this paper, I have included a the contribution of sensemaking theory to the understanding of risk and crisis scenarios a changing organization (company) may experience, with the hope that it would help the target audience (companies) in this master's thesis be proactive in the face of such situations and ultimately succeed. American psychosociologist Weich R. (1979, 1988, 1993, 1995, 2005) and others, such as Laroche H. and Steyer V. (2012), have studied and researched Sensemaking theory, and their findings are summarized in the attached work. The synthesis discusses several elements that affect the connectedness of an action's participants to the outside world (reality).

1.4 Circular economy in the water and wastewater sector

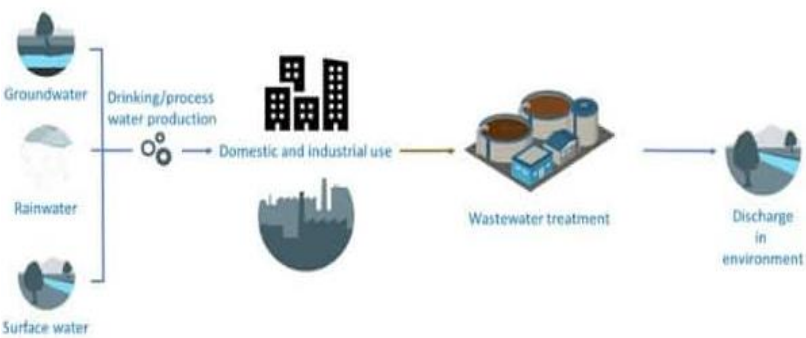


Figure 3: Linear water use model. Source:BOSAQ, 2020

Water and wastewater management is a crucial area for public health and environmental protection since it assures the safe supply and treatment of water, as well as the correct disposal of waste (sewer sludge). Nevertheless, the conventional linear model of water and wastewater management (cf. figure 3), which is based on production (water treatment), waste disposal (sludge), and services (water supply), is not sustainable over the long term. The linear model leads to the depletion of resources, the production of more waste, the destruction of limnic waterbodies, greenhouse gas emissions (hereinafter GHG), and the fragmentation of systems, which reduce the sector's efficiency and resilience. Unfortunately, most of the world's water treatment systems use a linear approach that takes water from the water cycle, uses it, and then returns it to the water cycle. This is considered one of the biggest problems with the linear management system. Because, after use in homes and industries, wastewater must undergo a series of treatment processes before it is released back into the environment. The treatment enabled the return of clean water to the environment rather than untreated effluent. This substantially helped to increase the quality of our water bodies and safeguard our water supply. Yet, this linear approach permits the extraction of large quantities of water from the environment, which is then released elsewhere, possibly resulting in local water scarcity problems or pollution threats. (BOSAQ, 2020).

The widespread lack of access to clean water everywhere is one of the most critical problems we face today. More than half of the world's population currently lives in urban areas, making them more vulnerable to water scarcity. As previously mentioned, projections show that the world's urban population will almost triple by 2050. This increase could have devastating consequences for urban water supplies. The World Bank (2020; 2021) estimates that by 20250, urban water consumption will account for 30 percent of all water consumed globally, an increase from the current 15 to 20 percent. The increase in urban water will lead to more pollution of catchments, lakes, and other natural recipients. Climate change is already having a tangible effect on the urban water cycle, altering the quantity, distribution, timing, and quality of available water in ways that exacerbate current water strains. These challenges will have the greatest impact on urban water supply and sanitation services, which are mostly provided by public entities, exacerbating performance deficiencies in several public sector organizations.

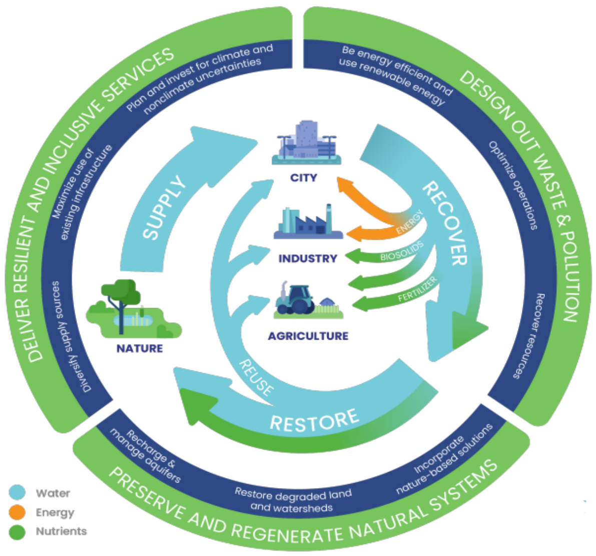


Figure 4: Water in Circular Economy and Resilience. World Bank. 2021

The principles of the circular economy provide an opportunity to consider the full value of water (as a service, an input into processes, a source of energy and a carrier of nutrients and other materials). The World Bank (2021) developed the framework in Figure 4 to help stakeholders in the water industry understand the necessity of moving to a circular water management system. By rethinking urban water from the perspectives of the circular economy and resilience, a more sustainable, inclusive, efficient, and resilient method of delivering water supply and sanitation services can be developed. To be truly successful, a circular water system must be robust and adaptable for all stakeholders. By including resilience in circular plans to prepare cities for crises and emergencies, it is possible to avoid the undesirable impacts of an interruption or breakdown in the water supply. The aim of this initiative is to ensure that everyone in the water sector has the same understanding of the circular economy and resilience principles. Its implementation reinforces the environmental, social, economic, and financial benefits of adopting a circular economy framework. Small and medium-sized water and wastewater treatment plants can accelerate into the future by using the circular economy paradigm to create resilient water systems that are both circular and sustainable based on their available resources and revenues (World Bank, 2020, 2021).

Considering the aforementioned reasons, there is a growing push to adopt a circular economy model that maximizes resource efficiency in water and wastewater treatment facilities, reduces waste (sludge landfilling), and cuts emissions via the creation of value from byproducts and waste streams. In the water and wastewater sector, circular economy is a comprehensive and holistic approach to resource management that strives to close the loops of waste, energy, and information flows and build sustainable and regenerative systems (Geissdoerfer et al., 2017). The water and wastewater sectors may benefit from the circular economy model in a multitude of ways, including the minimization of water use, the establishment of new value streams, and the enhancement of environmental and social results. According to the World Bank (2020), to move sustainable sanitation services toward a circular economy in which wastewater is seen as a valuable resource rather than a liability, a significant paradigm shift is required at various levels. Wastewater has several potential uses, including the production of energy, clean water, fertilizers, and nutrients, all of which may contribute to the United Nations Sustainable Development Goals (hereinafter SDGs). The production of biogas and biochar from wastewater treatment facilities is one of the potential circular economy approaches that may alleviate some of the constraints of the Norwegian water and wastewater sector and produce many advantages.

Beyond the production of biogas and biochar, many other things can emerge from circular thinking. Figure 5 below shows various services and products that can be generated by drilling deep into the use of the circular economy and its full implementation in the water and wastewater sectors (Israeli, 2021).

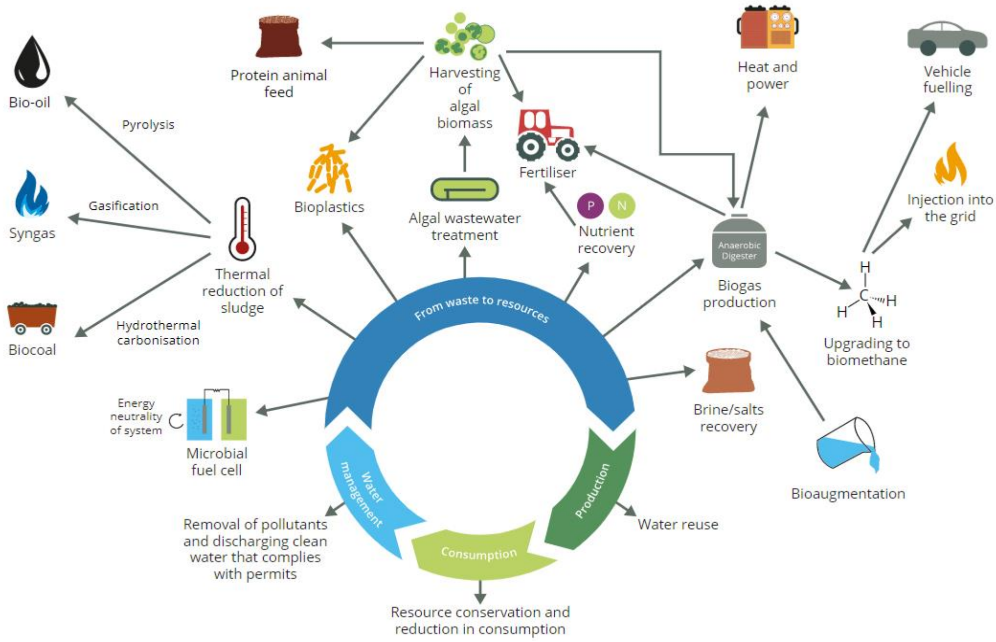


Figure 5: Possible services and products that can be generate from the circular economy in the water and wastewater sector. Source: Israeli, 2021

Biogas is a renewable energy source that can be generated from organic matter, such as wastewater sludge, and exploited for heat, electricity, and transportation. Produced from water and wastewater sludge or other organic waste, biochar is a soil amendment that may increase soil fertility, carbon sequestration, and water retention (Kapoor et al., 2022). Biogas and biochar production from wastewater treatment plants may bring many advantages, such as revenue streams from energy and fertilizer production, lowering of greenhouse gas emissions and waste disposal costs, and improving soil quality and biodiversity (Farghali et al., 2022; Tanigawa, 2017).

In Norway , as in other countries, the potential for biogas and biochar generation from wastewater treatment plants is recognized, and various pilot projects and commercial operations have been undertaken (Carbon Limits, 2019; Carbon Limits, 2021; Norsus, 2023). Nevertheless, the application of large-scale (industrial level) biogas and biochar production in the Norwegian water and wastewater sector has several technical feasibility, economic viability, regulatory constraints, and stakeholder acceptability issues. Thus, it is necessary to explore the possibilities of biogas and biochar generation in the Norwegian water and wastewater sector and assess their viability and efficacy in individual circumstances (water or wastewater treatment facilities). In addition, it is important to assess the literature from various countries about the potential, feasibility, and profitability of biogas and biochar generation from wastewater treatment facilities in various situations and identify the factors that enable or impede their implementation. This is the work carried out further in this report.

2 OBJECTIVES AND PROBLEM STATEMENT

2.1 Background

Population growth across Norway's municipalities, “strict new” EU and national requirements for wastewater treatment (removal of phosphorus, nitrogen, pharmaceuticals, and cosmetics), support for the circular economy's “from waste to resources” goal, constantly developing legal requirements, varying water and wastewater fees, environmental (climate) change, different uncertainties, and other factors, all pose challenges. To cope with this, more than adequate funding must be in place, there must be global knowledge of the potential the sector can provide, and qualified personnel must work diligently to implement the plan and report on progress at regular intervals. This master's thesis examines the possibility of generating financial resources by reusing the sector's potential resources.

This thesis is written in collaboration with the following Lier municipality enterprises:

1. Lier municipality road, water, and wastewater entreprise (“Lier vei, vann og avløp kommunalt foretak”, hereby: Lier VVA KF). Lier VVA KF administers and operates all municipal roadway, water, and wastewater systems in the municipality of Lier. The enterprise was established by the municipal council of Lier in the autumn of 2018 due to municipal reform and was put into operation in January 2020. Lier VVA KF is wholly owned by the municipality of Lier. The enterprise has its own operating structure, with a board of directors elected independently by the municipal council. Lier VVA KF is also responsible for the planning and development (construction) of public roads, water, and wastewater infrastructure in the municipality of Lier. Investments, operations, and administration responsibilities are planned and carried out in accordance with the municipality's financial framework and overarching social objectives (Lier kommune, 2023a).
2. Agriculture Office (“Landbrukskontor”), an enterprise under the municipality of Lier's department of Agriculture and Environment. The department is responsible for agriculture, forestry, wildlife, inland fisheries, and the Agriculture Office's administration. The Agriculture Office is responsible for the administration of Lier municipal forests, pollution, water resources, decentralized wastewater treatment systems (hereafter: DEWATS), and Supervision office management (Lier kommune, 2023b).
3. The supervision for small wastewater treatment facilities (“Tilsynet for små avløpsanlegg or Tilsynskontoret”, hereby: Supervision Office) is subordinate to the Agricultural Office

of the municipality of Lier and oversees decentralized and compact wastewater treatment systems. The Supervision Office also hosts the coordination, supervision, and follow-up of DEWATS and small compact wastewater treatment facilities for seven municipalities. Among them are the municipalities of Drammen, Hole, Holmestrand, Krødsherad, Lier, Modum, and Øvre Eiker. The hosting agreement covers the following responsibilities (Lier kommune, 2023c):

i. Supervise all compact wastewater treatment facilities with less than 50 persons connected (herby: person equivalent or PE) and ensure that these facilities do not cause pollution or health issues.
ii. Process applications for discharge permits under Chapter 12 of the Norwegian Pollution Regulations.
iii. Advise small compact wastewater treatment facility owners.
iv. Administer sludge emptying.
v. Conduct a survey of pollution from all DEWATS and small compact wastewater treatment facilities;
vi. Assist the cooperating municipalities in all matters related to DEWATS and small compact wastewater treatment plants.

The thesis uses a case study approach to analyze the possibility, potentiality, and feasibility of producing and selling biogas and biochar to the local market regarding the ongoing project for a new wastewater treatment plant in the municipality of Lier.

2.2 Purpose

The purpose of this master's thesis is to provide a summary of current knowledge (literature review) and the reasons for the limitations on the use of resources other than water provided by the water and wastewater sectors, as well as the barriers to the implementation of previous literature findings. Increase incentives for the circular economic water and wastewater sector by demonstrating the benefits that may accrue to municipalities, treatment facilities, investors, and other stakeholders. Demonstrate how present actors in the sector can help achieve the UN's sustainability objectives by boosting the sector's sustainability profile via alterations to work procedures and the water consumption life cycle. The last step is to investigate the economic and ecological returns on an investment in a circular economic water treatment facility.

My desire to gain a practical understanding of the water consumption cycle and the potential use of other resources in water and wastewater treatment, particularly wastewater sludge, motivated this master's thesis collaboration with the municipality of Lier. Additionally, investigate the potential business opportunities presented by wastewater sludge. Finally, yet importantly, develop better comprehension for the work of the circular economy and environmentally responsible innovation. What challenges can be addressed, as well as how they can be resolved, through cooperative effort and empirical knowledge?

2.3 Relevance and dissemination

Figure 6: The UN's Sustainable Development Goals. Source: www.kwrwater.nl

By emphasizing sustainability, the UN Sustainable Development Goals (hereinafter SDG) add a new dimension to the water and wastewater sector's challenges. The water-related objectives of the SDGs include increasing water quality, adopting and applying integrated water resources management, attaining water use efficiency across sectors, reducing the number of people and communities suffering from water scarcity, and rebuilding water-related ecosystems (World Bank, 2020).

The relevance of this master's thesis relies on the potential contributions of the following SDGs:

- SDG 2, by promoting sustainable agriculture using biochar as fertilizer
- SDG 6, by implementing circular economy principles to assure better utilization and management of the sector's resources, also generates financial resources to upgrade water and wastewater infrastructures.
- SDG 7, through the production of biogas with the potential to upgrade to a more sustainable energy source available to everyone.
- SDG 8, by selling biogas and biochar to finance the sector's initiatives and generate employment.
- SDG 9, by developing new innovative infrastructures for the production of biogas and biochar.

- SDG 12, by reducing water requirements in agribusiness using biochar as fertilizer.
- SGD 13, by substituting upgraded biogas for biomethane or hydrogen as a sustainable fuel to reduce emissions
- SDG 14, by reducing eutrophication and the loss of aquatic life using biochar in agriculture.
- SDG 15, by utilizing biochar to enhance the soil's carbon content as a soil conditioner and by incorporating biochar into livestock feed;
- SDG 17, by accelerating the implementation of the circular economy and the efficient use of all available resources through sector-wide collaboration between various actors.

These SDGs are a significant contribution to society and the environment. Moreover, circular economy is a central concept for enhancing the utilization and administration of natural resources, particularly in the water and wastewater sector, which is among the most polluting sectors.

Environmental and social benefits are accompanied by economic and financial benefits when circular economy practices are implemented in the water and wastewater sectors. The examples in this master's thesis demonstrate that investments in resilient and circular systems provide economic and financial returns and can help attract private sector funding. The report provides examples such as a business model for the production and sale of sludge-produced biogas and biochar by a wastewater treatment facility, a municipal agricultural office, and local farmers. In addition, it emphasizes the role of the water and wastewater sectors in reducing greenhouse gas emissions via energy efficiency measures and self-generation of renewable energy, for instance.

Water and wastewater treatment plant managers, municipal agricultural offices, cultivators, farmers, energy recovery companies, recycling companies, nature and environment managers and regulators (authorities, scientists, and advisors), and society (consumers of biogas and biochar) are the major beneficiaries of this paper. As depicted in figure 6 above, each of the SDGs has a distinct theory, vision, and target audience that I consider in each assessment along the way.

The present report's findings are beneficial as input: First, the findings will assist wastewater treatment facilities in efficiently utilizing wastewater resources, thereby contributing to the water and wastewater sector's goal of reducing emissions and pollution and enhancing its own corporate social responsibility (hereinafter CSR). Second, the results will assist both municipalities and farmers in realizing the benefits of shifting to a circular mindset and work processes, and in developing and implementing a circular business plan that facilitates the transformation of wastewater sludge and livestock manure into new products (biogas and biochar) or secondary materials (raw materials) for other uses. Thirdly, the results will assist project managers in involving all stakeholders in the biogas and biochar value chain earlier in the project planning, logistics planning, and environmental emissions calculation phases (project climate footprint). Lastly, to the authorities and regulators for designing a more effective policy for the administration and transformation of wastewater sludge and biological waste into socially useful products.

In short, the thesis contributes to the literature on the circular economy and sustainable wastewater management and provides insights for policymakers, practitioners, and researchers.

2.4 Problem statement

Based on the theoretical possibilities and potential benefits of local biogas and biochar production at a municipal wastewater treatment plant as a circular economic measure (Nguyen et al., 2022), this solution proves to be among the best for financing various project costs and improving sustainability in the Norwegian water and wastewater sector. However, there appears to be a potential lack of empirical evidence and practical guidelines to promote incentives for the implementation of circular economy measures in the sector. This knowledge gap likely limits the use of circular economy approaches in the sector and thus hinders the achievement of environmental, economic, and social goals. As a theoretical barrier, this argument forms the basis for the problem statement in this master's thesis:

What is the potential for local biogas and biochar production as a circular economy measure to finance operating and maintenance costs and increase the sustainability of a Norwegian water and wastewater treatment plant? What are the enabling and hindering factors for the full implementation of the circular economy in the Norwegian water and wastewater sector?

Some research questions have been generated at the conclusion of the "States of Knowledge" chapter in the second part of this thesis to elucidate the solution to the problem statement.

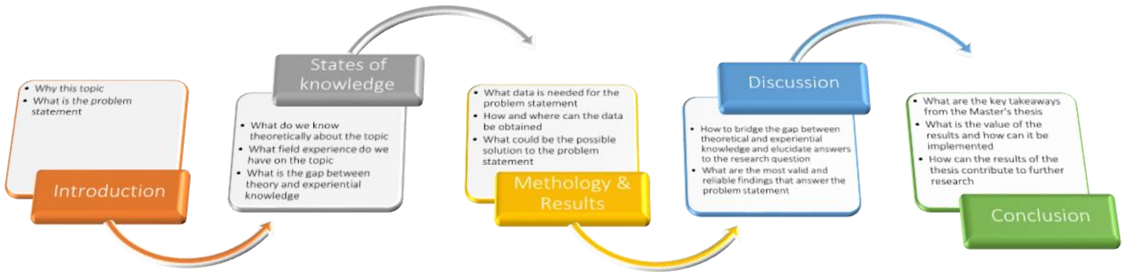
2.5 Delimitation

This master's thesis report examines the circular economy to identify indicators that make wastewater sludge both a problem and an asset for the water and wastewater sectors. It emphasizes the production and sale of biogas and biochar to finance wastewater treatment plant initiatives. The following considerations are omitted or given minimal weight:

- Chemical and biological algebraic calculations
- Life Cycle Analysis (LCA), Life Cycle Costing (LCC), Life Cycle Inventory (LCI), and Life Cycle Impact Assessment (LCIA).

2.6 Structure of the paper

Due to the scope and complexity of the topic, I have opted to structure this report (research) regarding a conceptual model. This provided me with an overall picture of the biogas and biochar value chains. In addition to how the production process, market, legislation, and different stakeholders interact and influence each other in the value chain. A conceptual model structure can be defined as a research design tool used to plan or visually represent the information structure of a system entity. The purpose of the model in the planning of this master's thesis was to organize and highlight ideas (information) that emerged along the way in the right order. This helped to shed light on the problem statement with the least possible derailment.



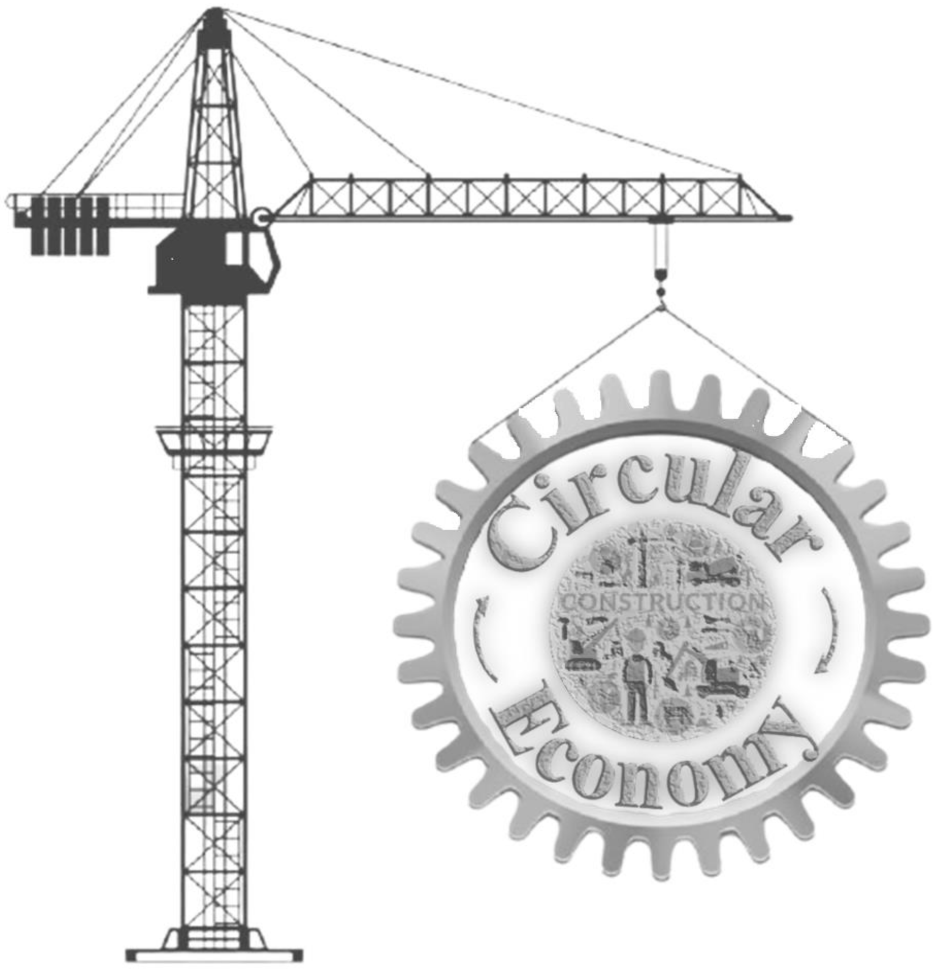
This report is divided into five major parts. Part 1 introduces the thesis and related research questions. Part 2 deals with existing theoretical knowledge and research, case studies, and field experience related to the problem statement, and concludes with research questions. Part 3 deals with the methodology that has been used to collect data, analyze it, ensure quality, and present the findings. Part 4 assesses the research questions by discussing the findings through an approximation of theoretical and empirical findings, and finally answers the problem statement based on the learning and my scientific knowledge on the topic. Part 5 concludes, recommends the findings, and suggests further work based on the values the master’s thesis can create.

After reading the entire master's thesis, a person with little knowledge will deeply understand what sludge is, why it is essential to value it, and, most importantly, what products can result from the proper carrying, treatment, and management of sludge. In addition, the text provides an exhaustive comprehension of biogas and biochar as byproducts of sludge treatment. The length of this thesis report is justified by the number of the intended audience who can benefit from it, including farmers who may not have a deep knowledge of water and wastewater treatment but are the most likely sludge-derived biochar customers. The sections 3.1 to 3.5 of part 2 (Theoretical Knowledge) of this paper are mainly targeted toward novice students and readers with limited knowledge of water and wastewater treatment, including sludge and its management. Audiences with greater knowledge can skip these sections and begin reading from section 3.6, which discusses biogas, and section 3.7, which discusses biochar.

By following this structure, this thesis presents clear and logical justifications for the valorisation of water and wastewater sludge and the enhancement of biogas and biochar production in a municipal wastewater treatment plant. The literature review and methodology provide a strong foundation for the study, while the results and discussion sections present a detailed analysis of the findings and their implications. The conclusion summarizes the study and its implementation and suggests directions for future research. Overall, this structure helps the thesis communicate its findings effectively to its intended audience, whether researchers, policymakers, or practitioners.

PART 2

THEORETICAL FRAMEWORK



3 STATES OF KNOWLEDGE

This chapter provides a wide overview of the present situation and state of knowledge regarding the subject of the present master's thesis. It examines the case of Lier municipality's new treatment plant to discuss sewage sludge production, treatment, regulation, and utilization as a valuable resource for the production of biogas and biochar, as well as previous research funding on similar topics, current challenges in implementing previous research recommendations, and significant theories that will support the discussion chapter. It concludes with research questions that clarify the problem statement.

3.1 Convectional water and wastewater treatment processes

For various reasons, understanding standard water and wastewater treatment procedures is critical before integrating sludge treatment for biogas and biochar production: This is because of the nature, volume, and qualities of the sludge produced are heavily influenced by these upstream processes. The methods used to treat water and wastewater can influence the physical, chemical, and biological aspects of the sludge, which affects the appropriate sludge treatment options, as well as its potential for reuse or disposal.

Sludge quality: The techniques used in water and wastewater treatment have a considerable impact on the content and quality of the sludge produced. This, in turn, impacts the feasibility and efficiency of producing biogas and biochar.

Toxic contaminants: When conventional treatment techniques are transformed to biogas or biochar, substances that are toxic or dangerous can be introduced. Understanding these processes aids in the development of methods to reduce their impact.

Process optimization: A thorough understanding of these processes can lead to innovations and improvements that optimize sludge creation, hence boosting biogas or biochar output.

Environmental and health safety: Understanding the entire water and waste treatment cycle can help to ensure that all activities, including biogas and biochar generation, are safe for the environment and public health.

A full understanding of these first treatment processes enables more efficient, effective, and long-term production of biogas and biochar, as well as safe management of the resulting product.

3.1.1 A key difference between drinking water and wastewater plants

Drinking water treatment plant produces water for residential and industrial use, whereas wastewater treatment plant processes water from sewers.

Typically, a conventional drinking water treatment plant (hereafter: WTP) employs the procedures of coagulation, flocculation, sedimentation, filtration, and disinfection. This is done to eliminate physical, chemical, and microbiological contaminants from water sources in order to produce potable water.

A conventional wastewater treatment plant (hereafter: WWTP) consists of preliminary treatment (screening and grit removal), primary treatment (sedimentation), secondary treatment (biological process to remove organic materials), and tertiary treatment (advanced treatment, if necessary, including disinfection). Its purpose is to treat municipal or industrial wastewater to the point where it can be securely discharged back into the environment.

Sedimentation is the only operation that both treatment plants share. Due to their different purposes, the level of disinfection at WTP and WWTP differs. Chlorination, Chloramination, ultraviolet light, and Ozone are primary methods for disinfection. In conventional WTP, chlorination and chloramination are usually employed as the ultimate disinfection step to eliminate harmful microorganisms. In contrast, conventional WWTP utilizes a variety of disinfection techniques, including UV radiation, chlorination, and ozone, depending on local regulations and the specific reuse purposes of the treated water. In WWTP, coagulation and flocculation do not occur.

3.1.2 Drinking water treatment plant (WTP)

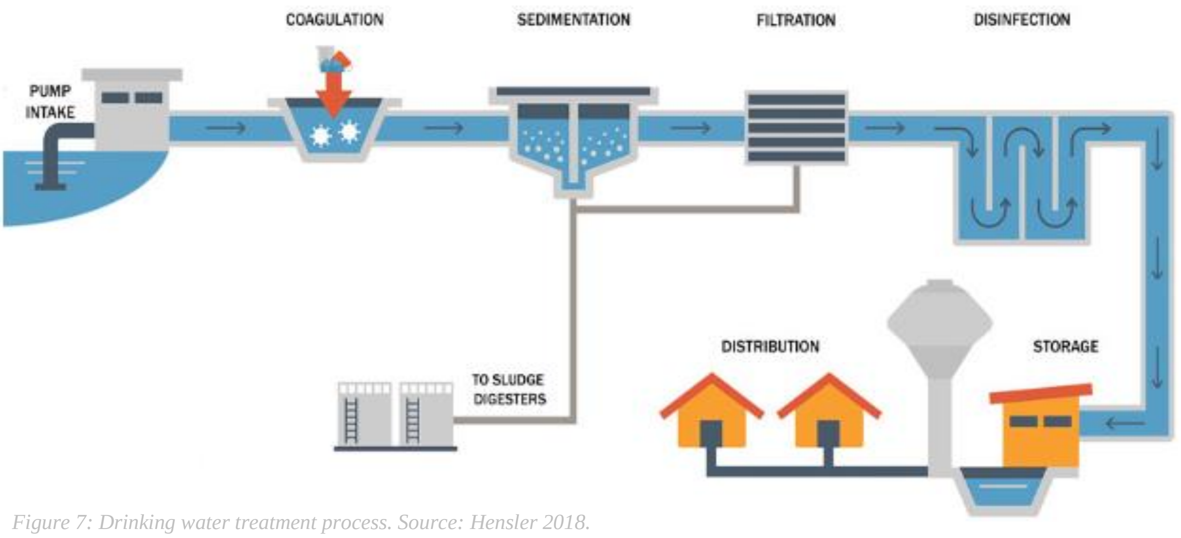


Figure 7: Drinking water treatment process. Source: Hensler 2018.

Each stage of a drinking water treatment plant (hereinafter WTP) is designed to remove various contaminants and ensure that the water is safe for human consumption. The standard procedure for treating potable water can be described as follows:

The first step in water purification is the **Intake**, which consists of collecting untreated water from a river, lake, or reservoir. Screens filter out large debris such as leaves, branches, and fish before the water enters the treatment facility.

The water is coagulated and flocculated at this point. During **Coagulation**, a coagulant is added to the water, which causes small particles to clump together and form larger particles. During **Flocculation**, the water is gently stirred so that newly formed particles can collide and cling together to form larger particles, or "flocs".

After flocculation, the water is transferred to a basin for **Sedimentation**, where it remains undisturbed for several hours. Gravity causes the heavier flocs to sink to the bottom during this phase, producing a layer of sludge.

During sedimentation, sludge is typically extracted and transported to a wastewater treatment facility for additional processing. It can also be dehydrated (dewatered) and disposed of in a landfill, or after appropriate treatment, it can be used for agricultural purposes.

After sedimentation, the water undergoes **Filtration** to remove any remaining contaminants. The water is filtered by passing it through one or more filters comprised of sand, gravel, and charcoal. These filters remove any remaining suspended particles and bacteria in the water.

Disinfection of the filtered water removes any remaining bacteria, viruses, or parasites. This is typically achieved by using a disinfectant such as chlorine or chloramine, or by employing technologies such as ultraviolet (UV) radiation or ozonation (Centers for Disease Control and Prevention, 2020).

Storage is the final stage in the drinking water treatment system. The treated water is stored in a storage basin or clear well (reservoir or tank) before being distributed to users via a network of pipes. The storage allows the disinfectant to inactivate any remaining pathogens.

3.1.3 Wastewater treatment plant (WWTP)

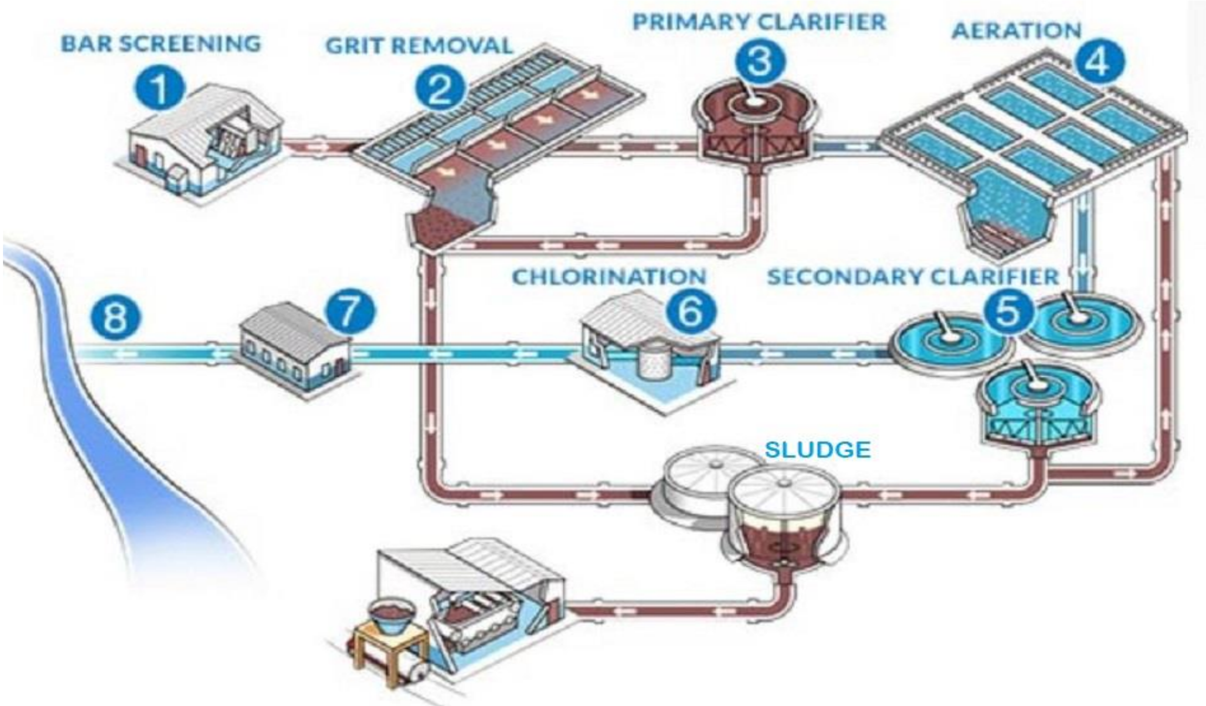


Figure 8: Wastewater Treatment Process. Source: www.coleparmer.com

The purpose of wastewater treatment facilities (hereafter: WWTP) is to process and treat wastewater before releasing it back into the environment. Pretreatment, primary treatment, secondary treatment, and sometimes tertiary treatment are the four main stages of the treatment procedure (Tchobanoglous et al., 2014).

Pretreatment: when wastewater, known as influent, enters the treatment plant, the process commences. This influent consists of water from residences, businesses, and storm runoff, and it typically contains solids, sediments, bacteria, and a variety of chemical pollutants. **Screening** consists of removing large debris such as rags, sticks, and other large objects. Additionally, **Grit** (sand and small stones) is extracted to safeguard the mechanical equipment utilized in the following stages.

The **Primary treatment** is the subsequent stage following the pretreatment. This stage is designed to separate suspended solids and organic matter from effluent. This entails the sedimentation (settling) process, in which wastewater is placed in large tanks (**Primary clarifier**) so that solid waste, or sludge, can settle to the bottom. Lighter than water, fats, oils, and greases float to the surface and are removed.

Secondary treatment: is the subsequent phase following the primary treatment. This stage entails the removal of dissolved and suspended organic matter by biological processes. This organic matter is consumed by bacteria and other microorganisms, and convert it into more bacteria, pollutants, and water. This generally occurs in **Aeration** tanks (basins) and is followed by a secondary sedimentation process (**Secondary clarifier**) in which bacteria-rich sludge settles out. Many WWTPs end the process from here and add disinfectants before releasing water into the environment, but in some cases, such as when the effluent is highly toxic, or when the effluent released into a recipient with a high risk of eutrophication, tertiary treatment may be required.

Tertiary treatment: is an optional, final step that can be taken to enhance the quality of wastewater before it is discharged into the environment. This stage can involve a variety of specific techniques, including the elimination of non-biodegradable pollutants, any remaining suspended solids, and inorganic compounds, the removal of nutrients such as phosphorus and nitrogen, and the disinfection of the water to inactivate any remaining bacteria or viruses. Frequently, chlorine or ultraviolet light is used to disinfect the effluent. After tertiary treatment, the wastewater is known as effluent and can be discharged into a body of water or further treated for irrigation, industrial cooling, or indirect potable reuse.

An essential aspect of wastewater treatment is the treatment of sludge removed during the aforementioned stages. It frequently entails thickening, digestion, dewatering, and disposal.

3.2 Sludge production

Sludge is a semi-solid slurry generated by a variety of industrial processes, including drinking water treatment, effluent treatment, and on-site sanitation systems (DEWATS). Sludge is a general word for solids that have been removed from suspension in a liquid, whereas sewage is a suspension of water and solid trash delivered by sewers to be disposed of or treated.

In the context of sustainability and circular economy principles, society is becoming increasingly aware of the need to minimize and repurpose waste wherever possible. While this trend may lead to a significant reduction in the generation of organic waste such as compostable or food waste, the production of sludge, a byproduct of water treatment processes, is expected to continue increasing. This is primarily due to the continual growth of the global population and the corresponding increase in the demand for water and wastewater treatment services. Thus, sludge can be regarded as a consistent and increasingly relevant waste stream that requires further attention for potential repurposing and utilization in various industries. By applying the principles of a circular economy to sludge management, it's possible to turn this growing waste stream into a valuable resource, contributing to sustainability goals while meeting industrial needs.

3.2.1 Drinking water sludge

In a conventional drinking water treatment facility (WTP), sludge is typically referred to as water treatment residuals (hereafter: WTR). It consists primarily of impurities precipitated from the water source, coagulation and flocculation chemicals, and microorganisms. WTR as a by-product includes particles of sand, silt and clay, colloidal organic matter, and chemical substances (geopolymers) that have been added. To protect public health and the environment, this sludge must be appropriately managed and disposed (Environmental Protection Agency, 2002).

The primary components of drinking water treatment residuals are sediment, metal (aluminum, iron, or calcium) oxides/hydroxides, activated carbon, and lime (Ahmad et al., 2016; Minnesota Pollution Control Agency, 2022).

3.2.2 Wastewater sludge

In a conventional wastewater treatment plant (WWTP), three varieties of sludge are generated: primary, secondary, and tertiary (Tchobanoglous et al., 2014; Environmental Protection Agency, 2002).

Primary sludge is the result of primary sedimentation in a wastewater treatment plant. It is comprised of the solids that gravitationally settle out in the primary clarifier. This sludge typically contains a high concentration of organic matter, such as feces, food waste, and other biodegradable substances.

Secondary sludge, also known as activated sludge, is generated during the biological treatment phase, which follows the primary treatment phase. The sludge contains a high concentration of microorganisms used to break down and consume organic material in wastewater. The activated sludge process entails aerating the wastewater to promote the growth of these microorganisms.

Tertiary sludge is produced if a tertiary or advanced purification process, such as the addition of a flocculation agent, is employed. The sludge frequently contains a high concentration of substances because of processes such as nutrient removal (nitrogen, phosphorus), pathogen reduction, and advanced oxidation.

3.2.3 A key difference between drinking water and wastewater sludge

Both drinking water sludge and wastewater sludge are by-products of the water treatment process, but their biological and physicochemical compositions are distinct due to their distinct sources and treatment processes.

Biologically, due to its origin in human and industrial refuse, wastewater sludge is typically richer in microorganisms, including pathogens, from a biological standpoint. In contrast, drinking water sludge is less likely to contain high concentrations of microorganisms or pathogens because it is predominantly a by-product of the treatment of relatively pure source water (Rosińska, 2019).

Physicochemically, wastewater sludge frequently contains a broader spectrum of organic and inorganic substances, including heavy metals and other pollutants found in sewage. In contrast, drinking water sludge typically contains large concentrations of inorganic coagulants, such as aluminium or iron hydroxides, employed in water treatment (Demirbas & Alalayah, 2017).

Due to these compositional differences, wastewater sludge typically requires more intensive treatment to be safe for disposal or reuse. In contrast, although drinking water sludge can contain residual chemicals from treatment procedures, it typically poses a lower environmental or health risk (Wu et al., 2018).

Both forms of sludge can be reused through processing. Due to its high nutrient content, wastewater that has been treated can be used as a soil conditioner or fertilizer after proper treatment. Once dehydrated and treated, drinking water sludge can be used in construction or as a soil amendment; however, its applications are typically more limited due to its high inorganic content (Muter et al., 2022; Carneiro et al., 2020).

3.2.4 Estimation of WWTP sludge production

In the estimation of sludge production, parameters such as Total Suspended Solids (TSS), Mixed Liquor Suspended Solids (MLSS), Mixed Liquor Volatile Suspended Solids (MLVSS), Volatile Suspended Solids (VSS), Volatile Solids (VS), Chemical Oxygen Demand (COD), and Biochemical Oxygen Demand (BOD) are typically determined through laboratory analysis (Norsk Vann, 2012d; Norsk Vann, 2012b; Ariza, 2019; Metcalf & Eddy, 2014). The calculation of sludge production may vary based on the wastewater treatment process employed, the design of the WWTP, and the composition of the wastewater being treated. It is crucial to note that the proportions specified in the forthcoming formulas represent typical average values, and actual amounts can vary considerably based on variables such as the season, wastewater source, and treatment technology (Wiesmeth, 2020). Using those provided formulas and parameters, WWTP operators can estimate the amount of sludge produced at their facility, thereby facilitating effective process management and control.

One of the primary factors to consider is **Suspended Solids** (SS), also known as **Total Suspended Solids** (TSS). Total Suspended Solids (TSS) refer to waterborne particles larger than 2 microns, whereas Total Dissolved Solids (TDS) comprise particles smaller than 2 microns. Through laboratory analysis, TSS is determined by filtering a known volume of wastewater and measuring the mass of solids retained by the filter paper. TSS is a crucial parameter for evaluating solids removal efficacy and determining the amount of sludge produced (Mawioo, 2020). The TSS calculation equation is as follows:

TSS (ppm or mg/L) = $\frac{m_2 - m_1}{V}$, where m_2 is the mass of the filter paper with dried solids, m_1 is the mass of the empty filter paper, and V is the volume of the sample filtered. Given the SS and wastewater flowrate (Q), TSS can be calculated using the formula:

TSS (kg/d) = **Q** (m^3/d) $*$ **SS** (mg/L) $*$ 10^{-3}.

Similarly, **Mixed Liquor Suspended Solids** (MLSS) reflect the concentration of suspended solids particles in an activated sludge process's aeration tank. MLSS plays an important role in managing the aeration process in a WWTP (Lefebvre, 2019; Mawioo, 2020; Metcalf & Eddy, 2014). The MLSS is calculated as follows: **MLSS** (mg/L) = $\frac{m_2 - m_1}{V}$, where m_2 is the mass of the filter paper with dried solids, m_1 is the mass of the empty filter paper, and V is the volume of the mixed liquor sample filtered.

Mixed Liquor Volatile Suspended Solids (MLVSS) and **Volatile Suspended Solids** (VSS) provide insights into the organic or biological fraction of the suspended solids. Important for estimating the biomass concentration in the activated sludge process and the potential sludge generated (Ariza, 2019; Mawioo, 2020; Metcalf & Eddy, 2014). VSS refers to the organic portion of TSS that can be volatilized at high temperatures, indicating a high level of biological activity and potential for sludge generation. The MLVSS formula is as follows:

MLVSS (mg/L) = $\frac{m_3 - m_4}{V}$, where m_3 is the mass of the crucible with ignited solids, m_4 is the mass of the empty crucible, and V is the volume of the MLSS sample used. Similarly, VSS follows the same equation: **VSS** (mg/L) = $\frac{m_3 - m_4}{V}$, but V represents the volume of the wastewater sample used.

When loading an anaerobic digester, **Total Solids** (TS) and **Volatile Solids** (VS) are crucial factors. VS represents the organic content of the sludge, while TS aids in determining the digester's compatibility with the incoming sludge volume (Fang & Jia, 2011; Metcalf & Eddy, 2014). VS estimation involves the use of the formula: $\mathbf{VS} = \frac{\mathbf{m_5 - m_6}}{\mathbf{m_7}} * \mathbf{100}$, where m_5 denotes the mass of the sample plus dish before ignition, m_6 is the mass of the sample plus dish after ignition, and m_7 is the mass of the wet sample.

Chemical Oxygen Demand (COD) and **Biochemical Oxygen Demand** (BOD) are indispensable for estimating the organic load in the wastewater, which affects the production of sludge during treatment. These parameters provide thorough insights into the organic compounds present in water and the potential sludge generated (Kelessidis & Stasinakis, 2012; Wiesmeth, 2020).

COD is a key parameter that estimates the total quantity of oxygen needed to oxidize all organic matter into carbon dioxide and water. Standard procedures for detecting COD employ oxidizing agents such as potassium dichromate ($K_2Cr_2O_7$) and potassium permanganate ($KMnO_4$). COD is calculated using the following formula: **COD** (mg/L) = $\frac{(\mathbf{A-B}) * \mathbf{F} * \mathbf{V}}{\mathbf{V_2}}$, where A is the volume of potassium dichromate solution used in the titration, B is the blank volume of potassium dichromate solution, F is the factor of the potassium dichromate solution, V is the volume of the wastewater sample used in the test, and V_2 is the volume of the wastewater sample taken for the test. Given the COD from laboratory and wastewater flowrate (Q), COD can be calculated using the formula:
COD (kg/day) = **Q** (m^3/day) $*$ **COD** (mg/L) $*$ $\mathbf{10^{-3}}$.

BOD refers to the quantity of dissolved oxygen required by microorganisms to break down the organic matter present in a water sample over a given time period. BOD is measured by incubating a water sample for five days at 20°C, which is referred to as BOD_5. The formula for calculating BOD_5 is: $\mathbf{BOD_5}$ (mg/L) = $\frac{(\mathbf{Initial\ DO - Final\ DO}) - \mathbf{Seed\ correction\ factor}}{\mathbf{Sample\ volume}} * \frac{\mathbf{Bottle\ volume}}{\mathbf{Sample\ volume}}$ or $\mathbf{BOD_5}$ (mg/L) = (**Initial DO** - **Final DO**) $*$ **DF**, where DO is the dissolved oxygen and DF is the dilution factor. DF = $\frac{\text{volume of diluted sample}}{\text{volume of undiluted sample}}$. BOD_5 can be calculated using the following formula when given BOD_5 from laboratory analysis and wastewater flowrate (Q):
$\mathbf{BOD_5}$ (kg/d) = **Q** (m^3/day) $*$ $\mathbf{BOD_5}$ (mg/L) $*$ $\mathbf{10^{-3}}$.

Other parameters that contribute to sludge production in wastewater treatment include (Ekama, 2010): **Hydraulic Retention Time** (HRT), **Organic Loading Rate** (OLR), **Sludge Retention Time** (SRT) or Sludge Age or Mean Cell Residence Time (MCRT), **Food to Microorganism Ratio** (F/M), and **Sludge Volume Index** (SVI). and OLR and HRT parameters impact the rate of organic matter degradation and the efficiency of the biological remediation process, thereby influencing sludge production (Fernandes et al., 2015; Ekama, 2010). The SRT represents the average time sludge particles spend in the system before being removed, which influences the growth rate of microorganisms and sludge production. Solids retention is based on what is leaving the activated sludge process, including the clarifier solids, whereas sludge age is based on what is in the aerator. The difference between the MCRT and SRT is that the MCRT equation incorporates clarifier solids while the SRT calculation does not (WWBlog, 2021; Shuokr & Jwan, 2021; Lenntech, 2023; MECC, n.d.; Netsol Water, n.d.). F/M is the ratio of organic matter mass applied to microorganism mass in the system, which controls the sludge production rate during the biological treatment process (Rajput et al., 2022; Ekama, 2010). SVI is a measure of the settling characteristics of sludge, which influences sedimentation efficiency and the quantity of sludge that is discarded (Rossetti et al., 2017; Fernandes et al., 2015; MECC, n.d.).

The following formulas can be used to calculate the aforementioned parameters (Rossetti et al., 2017; Lenntech, 2023; MECC, n.d.; Netsol Water, n.d.; Ekama, 2010; Rajput et al., 2022; WWBlog, 2021; Fernandes et al., 2015; Wongburi & Park, 2022; Norsk Vann, 2012d; Norsk Vann, 2012b):

$$\textbf{HRT}\ (\mathrm{h}) = \frac{\textbf{Tank volume}\ (\mathrm{m^3})}{\textbf{Influent flow rate}\ (\mathrm{m^3/h})}$$

$\textbf{OLR}\ (\mathrm{g/L\text{-}d}) = \dfrac{\textbf{Influent flow rate}\ (Q) * \mathbf{S_o}}{\textbf{Tank volume}} = \dfrac{\mathbf{S_o}}{\textbf{HRT}}$, where S_o is the influent substrate concentration, measured on a VS or COD basis.

$$\textbf{SRT}\ (\mathrm{d}) = \frac{\textbf{MLVSS}\ (\mathrm{mg/L})}{\textbf{Flowrate of wastewater}\ (\mathrm{m^3/h}) * \textbf{Concentration of MLVSS in the aeration tank}\ (\mathrm{mg/L})}$$

$$= \frac{\mathbf{TSS_{influent}}}{\mathbf{TSS_{effluent}}}$$

$$\textbf{Sludge age}\ (\mathrm{d}) = \frac{\textbf{Total MLSS in aeration tank}}{\textbf{Daily TSS in the influent}} = \frac{\textbf{Bioreactor solids}}{\textbf{Wasted solids + Effluent solids}}$$

$$\textbf{MCRT}\ (\mathrm{d}) = \frac{\textbf{MLSS in the tank}}{\mathbf{SS_{influent} + SS_{effluent}}} = \frac{\textbf{Bioreactor solid + Clarifier solids}}{\textbf{Wasted solids + Effluent solids}}$$

$$\textbf{F/M} = \frac{\textbf{Influent BOD}\ (\mathrm{mg/L}) * \textbf{Influent flow rate}\ (\mathrm{m^3/h})}{\textbf{Tank volume}\ (\mathrm{m^3}) * \textbf{MLVSS}\ (\mathrm{mg/L})}$$

$\textbf{SVI}\ (\text{mL/g}) = \frac{\textbf{Settled sludge volume}\ (\text{mL/L})}{\textbf{MLSS}\ (\text{mg/L})} * \mathbf{10^3}$.

Population Equivalent (PE): indicates that one individual residing in a typical residence generates approximately 200 liters of wastewater containing 60 grams of BOD per day. PE is applied in the design and sizing of wastewater treatment facilities and has an indirect impact on sludge production (Norsk Vann, 2012d; Norsk Vann, 2012b; Estevez et al., 2021).

The general formula for estimating sludge production (SP) at a WWTP can be (MECC, n.d.; Lenntech, 2023; WWBlog, 2021; Netsol Water, n.d.):

$\mathbf{SP} = \mathbf{Q} * (\mathbf{S_i} - \mathbf{S_e}) * \mathbf{X_v} * \mathbf{Y}$, where SP is the daily produced sludge (kg/d), Q is the daily flow of wastewater (m^3/d), S_i is the initial concentration of the substance (kg/m^3), S_e is the final concentration of the substance (kg/m^3), X_v is the volumetric fraction of the substance that ends up in the sludge (dimensionless), and Y is the yield coefficient or the mass of sludge produced per unit mass of substance removed (kg sludge/kg substance).

Other frequent formulas include:

$\mathbf{SP} = \mathbf{Q} * \mathbf{BOD} * \mathbf{Y}$, where Q is the daily flow of wastewater (m^3/day), BOD is the concentration of Biochemical Oxygen Demand (kg/m^3), Y represents the yield coefficient, or the amount of sludge produced per kilogram of substance removed (kg sludge/kg substance).

Primary sludge production (PSP) can be calculated as:
$\mathbf{PSP} = \mathbf{Q} * (\mathbf{TSS_{in}} - \mathbf{TSS_{out}}) * (\mathbf{1} - \mathbf{R})$, where Q is the flow rate (m^3/day), TSS_{in} and TSS_{out} are the influent and effluent TSS respectively (g/m^3), and R is the recycle ratio.

Secondary sludge production (SSP) can be calculated as:
$\mathbf{SSP} = \mathbf{Q} * (\mathbf{VSS_{in}} - \mathbf{VSS_{out}}) * \mathbf{Y}$, where Y is the yield coefficient, which varies depending on the specific process and microorganisms involved.

These aforementioned formulas and parameters enable administrators of wastewater treatment plants to estimate the amount of sludge produced at their facility, thereby facilitating effective process management and control.

3.3 Conventional pretreatment of wastewater sludge

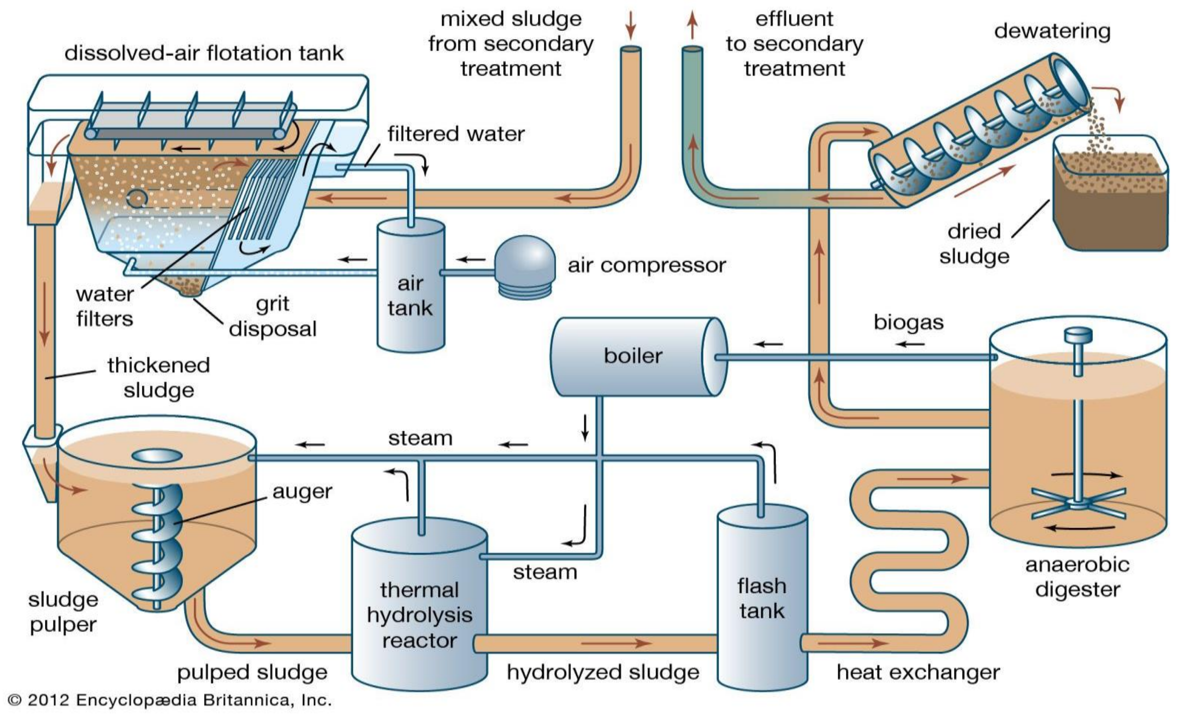


Figure 9: Sewage sludge treatment. Source: Encyclopædia Britannica

The type of water that enters the treatment plant determines the physicochemical composition of the sludge. As a result, sewage sludge has a great variety in chemical composition, comprising beneficial fertilizers and hazardous compounds for the environment. Traditional organic pollutants found in sludge include absorbable organic halogens (AOX), polycyclic aromatic hydrocarbons (PAHs), polybrominated biphenyls (PBBs), polychlorinated biphenyls (PCBs), polybrominated diphenylethers (PBDEs), polychlorinated dibenzofurans (PCDFs), perfluorinated compounds (PFCs), pesticides (organochlorine pesticides OCP). As a result, effective techniques are required to eliminate pollutants and reduce the adverse impact of sludge on the environment (Rosińska, 2019).

The standard activated sludge (CAS) treatment process is the most often utilized technique in urban WWTPs for the removal of carbonaceous materials and nutrients. The technique mixes pretreatment wastewater with microorganisms for nutrient absorption into microbial biomass and carbonaceous organic matter oxidation. The conventional method of pretreatment for sludge from drinking water and wastewater facilities consists of a series of procedures aimed at reducing volume, stabilizing the material, removing odors, ensuring the material's use, and inactivating pathogens (Encyclopaedia Britannica, 2023; Conserve Energy Future, 2023).

Thickening: is the initial stage, which aims to reduce sludge volume by eliminating water (Rosiska, 2019). This makes following treatment operations more efficient by reducing transportation and handling expenses (Demirbas & Alalayah, 2017).

Dewatering: decreases the sludge volume further by extracting more water using mechanical processes such as centrifugation. Thus, the dewatering procedure reduces storage and disposal costs (Yan et al., 2018).

Sludge digestion: a biological process that stabilizes sludge by reducing organic content, lowering the risk of hazardous bacterial growth and odors (Carneiro et al., 2020).

Anaerobic digestion: is a method of sludge digestion that creates biogas, a sustainable energy source, in addition to stabilizing the sludge (Carneiro et al., 2020).

Disposal: is a critical stage in which processed sludge is safely and correctly discarded, often in landfills. This guarantees that the sludge does not endanger the environment (Muter et al., 2022).

Incineration: is another form of disposal that involves burning the sludge to considerably reduce its volume. Furthermore, the thermal energy generated can be used for additional purposes (Ahmad & Alam, 2017).

Landfills: serve as a final dumping site for sludge, particularly after incineration (Ahmad & Alam, 2017).

Each stage of the sludge treatment process is critical, with every stage working together to provide safe and effective sludge management. The resulting treated sludge is a considerably more controllable, stable, and volume-reduced substance. It might also be used as a resource, such as a soil conditioner in agriculture or a renewable energy source (Muter et al., 2022; Carneiro et al., 2020).

3.4 Sludge management and policies

For multiple reasons, WTP and WWTP sludge need rules, management, and monitoring, following are some:

Environmental protection: sludge include heavy metals and germs. These might pollute land, water, and air if mismanaged. **Human Health**: poorly handled sludge may contaminate water sources or food crops with diseases or toxic substances. **Odour**: untreated sludge can produce a foul odor, making it unpleasant for people living or working nearby. **Resource Recovery**: sludge treatment can recover nutrients for agriculture and energy from anaerobic digestion. This promotes a circular economy and sustainability. **Regulatory Compliance**: policies and management systems are necessary to ensure compliance with regulations regarding waste management, environmental protection, and public health. E.g., penalties ensure compliance.

WTP and WWTP sludge can present environmental and health dangers than advantages without effective management and monitoring. Responsible and sustainable usage of these resources requires such systems.

3.4.1 European Union policy on usage of sludge and related products

The treatment, disposal, and use of sludge from Water Treatment Plants (WTP) and Wastewater Treatment Plants (WWTP) in the European Union are regulated under a framework aiming at environmental protection and the development of circular economy principles (European Commission, 2020).

The Sewage Sludge Directive (86/278/EEC), which specifies the criteria for the use of sewage sludge in agriculture to prevent detrimental impacts on soil, plants, animals, and humans, is the policy's cornerstone (European Union, 1986). It requires that sludge be treated before use, either by digestion, liming, or another permitted procedure, in order to limit its potential dangers (EU Monitor, n.d.).

The directive establishes heavy metal limitations in sludge and soil where sludge is applied, with the goal of preventing the long-term build-up of dangerous compounds (Mininni et al., 2015). It also requires that the quality of sludge and soil be assessed on a regular basis and that records of sludge usage be retained (European Union, 2023b).

Aside from the Sewage Sludge Directive, the EU supports the concept of a circular economy, in which waste is reduced and resources are reused for as long as feasible. This has consequences for sludge management since it supports nutrient recovery and recycling from sludge (European Commission, 2020).

New views on sludge management are being debated, including proposed amendments to the directive to better align it with circular economy goals and account for growing pollutants of concern (EurEau, 2021; Water Europe, 2021). However, due to concerns about pollution and the presence of pollutants, there are limits on the use of sewage sludge in particular agricultural situations (Hudcová et al., 2019).

3.4.2 Norwegian policy on usage of sludge and related products

The treatment, disposal, and utilization of sludge from Water Treatment Plants (WTP) and Wastewater Treatment Plants (WWTP) in Norway are regulated by national regulations and policies (Lovdata, 2023a). The most important legal documents are the Regulation on sewage sludge (Forskrift om avløpsslam) and the Local rules on the discharge of sanitized wastewater from small and discarded wastewater treatment plants (Lokal forskrift om utslipp av sanitaert avløpsvann fra mindre avløpsanlegg). The sewage sludge regulation establishes standards for the treatment and utilization of sewage sludge, including disposal and methods, with the primary objective of protecting the environment, especially water and soil resources, from potential contamination by hazardous substances present in the sludge (Lovdata, 2023a).

In Norway, sewage treatment and disposal are primarily the responsibility of the municipal water and wastewater sector (VA-finansiering, 2023). Municipal, regional, and national regulations regulate this industry (Kommunal- og moderniseringsdepartement, 2020). Local municipalities are responsible for water services, including sewage and effluent treatment (VA-financing, 2023). These municipalities are required to adhere to the total cost (self-cost) principle (cf. Selvkostprinsippet in Norwegian), which states that the rates levied on customers must cover all the cost of water and wastewater services (VA-finansiering, 2023). The Norwegian Water Association (Norsk Vann) provides technical and legal research assistance to these municipalities (Norsk Vann, 2023a).

The Regulation on sewage sludge and supplementary regulations published by the Norwegian Food Safety Authority (Mattilsynet) outline specific quality standards that must be met for sludge to be used as a fertilizer in agriculture (Mattilsynet, 2023; Landbruksdirektoratet, n.d.). These standards include restrictions on the presence of heavy metals and other contaminants, as well as sanitary requirements for sludge (Norsk vann, n.d.; Landbruksdirektoratet, n.d.). Notably, there is an emphasis on recycling nutrients from municipal sewage sludge and integrating them into a circular economy framework (Norsk vann, 2023b). In addition, interest in producing biogas from sewage refuse is growing (Stortinget, 2023b). However, the use of sewage sludge in agriculture has been the subject of debate and rule changes (Europalov, 2023; Stortinget, 2023a). Concerns have been raised regarding the potential contamination of soil and water resources, as well as the presence of microplastics and emergent pollutants in sludge (Landbruksdirektoratet, n.d.; Landbruksdirektoratet, 2014a; 2014b).

Norway's policy on the treatment, disposal, and utilization of sludge from WTPs and WWTPs is comprised of national regulations, local government operations, and industry practices, with a strong emphasis on environmental protection and circular economy principles (Klima- og miljødepartementet, 2020).

3.4.3 Regulation and organizational convergence and divergence

Water Treatment Plant (WTP) and Wastewater Treatment Plant (WWTP) sludge treatment, disposal, and utilization in the European Union (EU) and Norway show both convergent and divergent regulatory and organizational structures.

In their respective regulatory approaches to sewage sludge, both the EU and Norway emphasize environmental protection and resource recovery. They also share stringent quality standards for the use of effluent and sludge in agriculture, emphasizing hygienic quality requirements and limiting the presence of heavy metals and other contaminants (Lovdata, 2023a; Europalov, 2023; Mattilsynet, 2023). Moreover, the EU and Norway share a commitment to the circular economy, with a focus on recycling nutrients from sewage sludge and the potential production of biogas (Norsk vann, 2023b; Europalov, 2023).

Nonetheless, divergences can also be observed. The decentralized nature of water services in Norway, where local municipalities are predominantly responsible for the treatment and disposal of sludge (VA-finansiering, 2023; Kommunal- og moderniseringsdepartementet, 2020), is a key distinction. EU operates on a more centralized level, member states are responsible for implementing EU-wide regulations and guidelines in their respective jurisdictions (Europalov, 2023).

Another deviation is the controversy surrounding the use of sewage sludge in agriculture in Norway, which is subject to ongoing debate and revision of relevant regulations due to concerns over potential soil and water resource contamination, as well as the presence of microplastics and other emerging contaminants in the sludge (Europalov, 2023; Stortinget, 2023a; Landbruksdirektoratet, 2014a; 2014b). This controversy may not be as prominent in the EU context, as comparative studies have yet to establish.

To elucidate on requirements for resource recovery, both the European Union and Norway stipulate that sludge utilized as a resource, such as in agriculture or energy production, must satisfy specific criteria. However, these requirements may vary in terms of specificity and rigor, necessitating a comparison of respective directives and regulations in great detail (Lovdata, 2023a; Europalov, 2023; Landbruksdirektoratet, n.d.; Mattilsynet, 2023).

Despite the fact that EU and Norwegian regulations share a commitment to environmental protection, resource recovery, and circular economy principles, they differ in their operational structures, degree of centralization, and perhaps the level of debate surrounding agricultural use of sewage sludge. Further exhaustive analysis and comparison of the specific regulations and guidelines of both jurisdictions is recommended for a comprehensive understanding.

3.5 Sludge treatment for resources recovery

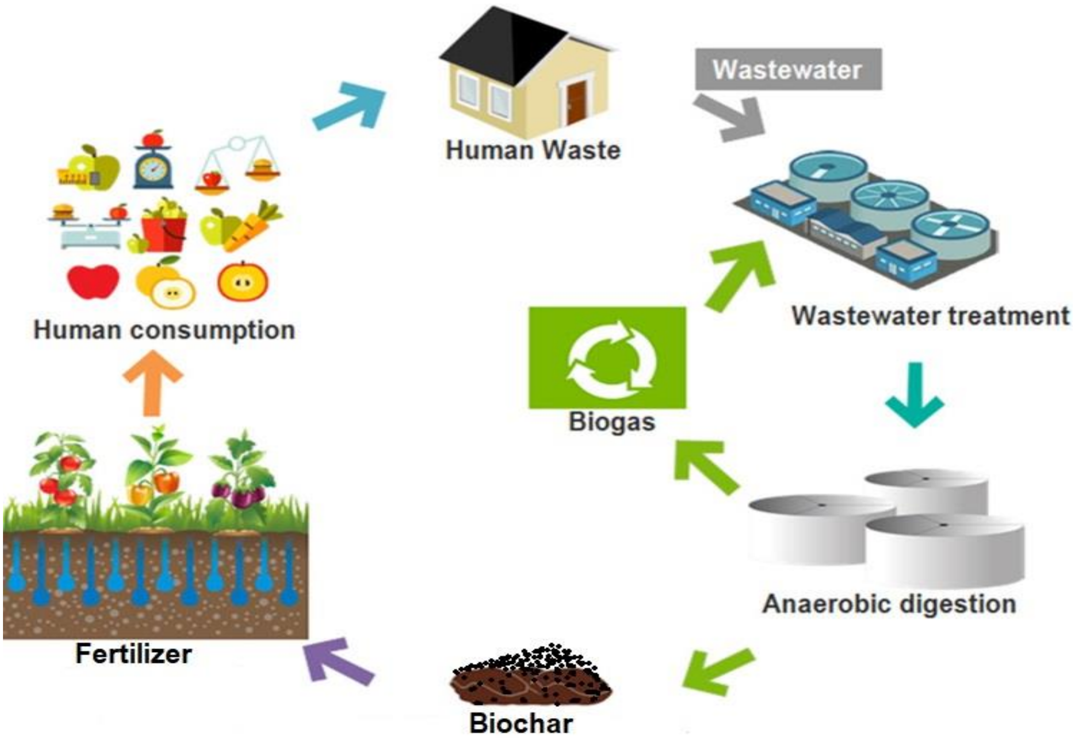


Figure 10: Anaerobic digestion of sewage and their implications for the circular economy. Source: Venegas et al.,2021.

Sludge treatment is vital for resource recovery. Waste can be converted into biogas for electricity and biochar for agriculture, reducing waste (IEA, 2017). The process also reduces water body pollution and greenhouse gas emissions from waste degradation (Rajput et al., 2022). Recovered resources can also boost local economies by creating new revenue streams, jobs, and cost-effective energy and fertilizer alternatives (Farooqi & Khan, 2023).

Sludge treatment for resource recovery processes require technical advancements such as sludge-to-energy mechanisms and wastewater treatment improvements to maximize resource recovery (Mawioo, 2020; Ariza, 2019). Zakaria (2019) states that handling fecal sludge in emergency and underprivileged urban settings requires novel technology and decision-support systems. Khalidi-Idrissi et al. (2023) argue that biological treatment of wastewater rich in emerging pollutants produced by pharmaceutical industrial discharges must be addressed to ensure retrieved resource quality and safety.

Sludge treatment systems need ongoing research to optimize the activated sludge process, including nutrient removal and separation techniques (Lefebvre, 2019; Rossetti et al., 2017). Skilled management tactics can incorporate wastewater treatment methods that prioritize post-treatment, reuse, and disposal techniques to maximize resource recovery (Bhola et al., 2017; Qasim & Zhu, 2017; Riffat & Husnain, 2022).

3.5.1 Drinking water sludge reuse

Drinking water treatment plant sludge known as water treatment residual (WTR) can be used for a variety of purposes such as in construction materials, soil amendment, and land reclamation (Turner et al., 2019). However, the feasibility of these applications is contingent upon the unique characteristics of the sludge, as well as local regulations and market conditions. Managing potential hazards associated with sludge use, such as the presence of harmful substances, is also essential.

Construction materials: WTR is appropriate for use in construction materials since it is inorganic. WTR can be used as a basic material in the manufacture of bricks, cement, and ceramics, thereby reducing the demand for virgin materials and contributing to the conservation of natural resources.

Soil amendment: WTR can also be used to enhance the soil's properties. The organic matter and nutrients present in sludge can improve soil fertility and structure, making it a valuable agricultural amendment.

Land reclamation: sludge is frequently abundant in nutrients and organic matter, which can aid in the restoration of degraded lands and controlling the soil erosion. It can be used in land reclamation initiatives to replenish soil nutrients, promote plant growth, and improve soil structure.

3.5.1.1 Utilization of WTR in the construction sector

Water treatment residuals (WTR) can be utilized in a variety of methods to produce bricks, ceramics, cement, and concrete, among other construction materials. However, the sludge must possess the following characteristics to guarantee the quality and safety of the resulting materials:

Composition: The sludge consists predominantly of inorganic materials, such as silica, alumina, and iron, which contribute to the strength and durability of building materials (Asuncion et al., 2016).

Physical properties: WTR's physical properties, such as particulate size and moisture content, can impact its suitability for use in construction materials. For instance, sludge with small particle sizes and low moisture content can be incorporated into cement and concrete more readily (Liu et al., 2022).

Chemical properties: The sludge's chemical properties, such as pH and the presence of beneficial elements such as calcium and silica, can impact its reactivity and contribution to the strength of the materials. Nevertheless, it is essential to limit the presence of potentially hazardous substances such as heavy metals (Duan et al., 2020).

Biological properties: The sludge should be adequately treated to reduce the presence of microorganisms and organic matter, which can compromise the quality and safety of building materials (Tarique et al., 2016).

Quality: The consistency of the sludge's quality is essential for the uniformity of the final product. Regular physical, chemical, and biological testing of sludge and the resulting products should be implemented as part of stringent quality control procedures (Pham et al., 2021).

Following are the advantages of using WTR as construction materials:

Bricks and Ceramics: due to its high silica and alumina content, WTR can be utilized in the production of brickwork and ceramics. WTR can be combined with clay or other ceramic materials, dried, and fired at high temperatures to produce bricks or ceramic products. To assure proper firing, the WTR must have a low organic content (Wolff et al., 2015).

Cement and Concrete: due to its pozzolanic properties, WTR can be utilized in the production of cement and concrete, thereby enhancing the products' strength and durability. WTR can be used to substitute a portion of the cement and aggregates in concrete. To ensure environmental safety, the WTR must have a low heavy metal content (Pham et al., 2021; Liu et al., 2022; Ruviaro et al., 2021).

Road Construction: due to its high alumina and silica content, WTR can be utilized as a soil stabilizer during road construction. In road construction, the stabilized soil can function as a subbase or base layer. For this application, the sludge should have excellent binding properties and a low organic content (Asuncion et al., 2016).

3.5.1.2 Utilization of WTR in soil amendment

Water treatment plant sludge (WTR) can be utilized as a soil amendment due to its high concentration of inorganic components such as aluminum, iron, and occasionally calcium. It can provide beneficial nutrients, improve soil structure, and increase water retention, making it suitable for agricultural lands, gardens, and land reclamation sites. WTR can be incorporated into the subsoil or utilized as a surface covering. Its use must be carefully regulated to prevent possible threats to the environment and human health. (Asuncion et al., 2016; Verlicchi & Masotti, n.d.).

The following are some advantageous properties and attributes of WTR:

Composition: WTR's large levels of inorganic constituents are advantageous for improving soil structure and fertility. To ensure safety, it should be low in hazardous substances such as heavy metals and pathogens (Tarique et al., 2016).

Physical properties: WTR is typically a fine, granular material that can improve soil structure by increasing its capacity to retain water and nutrients (Asuncion et al., 2016).

Chemical properties: WTR is frequently alkaline in composition, which can be advantageous for balancing the pH of acidic soils. Its high aluminum and iron content can be used to bond phosphorus and reduce its discharge into waterways (Dahhou et al., 2023).

Biological properties: WTR may contain organic matter and beneficial microorganisms, which can boost soil fertility and microbial activity (Asuncion et al., 2016).

Quality: The presence of hazardous substances, such as heavy metals and pathogens, determines the grade of WTR as a soil amendment (Tarique et al., 2016). It should be treated and evaluated to ensure that it complies with relevant regulatory standards for safe use in agriculture.

3.5.1.3 Utilization of WTR in land reclamation

Water Treatment Residuals (WTR) can be used as a soil additive to play a significant role in land reclamation. Its organic content, nutrients, and minerals can enhance soil structure and fertility, allowing plants to thrive and ecosystems to recover. WTR's efficacy is mostly determined by its composition, and physical, chemical, and biological features (Boscov et al., 2021; Tarique et al., 2016; Verlicchi & Masotti, n.d.).

Following are some significant characteristics and attributes WTR have:

Composition: WTR is often high in organic matter, and vital nutrients such as nitrogen, phosphorus, and potassium. It contains minerals such as aluminum, iron, and silica. This combination has the potential to improve soil structure and fertility (Tarique et al., 2016; Boscov et al., 2021).

Physical properties: Sludge with a high moisture-holding capacity and adequate density might enhance soil texture and structure, root penetration, soil water-holding capacity, and potentially reduce soil erosion (Breesem & Manal, 2016; Dube et al., 2018).

Chemical properties: WTR can have a high pH and residual coagulants such as alum and ferric chloride depending on the treatment technique. These can aid in the neutralization of acidic soils and the immobilization of some pollutants. To minimize soil contamination or injury to the local flora and fauna, the sludge should have a neutral to slightly alkaline pH, low salinity, and low amounts of heavy metals and hazardous chemicals (Tarique et al., 2016; Letshwenyo & Mokgosi, 2021).

Biological properties: WTR contains microorganisms that aid in nitrogen cycling and soil health. WTR, on the other hand, should be thoroughly treated to eliminate any possible microorganisms (Asuncion et al., 2016; Bhujbal, 2023).

Quality: WTR quality should be thoroughly checked for impurities such as heavy metals and hazardous organic compounds. To lower odor and pathogen levels, the sludge should be stabilized and sanitized. Its quality should fulfill local land application restrictions (Tarique et al., 2016; Asuncion et al., 2016).

WTR can be put to the soil's surface or mixed in as an amendment. Its use can enhance soil qualities, making them more favorable for plant growth and aiding in land reclamation initiatives. To mitigate any possible dangers, the specific application of WTR should be led by rigorous characterization, safety evaluations, and local restrictions. To assure the compatibility and safety of the sludge and the location for land reclamation, a thorough investigation of the sludge and the site is required (Dube et al., 2018; Turner et al., 2019; Wang et al., 2018).

3.5.1.3 Utilization of WTR to remove P and N from wastewater

Drinking water treatment plant sludge (WTR) can be used to remove phosphate (P) and nitrogen (N) from wastewater. These pollutants contribute to the eutrophication of surface water bodies, resulting in toxic algal blooms and consequent oxygen depletion in the water, harming aquatic life (Asuncion et al., 2016).

WTR has the following major qualities and attributes:

Composition: WTR is composed mostly of iron, aluminum, and calcium compounds, which may bind phosphates and nitrates and thereby remove them from wastewater (Wang et al., 2021).

Physical properties: WTR's physical characteristics, such as particle size, porosity, and specific surface area, can influence its capacity to adsorb phosphorus and nitrogen. Smaller particles with higher porosity and surface area are more effective in general (Wang et al., 2014).

Chemical properties: the chemical characteristics of WTR, notably its metal ion concentration, are crucial for nutrient removal. These ions can form insoluble complexes with phosphates and nitrates, removing them from solution (Wang et al., 2019).

Biological properties: because of the treatment steps it goes through, WTR is "normally" a sterile substance. As a result, its biological characteristics are rarely important for nutrient removal (Ahmad et al., 2016).

Quality: WTR quality should be such that it contains no dangerous pollutants that might be leached into the environment. Routine testing and compliance with applicable standards are critical (Tarique et al., 2016).

WTR can be utilized either directly or after treatment to improve its nutrient removal capability. Acid treatment, for example, can improve the solubility of metal ions in WTR, enhancing its capacity to remove phosphorus (Yang et al., 2014). Furthermore, thermal treatment can increase WTR's physical and chemical characteristics, improving its performance (Boscov et al., 2021).

Overall, WTR has tremendous potential for removing phosphorus and nitrogen from wastewater, hence aiding in the avoidance of eutrophication. More study is needed, however, to maximize its usage for this purpose and to handle any environmental dangers.

3.5.2 Wastewater sludge biorefinery

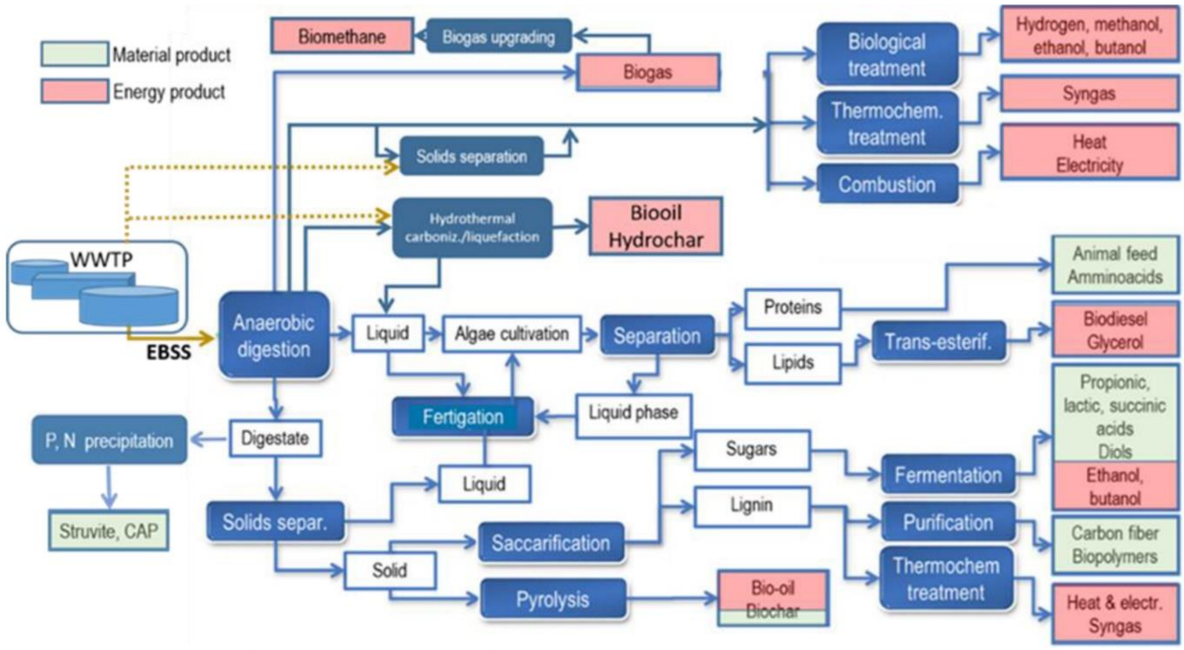


Figure 11: Possible products from a sewage sludge biorefinery. Source: Cecconet & Capodaglio, 2022

The concept of wastewater sludge biorefinery entails using several treatment techniques to transform sludge into a variety of high-value products. The technique increases resource recovery while minimizing waste output, encouraging the circular economy. The biorefinery method allows for the recovery of a wide range of products from wastewater sludge. Among these items are:

Biogas: Anaerobic digestion is a commonly used technique for converting organic matter present in sludge into biogas. The resultant biogas consists mostly of methane (CH_4) and carbon dioxide (CO_2). As mentioned earlier, biogas has the potential to be a sustainable energy source for producing heat and power, or it can be converted into biomethane and injected into existing natural gas infrastructure (Cecconet & Capodaglio, 2022).

Biochar: This product is made from sludge using the pyrolysis method, which includes thermal decomposition. This leads to the production of a carbon-rich solid substance. As mentioned, several times above biochar has the potential to be useful in soil amendment, carbon sequestration, and energy generation (Hemmati & Abedzadegan, 2019).

Nutrient-rich fertilizers: The processing of sludge can result in nutrient-rich fertilizers containing vital elements such as nitrogen (N), phosphorus (P), and potassium (K) that can be used in agriculture. The use of nutrient-rich fertilizers can reduce reliance on synthetic fertilizers and help to close the nutrient loop (Cecconet & Capodaglio, 2022).

Organic acids: The sludge fermentation process can produce organic acids such as acetic acid (CH3COOH), propionic acid (CH3CH2CO2H) also known as propanoic acid, and butyric acid (CH3CH2CH2CO2H). These organic acids have the potential to be useful in a variety of sectors, including the chemical and pharmaceutical domains (Farghali et al., 2022).

Hydrogen (H2): This product may be produced through various methods, one of which is the thermochemical conversion of sludge. Hydrogen has a high energy potential and may be used as a sustainable fuel or in a variety of industrial applications (Farghali et al., 2022).

Value-added chemicals: Using sludge as a feedstock to produce value-added chemicals such as volatile fatty acids (VFAs), bio-based polymers, and bio-based solvents is a viable option. Such chemicals have the potential to replace fossil fuel-based alternatives, facilitating the creation of a more ecologically responsible chemical sector (Cecconet & Capodaglio, 2022).

Water treatment sludge biorefinery can produce a wide range of products. Variables such as the specific treatment procedures used, the characteristics of the sludge, and market demand for the products all influence the determination and amalgamation of these products.

3.5.3 Anaerobic digestion

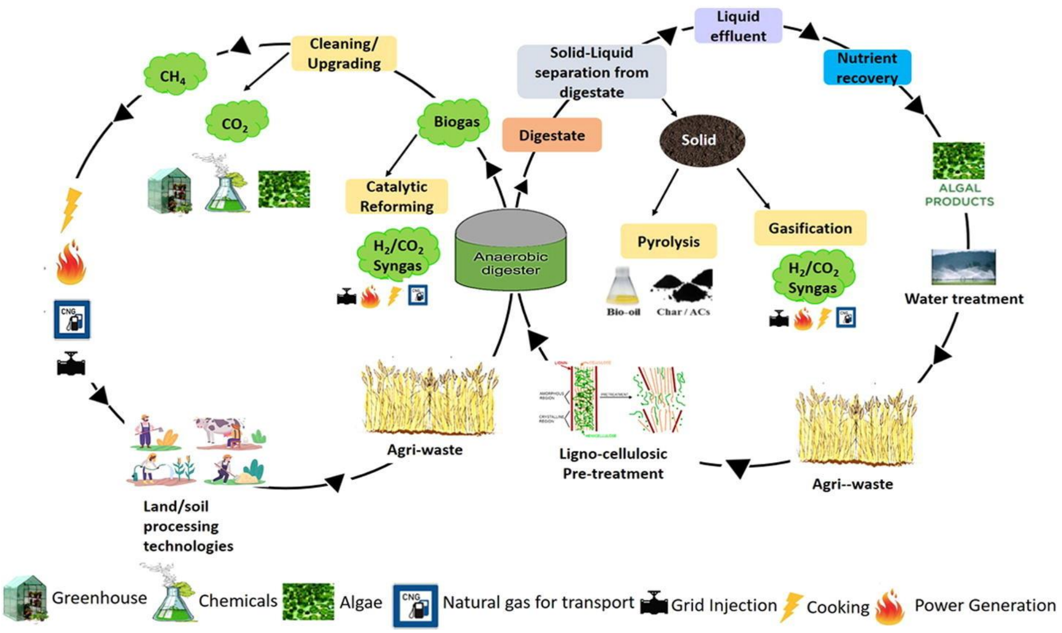


Figure 12: Valorization of agricultural waste for biogas based circular economy. Source: Kapoor et al., 2020

Anaerobic digestion is a series of biological processes in which microorganisms decompose organic matter in the absence of oxygen (Venegas et al., 2021). Four stages comprise the process: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During these stages, organic materials are broken down into simpler compounds and ultimately methane, carbon dioxide, and trace gases, which are referred to collectively as biogas (Kapoor et al., 2020).

In contrast to other methods of organic waste treatment, anaerobic digestion operates in an oxygen-free environment and produces methane as a byproduct. Other methods, such as composting and incineration, expose waste to oxygen and produce predominantly heat and carbon dioxide as residues. Aerobic processes are also more costly in terms of energy due to the need for a constant supply of oxygen, whereas anaerobic digestion produces net energy (Cecconet & Capodaglio, 2022).

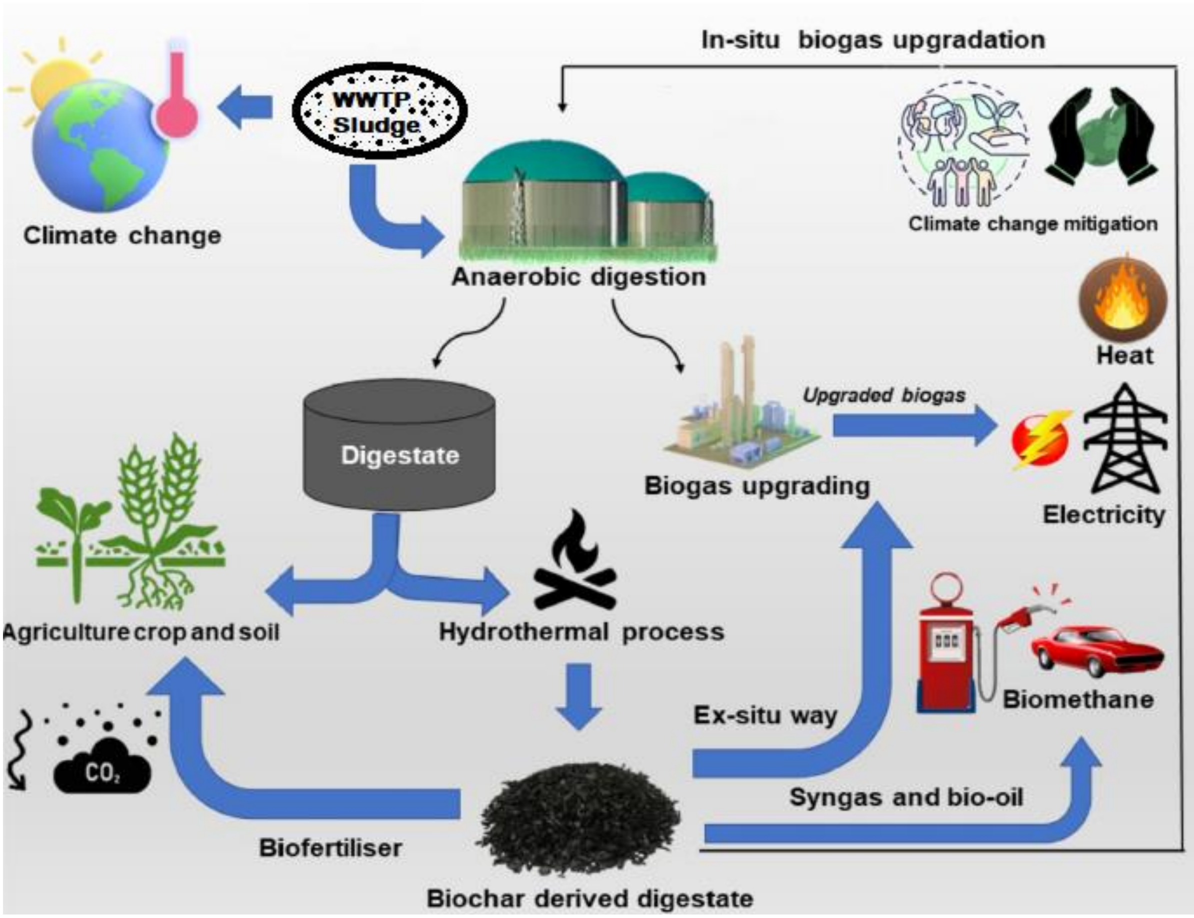


*Figure 13: Integration of biogas systems into a carbon zero and hydrogen economy. Source: **Farghali** et al., 2022*

Anaerobic digestion can result in multiple products and services. First, biogas production provides a renewable energy source that can be used for heating, electricity generation, or conversion to biomethane for use in gas networks or as a vehicle fuel. The digestate (bio-residues), which is the residual material after digestion, is a nutrient-rich biofertilizer that can replace synthetic fertilizers in agriculture. In addition, water recovery and utilization from the digestion process could decrease freshwater consumption. The process can also contribute to waste management services by decreasing the volume and mass of organic waste (Kapoor et al., 2020; Symbiosis Center Denmark, 2019b).

By converting organic waste into valuable resources, such as biogas and digestate, anaerobic digestion positively impacts the green transition and the circular economy. This procedure reduces greenhouse gas emissions by capturing the potent greenhouse gas methane and using it as a source of renewable energy. Additionally, it reduces reliance on fossil fuels and synthetic fertilizers, which promotes resource efficiency and sustainability (Venegas et al., 2021; World Bank, 2020).

However, there are possible negative impacts. When digestate is applied to land, anaerobic digestion may not effectively remove micropollutants from effluent, posing environmental and human health threats. This issue necessitates careful management and more investigation to optimize the digestion process for micropollutant removal (Venegas et al., 2021).

Anaerobic digestion plays an essential role in increasing the production and sale of biogas and biochar derived from WTP and WWTP sludge. The residue remaining after anaerobic digestion can be utilized to generate biochar, a carbon-rich byproduct of the pyrolysis of organic materials. WTPs and WWTPs can generate revenue by marketing biogas and biochar as renewable energy sources and soil amendments (Bandyopadhyay et al., 2021; EBC, 2023).

By incorporating anaerobic digestion into a biorefinery model for sewage sludge, WTPs, and WWTPs can increase their production, revenue, and sustainability. The central process of this model is anaerobic digestion, which is supplemented by pyrolysis for biochar production and water recovery systems. This model optimizes the recovery of resources from waste, adds value to residues, and reduces the environmental impact of waste treatment (Cecconet & Capodaglio, 2022).

Implementing anaerobic digestion strategically in WTPs and WWTPs necessitates consideration of technical, economic, and environmental factors. To determine the optimal scope and structure of the digestion system, technical feasibility studies must be performed. Economic analyses should consider capital and operational costs, potential revenues from biogas and digestate sales, and the possibility of cost reductions from reduced waste disposal and energy consumption. Environmental assessments should consider greenhouse gas emissions, nutrient recycling potential, and impacts on water resources (Hu et al., 2020; Ge et al., 2023).

Within the context of the circular economy, anaerobic digestion is a viable method for organic waste management. It can increase the production and sale of valuable products such as biogas and biochar, thereby improving the profitability and sustainability of WTPs and WWTPs. However, cautious planning and administration are necessary to maximize its benefits and mitigate any potential negative effects (Wiesmeth, 2020).

3.5.4 Gasification

Gasification is a thermal conversion process that transforms organic or fossil-based carbonaceous materials into carbon monoxide, hydrogen, and carbon dioxide (Carlson & Ebben, 2022). In the case of sludge treatment, organic solid waste undergoes controlled thermal conversion in an oxygen-deficient environment, resulting in the formation of syngas, a mixture primarily constituted of hydrogen, carbon monoxide, and frequently a small quantity of methane (Hemmati & Abedzadegan, 2019). By extracting energy and nutrients from waste, this process can contribute to resource recovery in a circular economy (Cecconet & Capodaglia, 2022).

The nature of the reaction environment and the ultimate product differentiate gasification from other methods such as digestion, combustion, and pyrolysis (Hemmati & Abedzadegan, 2019). Gasification can produce a variety of products and services. Direct byproducts of the gasification process include syngas, which can be upgraded to produce biofuels and synthetic chemicals or used directly in gas engines, turbines, or fuel cells to produce electricity and heat (Xu & Lancaster, 2012). In addition, the process can produce biochar that can be used as a soil amendment to increase soil fertility and sequester carbon, thereby contributing to the mitigation of greenhouse gas emissions (Muter et al., 2022). Moreover, the nutrient-rich ash produced can be used as a fertilizer in agriculture, thereby contributing to nutrient recovery (Cecconet & Capodaglio, 2022).

Gasification contributes in multiple ways to the green transition and circular economy. The process enables the conversion of waste into valuable resources such as biochar and syngas, resulting in a decrease in waste disposal in landfills, greenhouse gas emissions, and dependence on fossil fuels (Wiesmeth, 2020). It encourages the utilization of local waste resources, thereby contributing to energy security and local economic growth (Scholten & Bosman, 2016). However, barriers such as high initial investment costs, technical complexities, and public acceptability issues can hinder the wide-scale implementation of gasification technologies (Nevzorova et al., 2019).

Gasification can be an effective part of a broader strategic approach for increasing the production and sale of biogas and biochar derived from WTP and WWTP sludge. By incorporating gasification into the treatment process, facilities can increase resource recovery and generate additional revenue through the sale of energy and biochar (Bachmann, 2015). However, a comprehensive techno-economic analysis that considers local conditions and market conditions is essential (SEAI, 2017).

Through collaborations in an industrial symbiosis model, in which waste and by-products from one industry serve as inputs for another, the strategic implementation of gasification in WTP and WWTP could be facilitated (Hu et al., 2020). For example, the heat generated during the gasification process can be utilized by other industries in an eco-industrial park (Symbiosis Center Denmark, 2017a), while biochar and ash can be sold to the agriculture sector (Cecconet & Capodaglia, 2022). Furthermore, municipal policies that encourage the development of these symbiotic networks can facilitate their growth (Symbiosis Center Denmark, 2021).

WWTPs and WTPs can allocate resources for the implementation of gasification as part of a sustainability strategy, based on the benefits derived from improved energy efficiency, reduced waste disposal costs, and revenue from byproducts, which can contribute to improving the long-term sustainability of the plants (Ingenbleek & Krampe, 2023; Wang et al., 2020).

3.5.8 Direct liquefaction

Direct liquefaction of sludge is a technology for sludge treatment for resource recovery that converts sludge from WTPs and WWTPs into liquid fuels and valuable compounds (Yan et al., 2020). In general, the process entails a series of thermochemical reactions under high pressure and temperature, which reduces the sludge's water content and decomposes complex organic substances into simpler forms (Amoedo et al., 2020).

Direct liquefaction differs from other methods such as digestion, combustion, gasification, and pyrolysis in that it produces bio-crude oil of higher quality and requires less energy input due to the sludge's inherent water content (Hemmati & Abedzadegan, 2019). In addition, unlike other technologies, it does not require a dehydrating procedure prior to liquefaction, which makes it more energy-efficient and cost-effective (Yan et al., 2020).

Direct liquefaction can result in a variety of products and services. It has the potential of producing bio-crude oil, which can be refined into renewable diesel, gasoline, and aviation fuel. It also produces biochar that can be used as a soil amendment or as activated carbon, and an aqueous phase product rich in nutrients such as nitrogen (N), phosphorus (P), and potassium (K) that can potentially be used in the production of fertilizer. In addition, gaseous products such as hydrogen (H2), carbon dioxide (CO2), and methane (CH4) could be produced and utilized for energy recovery or chemical synthesis (Yan et al., 2020).

The direct liquefaction of waste contributes substantially to the green transition and circular economy. It utilizes a waste product (sludge), thereby reducing waste disposal in landfills and the associated environmental impacts. In addition, it generates renewable energy products, such as bio-crude oil and gas, which contribute to the reduction of fossil fuel consumption and greenhouse gas emissions (Cecconet & Capodaglio, 2022). However, if not properly administered, it could negatively impact the environment. The process may produce hazardous substances such as heavy metals, polycyclic aromatic hydrocarbons (PAHs), and other organic pollutants that must be adequately treated to prevent contamination (Amoedo et al., 2020).

The strategic implementation of direct liquefaction could increase WTP and WWTP's production and revenues. The sale of bio-crude oil, biochar, and fertilizers derived from the process could generate additional revenue. In addition, the produced gas could be used for energy requirements within the treatment facilities, thereby reducing energy costs (Xu & Lancaster, 2012). By converting waste into valuable resources, these facilities may reach a higher level of sustainability and conform to the principles of the circular economy (Cecconet & Capodaglio, 2022).

Direct liquefaction has the potential to be a viable technology for resource recovery from sludge, contributing significantly to the green shift, circular economy, and WTP and WWTP sustainability. Nonetheless, mindful management is necessary to mitigate potential environmental impacts.

3.5.9 Supercritical water oxidation (Hydrothermal oxidation)

Supercritical water oxidation (SCWO), also known as hydrothermal oxidation (HTO), is a resource recovery technique for sewage. To facilitate the oxidation of organic compounds in sludge, this process employs supercritical water, i.e., water under high pressure and temperature conditions that give it the properties of both a liquid and a gas (Xu & Lancaster, 2012). SCWO is a promising technology for resource recovery and waste minimization because it effectively degrades organics and converts sludge into innocuous end products such as carbon dioxide, water, and nutrients (Xu & Lancaster, 2012).

The process dynamics and product yield differentiate SCWO from other methods such as anaerobic digestion, combustion, gasification, and pyrolysis. The mentioned processes generate products that can be utilized as a fuel source. Nevertheless, they frequently leave behind residual solid waste that must be managed (Hemmati & Abedzadegan, 2019). In contrast, pyrolysis and SCWO yield more valuable byproducts, such as biochar and bio-oil (Hemmati & Abedzadegan, 2019; Carlson & Ebben, 2022).

SCWO can result in the creation of a variety of beneficial products. These include heat and power as a result of the exothermic nature of oxidation reactions, pure water for reuse, and nutrients such as phosphorus and nitrogen that can be recovered and used as fertilizers (Muter et al., 2022; World Bank, 2020; Xu & Lancaster, 2012). SCWO is a prospective contributor to resource recovery and circular economy initiatives due to its high efficiency and product diversity (Cecconet & Capodaglia, 2022).

The SCWO process can positively contribute to the green shift and circular economy by maximizing the use of resources and decreasing environmental pollution. For instance, the recovery of heat and nutrients in SCWO can offset the energy and fertilizer requirements of WTP and WWTP (Cecconet & Capodaglia, 2022). Moreover, SCWO reduces the emission of hazardous pollutants, thereby contributing to an improvement in environmental health (Xu & Lancaster, 2012). However, SCWO has potential disadvantages. The procedure necessitates high pressure and temperature, resulting in high energy requirements and operational expenditures (Xu & Lancaster, 2012). The corrosive nature of the SCWO environment also poses difficulties in terms of material selection and equipment durability, potentially increasing the total operating costs (Xu & Lancaster, 2012).

While SCWO does not directly produce biogas, the thermal energy recovered from the process can be used to enhance other biogas-producing methods, such as anaerobic digestion, thereby increasing overall plant efficiency (Bachmann, 2015). The nutrients recovered from SCWO can also be used to increase biogas production from energy crops when applied to agricultural land (Nevzorova et al., 2019). SCWO's biochar has prospective applications in agriculture for enhancing soil fertility and crop yield, as well as in the industry as a raw material for activated carbon production (Carlson & Ebben, 2022; Dickinson et al., 2015).

Strategic SCWO implementation in WTPs and WWTPs can enhance production, revenues, and sustainability. SCWO can be incorporated into the existing infrastructure as a tertiary treatment stage, utilizing high-organic-content sludge as a resource for energy and nutrient recovery (Cecconet & Capodaglio, 2022). By decreasing waste volume and recovering valuable products, SCWO can increase revenue and contribute to the sustainability objectives of the facilities. Moreover, SCWO integration can promote industrial symbiosis, in which waste or residues from one process become input for another, thereby increasing the overall plant efficiency (Agudo et al., 2023; Hu et al., 2020).

3.5.4 Pyrolysis

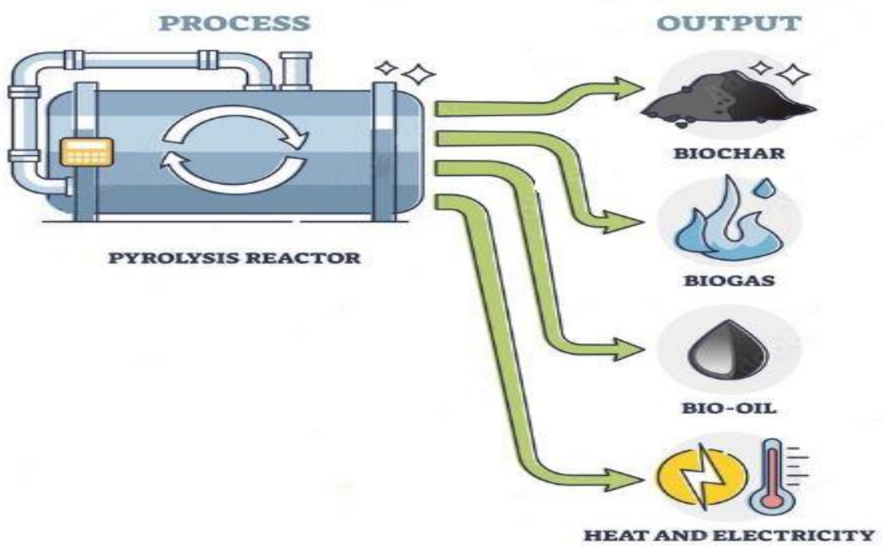


Figure 14: Pyrolysis process. Source: www.stock.adobe.comA

In sludge treatment, pyrolysis is a thermochemical decomposition process in which organic materials are broken down into simpler compounds by heating in the absence of oxygen (Barry et al., 2019). Pyrolysis enables the conversion of sludge, a byproduct of WTP and WWTP into valuable products such as syngas, biochar, and bio-oil, thereby contributing to the principles of resource recovery and circular economy (Barry et al., 2019).

The main difference between pyrolysis and other processes such as digestion, combustion, and gasification rests in the procedure and the resulting products. Pyrolysis operates in an oxygen-free environment and yields a mixture of solid, liquid, and gaseous fuels (Hemmati & Abedzadegan, 2019).

The pyrolysis byproducts, which include syngas, biochar, and bio-oil, have various uses. Biochar can increase soil fertility and agricultural yields. It can also be used as a source of activated carbon to purify polluted water or gases (Dickinson et al., 2015; Carlson & Ebben, 2022). Syngas, a combination of hydrogen and carbon monoxide, can be converted into other compounds or used to generate heat and electricity. Bio-oil, a liquid product, can be converted into transportation fuels or used in the chemical industry (Barry et al., 2019).

Pyrolysis contributes positively to the green shift and circular economy by converting waste into valuable resources, thereby reducing the demand for virgin materials and fossil fuels. The production of biochar reduces the demand for chemical fertilizers, thereby reducing the environmental impact of agriculture (Dickinson et al., 2015). Unfortunately, pyrolysis can produce pollutants such as particulate matter, polycyclic aromatic hydrocarbons (PAHs), and heavy metals, which, if not properly managed, can have negative environmental effects (Barry et al., 2019). Regarding biogas production, pyrolysis does not produce biogas on its own, but it can supplement anaerobic digestion (a biogas-producing procedure) in a biorefinery context. This integration can optimize resource recovery from sludge, contributing to the profitability and sustainability of WWTP and WTP (Cecconet & Capodiglio, 2022; Bachmann, 2015).

Strategic implementation of pyrolysis in WWTP and WTP necessitates meticulous planning and integration with existing systems. For instance, the heat produced by pyrolysis can be used to increase biogas production by enhancing the digestion process (Xu & Lancaster, 2012). In addition, the synergy between pyrolysis and other sludge treatment processes can be part of an industrial symbiosis model, thereby increasing the overall efficiency and sustainability of the system (Hu et al., 2020; IWA, 2022). In terms of revenue generation, the sale of pyrolysis products can provide WWTP and WTP with a substantial revenue stream. For example, the sale of biochar to agricultural sectors or the use of syngas for on-site energy generation can reduce operational costs and improve the economic viability of these facilities (Dickinson et al., 2015; SEAI, 2017). Therefore, incorporating pyrolysis into WWTPs and WTPs can contribute to the overall objective of attaining a circular economy in water and waste management by transforming waste into valuable resources and improving the sustainability and profitability of these facilities (KWR, 2019; Muter et al., 2022).

3.5.3 Composting

Composting in sludge treatment for resource recovery entails the bio-oxidative degradation of organic matter present in sewage sludge by microorganisms. This process contributes to the transformation of organic matter into stable humus-like substances, resulting in the sanitization and stabilization of sludge, thereby reducing its volume and potential health hazards, as well as the production of nutrient-rich soil amendment. In addition, decomposition could reduce the demand for synthetic fertilizers, contributing to the circular economy (Muter et al., 2022).

Composting is distinct from waste treatment techniques such as digestion, combustion, gasification, and pyrolysis. Composting, on the other hand, concentrates predominantly on resource recovery, particularly nutrients and organic matter for soil amendment (Hemmati & Abedzadegan, 2019; Barry et al., 2019; Muter et al., 2022).

Composting produces a variety of primary products, including compost for agricultural use that can increase soil fertility and productivity, thereby contributing to a more sustainable food production system (Muter et al., 2022). This method can also be incorporated into the strategy of a WWTP to attain a circular economy and enhance its sustainability (IWA, 2022). In addition, the process can contribute to the green transition by recycling nutrients and reducing greenhouse gas emissions in comparison to other sludge disposal methods (Muter et al., 2022). Negatively, composting necessitates a sizable area for operation, and the process is susceptible to atmospheric conditions. In addition, it can emanate greenhouse gases and produce aromas, which could have a negative impact on the local environment and population (Muter et al., 2022).

Strategic composting implementation could increase WWTP production and revenue. By selling the compost produced, a WWTP can generate additional revenue. The compost could be sold to the agriculture industry or residential garden proprietors, thereby reducing the WWTP's overall operating costs and fostering local circular economies (Muter et al., 2022).

Composting does not directly contribute to the production of biogas or biochar, but it could be a component of a larger integrated strategy for sludge management in WWTP. It is possible to implement a combination of digestion (for biogas production) and composting, where the digested byproducts are composted. Alternatively, biochar could be created through pyrolysis and then combined with compost to produce a high-quality soil amendment (Barry et al., 2019; Dickinson et al., 2015).

3.5.4 Incineration

In the context of sludge treatment and management, incineration refers to the thermal decomposition of organic matter present in wastewater sludge at high temperatures (typically greater than 850°C). The process achieves an important reduction in volume, sterilizes the sludge, and enables the recovery of energy in the form of heat, which can be used to generate electricity or for heating (Xu & Lancaster, 2012).

In comparison to other waste treatment methods such as digestion, combustion, gasification, and pyrolysis, incineration possesses numerous distinctive characteristics. Combustion can be approached to incineration, but this first typically operates at lower temperatures and under less stringent control (Hemmati & Abedzadegan, 2019).

Products and services derived from sludge incineration include the generation of heat and electricity, as well as the recovery of residue (ash) and metals. Incineration produces steam that can be used to generate electricity due to the high temperatures involved. The process also produces ash, which, after appropriate treatment and elimination of hazardous substances, can be used in construction materials or as a source of phosphorus in agriculture (Cecconet & Capodaglio, 2022). In addition, incineration enables the recovery of metals embedded in sludge, thereby facilitating recycling (Cecconet & Capodaglia, 2022).

The green shift and the circular economy are affected both positively and negatively by incineration. Positively, energy recovery from incineration reduces reliance on fossil fuels, which is consistent with the broader objectives of energy transition (Scholten & Bosman, 2016). In addition, the recovery and recycling of resources (such as metals and phosphorus) from the ash are consistent with the principles of a circular economy, thereby contributing to resource efficiency (Cecconet & Capodiglio, 2022). On the negative, incineration can contribute to greenhouse gas (GHG) emissions, especially CO2, if the sludge contains a significant amount of non-renewable organic material (Wiesmeth, 2020). Further, it may discourage the production of biogas from anaerobic digestion, which is more beneficial in terms of GHG emission reduction and alignment with the principles of the circular economy (SEAI, 2017). However, the optimal choice between incineration and anaerobic digestion is dependent on the local context, including energy and nutrient requirements, as well as environmental regulations (Bachmann, 2015).

Incineration can indirectly support the production and sale of biogas and biochar derived from WWTP and WTP sludge. While incineration does not produce these products, it can be used as a complementary solution when biogas or biochar production is not feasible or optimal, such as when sludge has low biodegradability or a high heavy metal content (EBC, 2023; Hemmati & Abedzadegan, 2019). Incineration can play a significant role in increasing the profitability and sustainability of WTPs and WWTPs. It can reduce disposal costs and generate revenue through the sale of electricity, heat, recovered metals, and purified ash. In addition, reducing the volume and public health hazards associated with sludge, increases the social acceptability of the sludge management process, thereby contributing to the sustainability of WTPs and WWTPs (Cecconet & Capodiglio, 2022; Xu & Lancaster, 2012).

In the context of industrial symbiosis, the heat and electricity produced by incineration can be supplied to adjacent industries, creating a mutualistic relationship that improves resource efficiency overall (Hu et al., 2020). Another possibility is that purified ash can be exchanged with industries requiring phosphorus or construction materials, thereby creating a network of industrial symbiosis that would benefit all parties involved (Symbiosis Center Denmark, 2017a; Hu et al., 2020).

Incineration can play a vital role in the treatment and management of sludge, contributing to resource recovery, energy transition, and the circular economy. However, its role should be evaluated carefully in light of the local context and in conjunction with other treatment options.

3.5.5 Landfilling

In sludge treatment and management for resource recovery, landfilling refers to the disposal of sludge in landfills, where it decomposes over time. In contrast to other methods such as anaerobic digestion, incineration, and composting, landfilling does not actively extract energy or valuable resources from the residue. It involves the confinement and storage of sludge in engineered landfills (Hemmati & Abedzadegan, 2019; Muter et al., 2022). As technological advancements may permit future recovery and utilization of sludge resources, landfilling can also serve as a temporary storage option (Cecconet & Capodaglia, 2022).

Compared to the other aforementioned methods for sludge management, landfilling has traditionally been regarded as the simplest and often the most cost-effective option. As a result of the potential for leachate and greenhouse gas emissions, landfilling is also the least sustainable method. This is due to the advantages of other methods which seek to extract value from waste. (Hemmati & Abedzadegan, 2019; Barry et al., 2019; Carlson & Ebben, 2022).

Direct derivatives from landfilling are usually landfill gas (a mixture of methane and carbon dioxide), which can be captured and incinerated to produce renewable energy sources such as heat or electricity (Symbiosis Center Denmark, 2019b). Biochar can be landfilled to sequester carbon and improve soil quality. In addition, the nutrient-rich leachate can be collected, treated, and utilized as fertilizer, albeit with precautions (EBC, 2023; Muter et al., 2022).

Strategically managed landfilling can contribute positively to the green transition and circular economy. For instance, it is possible to reduce greenhouse gas emissions and generate renewable energy by capturing and using landfill gas for energy (SEAI, 2017). However, the process is intrinsically linear, whereas other treatment methods, such as pyrolysis or digestion, may generate products with additional value in a circular economy, such as biochar or biogas. Leachate and methane emissions may result from improper landfill management, thereby contributing to groundwater contamination and climate change (Bachmann, 2015; Barry et al., 2019; Muter et al., 2022).

Regarding the production of biogas and biochar from WWTP and WTP sludge, landfilling seems counterintuitive, as it typically implies waste burying and containment rather than value recovery (Hemmati & Abedadegan, 2019). However, landfill gas and biogas share a comparable chemical composition and can be utilized similarly (SEAI, 2017). In contrast, landfilling biochar produced from sludge pyrolysis can enhance soil quality and provide carbon sequestration over the long term (EBC, 2023).

Through the development of a circular economy model that views waste as a resource rather than a problem, landfilling can be used strategically within WWTPs and WTPs to improve production, revenue, and sustainability. For instance, incorporating landfilling into an industrial symbiosis network can facilitate the sharing of resources such as energy or nutrients and generate revenue from waste management services (Hu et al., 2020; Linkopings universitet, n.d.). By implementing comprehensive management strategies and combining landfilling with other sludge treatment technologies, WTPs, and WWTPs can potentially increase their revenue, sustainability, and contribution to the circular economy (Cecconet & Capodaglio, 2022; IWA, 2022).

Even though landfilling has traditionally been viewed as a final disposal method, its role in a circular economy context is evolving, with opportunities for the generation of energy, material recovery, and integration into expanded industrial symbiosis models.

3.6 Biogas

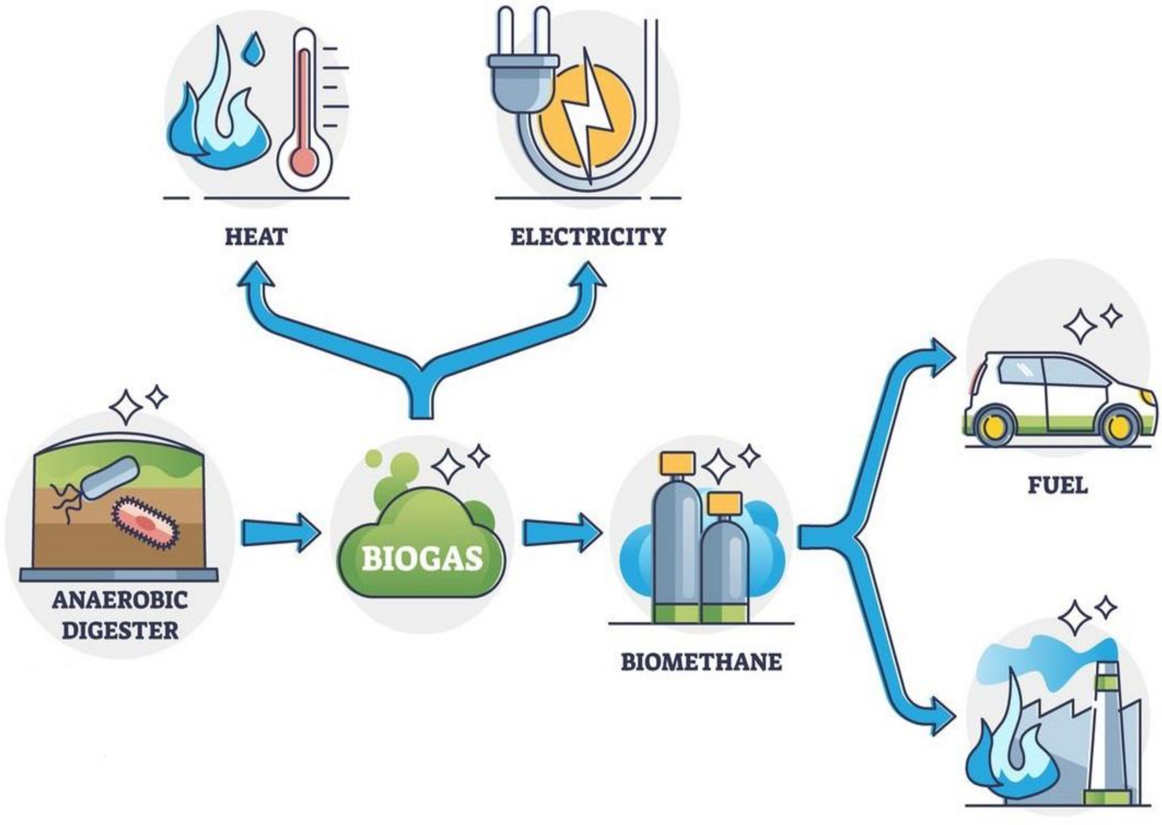


Figure 15: Biogas as source of sustainable energy. Source: Kuchta. 2022.

Biogas in sludge treatment for resource recovery refers to the use of anaerobic digestion to convert organic matter present in wastewater sludge into biogas (a mixture of methane, carbon dioxide, and other trace gases). This conversion method offers a sustainable approach to waste management by producing a renewable energy source and reducing greenhouse gas emissions (Farghali et al., 2022). Biogas is distinguished from other forms of gas primarily by its composition and production process. Biogas is produced by biological decomposition under anaerobic conditions and contains less methane (45% to 85%) than natural gas (70-90%) (Frazier & Ndegwa, 2019; Herout et al., 2018; Cecconet & Capodaglia, 2022).

Anaerobic digestion is the most prevalent, safe, and cost-effective technique for producing biogas from WTP and WWTP sludge. Several variables can impact the production of biogas from sludge. For the growth of bacteria, temperature, pH, the concentration of organic matter, and the balance of nutrients (micro and macronutrients) are crucial factors. For instance, micronutrients such as trace metals are known to play an important role in maintaining microbial health and optimizing the anaerobic digestion process (Cecconet & Capodiglia, 2022).

Using sludge as raw material, a conventional biogas production procedure includes the following steps: pretreatment, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Pre-treatment involves physical, chemical, or thermal processes that prepare the sludge for digestion. The hydrolysis process breaks down complex organic molecules. During the process of acidogenesis, these simpler molecules are broken down further into volatile fatty acids. The process of acetogenesis transforms these fatty acids into acetates. Finally, methanogenesis produces methane from acetates or hydrogen and carbon dioxide (Cecconet & Capodaglia, 2022). There are many different products and services that can be derived from biogas. Using biogas for heat or electricity generation is the most direct method. In addition, biogas can be converted to biomethane, which can be injected into natural gas facilities or used as fuel for vehicles. Due to its high nutrient content, digested sludge can also be used as a fertilizer or soil conditioner (SEAI, 2017).

Biogas production positively impacts the green transition and circular economy by reducing greenhouse gas emissions, providing renewable energy, and recycling nutrients back into the soil. If the digested sludge is not properly treated, it can pose a risk to human health or the environment due to the presence of contaminants or pathogens (Venegas et al., 2021). Several measures can be taken to increase the production and sale of biogas derived from WTP and WWTP sludge. These include enhancing the effectiveness of the digestion process through optimization and the use of innovative technologies, policy support, incentives for the use of renewable energy, and raising awareness about the advantages of biogas (Wang et al., 2020).

By selling the produced energy and byproducts, biogas can influence and be strategically implemented to increase WTP and WWTP's revenues and sustainability. This can generate a new revenue stream and reduce overall waste treatment costs. Moreover, the nutrient recycling aspect of biogas production is consistent with circular economy principles and contributes to sustainability (Israeli, 2021).

3.6.1 Estimation of biogas potential and price

Prior to investment, it is crucial to estimate the potential and price of biogas to ensure financial viability and optimal resource allocation. This forecast assists in estimating potential revenues and repayment period, thereby facilitating investment decisions. Moreover, it informs the sizing of the facility and the operations, which has direct effects on profitability and sustainability.

3.6.1.1 Theoretical Estimation of Biogas potential

The biogas potential of a municipal WWTP WTP can be calculated using various factors such as the amount of personal equivalent (PE), sludge volume, composition of the sludge, volatile solids %VS, total solids %TS, chemical oxygen demand COD, biological oxygen demand BOD, and more. The volatile solids (VS) are what remain after water and inorganic matter have been extracted from the substrate. Volatility quantifies the ease with which a substance can evaporate. Total solids in a liquid are the sum of dissolved solids and suspended solids. VS is a measure of organic matter, and TS is used to determine which digester is adequate for the amount of waste entering the facility (or reactor). There are many formulas to estimate biogas potential; however, some common ones include the calculation of the organic loading rate (OLR) retention time (HRT), and biogas yield (AEPC, 2014; Wu et al., 2016):

$$\mathbf{OLR} = \frac{\text{VS feed}}{\text{Reactor vloume}}\ ;\ \mathbf{HRT} = \frac{\text{Reactor vloume}}{\text{Wastewater flow rate}}\ ;\ \mathbf{Biogas\ yield} = \frac{\text{Biogas volume}}{\text{VS or TS fed}}$$

For example, sludge concentration and quality can have an impact on biogas potential. Higher the %VS or %TS in the sludge, the greater the potential for biogas production, which is influenced by digester temperature and pH (BRC, n.d.; Siddiki et al., 2021). The Biogas recovery rate is another essential factor, which relates to the system's capacity to capture and use the produced biogas (Wanjohi, 2023). The following is the typical chemical composition of biogas (Frazier & Ndegwa, 2019; Herout et al., 2018): 45–85% CH_4 (methane), 20–45% CO_2 (carbon dioxide), and the remainder comprises H_2 (hydrogen), N_2 (nitrogen), and H_2S (hydrogen sulfide).

The following are additional generalized methods for estimating biogas potential, with the understanding that these formulas can provide near approximations, but actual results may vary due to a variety of factors including digester design, feedstock characteristics, and operational conditions:

(1) The estimation of biogas potential can be determined by utilizing the personal equivalent (PE) approach. It is necessary to modify the production rate in accordance with the specific characteristics of the local environment (AEPC, 2014).

Biogas yield (m^3/d) = **PE** $*$ **Average biogas production per person per day**

(2) Given the volume and composition of the sludge, the volatile solids (VS) content can be used to estimate its biogas potential.

Biogas yield (m^3/d) = **Sludge volume** (m^3/d) $*$ **VS content** (kg VS/m^3) $*$ **Biogas yield per VS** (m^3/kg VS).

Yield, also known as biomethane potential, is dependent on feedstock type, composition, and other variables, which can be determined from laboratory tests, published data, or literature values (Siddiki et al., 2021).

(3) Wastewater flow rate and composition (COD, BOD) also provide an estimation of biogas potential.

Biogas yield (m^3/d) = **Wastewater flow rate** (m^3/d) $*$ **COD** or **BOD concentration** (kg/m^3) $*$ **Biogas yield per COD** or **BOD** (m^3/kg).

The yield per COD or BOD, or conversion efficiency, depends on anaerobic digester efficiency and can be decided through laboratory tests or published values (Wanjohi, 2023; Wu et al., 2016).

The volume or flow rate of biogas produced by anaerobic digestion of organic waste or sewage sludge can be calculated as follows (Ganesapillai et al., 2023):

Biogas Production Rate (m^3/day) = **Biogas Yield** (m^3/kg) $*$ **Feedstock Input Rate** (kg/day).

The procedure of upgrading biogas by removing contaminants like CO2 and H2S increases its methane content (Angelidaki et al., 2018). This process's effectiveness can differ depending on the applied technology and can be calculated as follows:

$$\textbf{Biogas Upgrading Efficiency}\ (\%) = \frac{\textbf{Upgraded Biogas Volume}\ (m^3/day)}{\textbf{Raw Biogas Volume}\ (m^3/day)} * \mathbf{100}$$

Energy Consumption for Biogas Upgrading (kWh/day) = **Biogas Upgrading Power Demand** (kW) $*$ **Operating Time** (h/day)

3.6.1.2 Theoretical Estimation of Biogas value

Estimating the cost of biogas can be difficult due to the multiple factors that can impact it. Its energy content, price of the energy source, price on the local market, cost of production (capital expenditures, investment cost, operational costs, and maintenance costs), and revenue from electricity sales or other end uses are all important factors (Salomon et al., 2011; Manninen et al., 2013). **Biogas cost** (in currency) $= \frac{\textbf{Total costs}\ (\textbf{investment} + \textbf{operational} + \textbf{maintenance})}{\textbf{Total energy produced by the biogas facility over its lifespan}}$

Biogas value can be estimated by factoring in the cost of production (capital expenses, costs for investment, operational costs, and maintenance costs), revenue from electricity sales or other end uses, transportation, bank interest rate, inflation rate, depreciation rate of materials, etc. The calculation incorporates the cost of biogas production and revenue from sales (Wu et al., 2016). **Value of biogas** (in currency) = $\frac{\textbf{Total costs} - \textbf{Total revenues}}{\textbf{Total biogas production}}$

Using the following equation, the value of biogas can also be determined based on its energy content and energy price (Salomon et al., 2011).

Value of biogas (in currency) = **Energy content of biogas** (MJ/m^3 or kWh/m^3) $*$ **Energy price** (currency/MJ or kWh).

The price of energy may reflect the price of a comparable energy type on the local market, such as natural gas. The energy content of biogas is primarily dependent on its methane (CH4) percentage, which is typically between 20 and 26 MJ/m3 (Salomon et al., 2011; Frazier & Ndegwa, 2019).

Several strategies, including the following, can be employed to reduce the price of biogas production.

Utilization of energy-efficient technologies can be performed by enhancing process efficiency, for instance using heat recovery systems, or by employing high-efficiency equipment. Optimizing operational conditions such as temperature and pH, feedstock mixture, and digester design can increase biogas plant efficiency and decrease production costs (Norsus, 2023; BRC, n.d.).

Utilizing waste or low-cost feedstocks or securing long-term supply contracts can reduce feedstock costs. Reusing digested sludge as fertilizer can partially mitigate production costs and boost overall profit (Carbon Limits, 2019; Carbon Limit, 2021).

Optimized operational procedures can include proper maintenance, optimization of the anaerobic digestion process, and quality control procedures. Due to economies of scale, expanding biogas facilities can reduce the unit cost of production (Carbon Limits, 2021; Carbon Limits, 2019).

Opportunities for revenue generation can be investigated, such as the sale of digestate as fertilizer, or by selling carbon credits. Co-digestion can increase biogas production and make the process more cost-effective. Using government renewable energy subsidies and incentives can also assist biogas plant operators in reducing their financial burden (Manninen et al., 2013; Norsus, 2023; Jica, 2015).

3.6.1.3 Cost-benefit analysis (CBA) and Sensitivity analysis of biogas

In the context of biogas production from sludge, a cost-benefit analysis (CBA) is an instrumental evaluation that compares production costs, including capital and operating costs, with the benefits derived from the sale of biogas, its upgraded products, and potential revenue from carbon credits. This economic analysis seeks to determine the biogas project's net economic value, which is typically expressed as net present value (NPV), paying back period, or return on investment (ROI) (Weidema, 2006).

The initiation of a CBA entails the identification and estimation of initial costs. Initial capital expenditure (CapEx) includes the cost of the design and construction of the biogas plant, machinery, and equipment. Operational expenditures (OpEx) include costs for running the plant, such as salaries, feedstock, utilities, and maintenance (Salomon et al., 2011). To annualize these costs over the plant's lifetime, an appropriate discount rate is applied using the **Annual Equivalent Cost** (AEC) formula (Boardman et al., 2018):

$\mathbf{AEC} = \mathbf{P} * \frac{\mathbf{r} * (\mathbf{1}+\mathbf{r})^{\mathbf{n}}}{(\mathbf{1}+\mathbf{r})^{\mathbf{n}}-\mathbf{1}} = \frac{\mathbf{r} * \mathbf{NPV}}{\mathbf{1}-(\mathbf{1}+\mathbf{r})^{-\mathbf{n}}} = \frac{\textbf{Present value of costs}}{\textbf{Annuity factor}}$, where “P” is the initial investment cost, “r” is the discount rate, and “n” is the project's lifespan.

Total costs can be calculated using the following formula:

Total costs = **ΣPV (costs)**, where PV denotes the present value.

The CBA process requires the identification and quantification of **Benefits** after cost estimation. These benefits include income from the sale of biogas or its upgraded products, as well as the possibility of income from carbon credits (Pearce, 2003; Manninen et al., 2013).

Biogas revenue (in currency) = **Volume of biogas produced per year** * **Price of biogas per unit volume** (currency/MJ or kWh).

Carbon credit revenues can be calculated simultaneously as follows:

Carbon credit revenues = **Amount of CO_2 equivalent emissions** * **Price per ton of CO_2 equivalent**.

The cumulative benefits can then be calculated with the following formula:

Total benefits = **ΣPV (benefits)**.

The calculation of the **Net Present Value** (NPV), which represents the totality of the present values of all costs and benefits over the project's lifetime, is a crucial aspect of the CBA (Brent, 2006). The NPV can be calculated using the formula

$\mathbf{NPV} = \sum \frac{(\mathbf{Bt} - \mathbf{Ct})}{(\mathbf{1} + \mathbf{r})^{\mathbf{t}}}$, where "Bt" represents the benefits in year "t", "Ct" the costs in year "t", "r" the discount rate, and "t" the year. NPV can also be calculated as follows:

NPV = **PV (benefits) - PV (costs)**.

A positive NPV indicates the economic viability of the project, as the benefits exceed the costs.

Payback period represents the time required to recoup the project's initial investment from net benefits. The payback period is calculated by using the formula (Weidema, 2006):

$$\textbf{Payback Period} = \frac{\textbf{Initial investment}}{\textbf{Cash flow per year}}$$

The **Return on Investment** (ROI) is a key indicator of the profitability of an investment and can be calculated using the formula (Boardman et al., 2018):

$$\textbf{ROI} = \frac{\textbf{Total Benefits} - \textbf{Total Costs}}{\textbf{Total Costs}} \text{ or } \textbf{ROI} = \frac{\textbf{Net Benefits}}{\textbf{Total Costs}} * \mathbf{100\%}$$

Lastly, carrying out a sensitivity analysis enables the testing of the results' robustness in the face of changes in key variables such as biogas price, feedstock cost, discount rate, and carbon credit price.

A biogas cost-benefit analysis requires a **Sensitivity analysis** to determine the robustness and dependability of the economic evaluation. It investigates how qualitatively or quantitatively the variation in the output of a system can be attributed to various sources of variation in the system's inputs (Saltelli et al., 2008). By carrying out sensitivity analysis, decision-makers can identify the main drivers of a biogas project's economic viability, enabling them to focus their attention and resources on managing these crucial variables (Pannell, 1997).

Typically, sensitivity analysis entails modifying the main inputs of the cost-benefit analysis one at a time while holding the others constant (a form of univariate sensitivity analysis) to determine the impact of each input on the output. Typical critical inputs include the discount rate, biogas price, feedstock cost, carbon credit price, CapEx, and OpEx.

If NPV is chosen as the indicator of economic viability, the NPV formula can be adjusted as follows for each key input "i" This analysis yields a range of NPVs for each variable, which illustrates the sensitivity of the project's economic viability to changes in each input (Boardman et al., 2018):

$\mathbf{NPV_i} = \sum \frac{(\mathbf{Bt} - \mathbf{Ct_i})}{(\mathbf{1} + \mathbf{r_i})^{\mathbf{t}}}$, where "Bt" is the benefits in year "t", "Ct_i" is the costs in year "t" adjusted for input "i", and "r_i" is the discount rate adjusted for input "i".

Additionally, a multivariate sensitivity analysis, in which all key variables are simultaneously varied, may also be performed to fully understand the interdependencies and combined impacts of changes to multiple inputs on the output.

The significance of sensitivity analysis lies in its capacity to provide an understanding of the uncertainty inherent in the cost-benefit analysis, thereby enhancing the decision-making process by supplying valuable information on the robustness of the project's economic viability under different scenarios (Saltelli et al., 2008).

3.6.2 LCA, LCC, LCI, and LCIA of biogas

Cycle Analysis (LCA) is an integrated approach for assessing the environmental impacts associated with all phases of a product's existence, from cradle to grave. This includes the extraction of raw materials, their processing, manufacturing, distribution, use, repair and maintenance, and their disposal or recycling (Han et al., 2021; Rognan, 2021). LCA enables a holistic view of a product's or service's environmental impacts, guaranteeing that all phases are evaluated, and potential trade-offs are considered (Rognan, 2021). Relevant LCA stages for biogas derived from WTP or WWTP sludge would include sludge collection, pre-treatment, anaerobic digestion, biogas purification and utilization, digestate management, and indirect effects such as nutrient recycling and shifting of fossil fuels (Han et al., 2021). LCA provides an extensive overview of the potential environmental advantages and disadvantages of biogas production, including reductions in greenhouse gas emissions, energy consumption, usage of resources, and potential pollutant emissions (Shao et al., 2021).

Life Cycle Costing (LCC) is an analysis technique that examines all costs associated with the life cycle of a product, service, or infrastructure, commencing with its acquisition, and continuing through its operation and disposal (Hauser, 2017; Rajkumar & Kumar, 2004). It involves identifying and summing up all costs incurred during the life cycle of the product. This method aids in the evaluation of the financial viability of long-term projects. Costs associated with biogas from sludge would consist of sludge collection, treatment, anaerobic digestion infrastructure, operation, and maintenance, as well as end-of-life disposal or recycling (Hauser, 2017; SEAI, 2017). LCC serves to emphasize the economic feasibility of biogas production from sludge, informing decision-making whilst contributing to the evaluation of the technology's economic viability (Mills et al., 2014; Rajkumar & Kumar, 2004).

Life Cycle Inventory (LCI) is a phase of LCA comprising the quantification of data regarding the inputs and outputs of a product system. LCI quantifies energy and raw material inputs as well as environmental emissions at each production stage (Medina-Martos et al., 2020; Weidema, 2006). For biogas production from sludge, key inputs may include the type and quantity of sludge, energy for treatment processes, and chemicals for conditioning (chemicals used in the production process), whereas key outputs may include the quality and quantity of biogas produced, any by-products or residues (waste), and emissions (Mills et al., 2014; Wang et al., 2019b). An LCI can provide useful data for determining the environmental performance of biogas production and identifying areas where resource efficiency can be improved (Muter et al., 2022).

Life Cycle Impact Assessment (LCIA) is the third phase of an LCA which seeks to fully understand and evaluate the magnitude and significance of the prospective environmental impacts identified in the LCI phase (Shao et al., 2021). LCIA converts LCI results into environmental impacts such as global warming potential, acidification, eutrophication, and human toxicity (Medina-Martos et al., 2020). For biogas production, LCIA could include impacts associated with biogas combustion emissions, such as GHS emissions, potential nutrient recycling, eutrophication or acidification potential, and potential human health impacts, as well as the avoidance of fossil fuels (Hu et al., 2020; Weidema, 2006). LCIA can provide a holistic view of the possible environmental impacts of biogas production, thereby informing the development of mitigation strategies (Medina-Martos et al., 2020).

LCA, LCC, LCI, and LCIA of biogas from sludge are crucial tools for WTP and WWTP stakeholders because they provide a deep understanding of the environmental and economic impacts of biogas production as a renewable energy source (Scholten & Bosman, 2016). LCA, LCC, LCI, and LCIA provide stakeholders in WTP and WWTP operations with information on resource use, energy efficiency, environmental emissions, and cost-effectiveness, providing a foundation for decision-making, policy development, and strategic planning (SEAI, 2017; Carlson & Ebben, 2022). In addition, these analyses contribute to the assessment of the green shift and circular economy by identifying opportunities for resource recovery, waste reduction, and economic optimization in the water sector. Thus, promoting the sustainable utilization of waste materials and decreasing reliance on nonrenewable energy sources (World Bank, 2021; IWA, 2022).

3.6.3 Biogas upgrading to biomethane

Biomethane is a biofuel with a high energy content that is derived from biogas, which is a byproduct of the anaerobic digestion of organic matter (Angelidaki et al., 2018). In addition to methane (CH4) and carbon dioxide (CO2), biogas also contains negligible traces of hydrogen sulfide (H2S), ammonia (NH3), and water vapor. By refining biogas, biomethane is produced, which is an enhanced form of biogas with a higher methane content and an energy capacity comparable to that of natural gas (Shen et al., 2015).

There are several advantages to upgrading biogas to biomethane. As a renewable energy source, biomethane could play a significant role in reducing greenhouse gas emissions and reliance on fossil fuels, thereby offering the potential for sustainable energy development (González-Arias et al., 2022). It is a multipurpose fuel that can be used for a variety of functions, including heating, electricity generation, and as a vehicle fuel, thereby enhancing local energy assurance and economic stability. In addition, as a byproduct of municipal wastewater treatment plants (WWTPs) and landfills, biomethane production contributes to the circular economy and waste-to-energy concepts, thereby reducing the environmental impact of waste disposal (Angelidaki et al., 2018).

However, despite these benefits, upgrading biogas to biomethane is not without limitations. The primary challenge is the energy input and associated costs required for the refining process, as well as the management of by-products including CO2 and H2S (Ghafoori et al., 2022). The removal of these gases is required for the production of high-quality biomethane, but the processes used can be expensive and energy intensive. In addition, the economic viability of biomethane production frequently depends on government support or policy incentives, such as feed-in tariffs or renewable energy certificates, which are subject to fluctuation or change over time (SEAI, 2017).

Several methods, including pressure swing adsorption (PSA), water scouring, chemical absorption, and membrane separation, can be used to upgrade biogas to biomethane. However, membrane separation is one of the most promising techniques because of its efficacy, adaptability, and potential for integration with existing infrastructure (Angelidaki et al., 2018).

This technology uses the selective permeability of a membrane to separate CO_2 from CH_4 in biogas, thereby increasing the concentration of methane. This process is driven by a pressure gradient, and due to the greater solubility and smaller kinetic diameter of CO_2 compared to CH_4, CO_2 can more easily permeate the membrane, leaving a CH_4-rich residual stream (Hauser, 2017). In addition, membrane separation technologies typically have smaller dimensions, lower energy requirements, and greater flexibility than other technologies, making them suitable for various biogas production site sizes and types (Gong et al., 2023).

The quantity and quality of upgraded biomethane from biogas can be estimated using a variety of variables, including biogas yield, biogas composition, and upgrading process efficiency. For example, if the biogas yield from the anaerobic digestion of sludge at a municipal WWTP is Y m^3/kg VS (volatile solids), the composition of the biogas is C% CH_4, and the efficiency of the refining process is E%, the quantity of biomethane produced would be:

Biomethane (m^3/kg VS) = $\mathbf{Y} * \frac{\mathbf{C * E}}{\mathbf{100}}$.

Moreover, depending on the effectiveness of the refining process, the methane content of the biomethane could be increased from the initial biogas composition (C%) to a higher value. However, other parameters, such as temperature, pressure, and retention time, may also influence biomethane production and must be optimized for each case (Yuan et al., 2021).

The cost of producing biomethane from biogas can be determined by considering various cost factors, such as the capital cost of upgrading equipment, operational and maintenance costs, cost of energy inputs, and cost of processing and disposal of byproducts (waste management cost). The total cost (TC) might thus be estimated as follows:

TC (currency/m^3 biomethane) = **CapEX** + **OpEX** + **EniEX** + **WmEx** – $\mathbf{G_{icv}}$, where CapEX is the cost of capital (incl. equipment), OpEX is the cost of operations and maintenance (incl. feedstock and labour), EniEX is the cost of energy inputs (excl. from OpEX), WmEX is the cost of waste management and disposal (excl. from OpEX), and G_{icv} is government environmental incentives subsidies (SEAI, 2017).

Biomethane is a promising renewable energy source that could play an important role in the development of sustainable energy. However, the conversion of biogas to biomethane presents significant technical and financial barriers that must be overcome. Future research should concentrate on enhancing the efficiency and reducing the cost of the upgrading process, as well as developing effective strategies for integrating biomethane production into existing waste management and energy systems.

3.6.4 Biogas upgrading to heat and energy

Biogas upgrading has many benefits, most notably energy recovery and greenhouse gas (GHG) emission reduction. Taking advantage of combustion and cogeneration techniques to convert biogas to energy (in the form of heat and electricity) is a well-established practice. (Buchmüller & Geraats, 2013; Gu et al., 2017) Energy recovered from biogas can be used directly on-site (e.g., in wastewater treatment facilities) to reduce external energy requirements, enhancing their energy autonomy and contributing to the transition to a circular economy. This could result in economic savings by lowering energy costs and generating revenue by selling excess electricity to the grid (Moreno et al., 2017; Lima et al., 2023). Using biogas for energy recovery also diversifies the energy balance and reduces reliance on fossil fuels, thereby enhancing energy security (Scholten & Bosman, 2016).

However, upgrading biogas for the production of heat and electricity is not without challenges and limitations. First, the use of biogas for heat production can be thermally inefficient if heat demand and the production of biogas are not synchronized. This may result in heat loss if the excess cannot be stored or distributed (Clark & Eisenberg, 2008; Enebe et al., 2023). Due to the lower calorific value of biogas, the conversion efficiency is considerably lower than that of natural gas and coal for the production of electricity (Johnstone & Haščič, 2013). Also, upgrading biogas for the production of heat and electricity requires substantial infrastructure and equipment investments, which can be barrier for small-scale operations (Nevzorova et al., 2019).

Several methods, including physical, chemical, and biological processes, are used to upgrade biogas. Physical methods include pressure swing adsorption (PSA), water scrubbing, and membrane separation. Chemical methods involve processes such as amine scrubbing and cryogenic separation. Biological methods, such as anaerobic digestion, are primarily used for biogas production rather than upgrading (Enebe et al., 2023; Venkatesh & Elmi, 2013). Each method has its advantages and disadvantages in terms of energy consumption, capital costs, operating costs, and product quality. Water scouring is one of the most prevalent and cost-effective methods for biogas upgrading (Manninen et al., 2013; Gong et al., 2023). In water scouring, biogas is passed through a scrubbing column where water absorbs impurities such as CO2, H2S, and moisture. The process of water scrubbing relies on the solubility difference between impurities and methane. The impurities can be selectively absorbed by altering the water flow rate and temperature, resulting in biogas with a higher methane content.

CHP (combined heat and power) system is frequently coupled with water scrubbing to maximize energy efficiency. In this configuration, the upgraded biogas is used as fuel for an internal combustion engine or a gas turbine, which in turn powers an electrical generator to produce electricity. The heat generated from the engine or turbine is recovered and utilized for various heating applications, such as district heating or industrial process heating applications (Lima et al., 2023; Buchmüller & Geraats, 2013). This combined heat and power generation allows the thermal and electrical energy potential of the upgraded biogas to be exploited.

CHP systems enable the simultaneous production of heat and electricity from a single energy source, resulting in a high overall energy efficiency. The heat produced during this process, which would otherwise be lost, is recovered, and utilized for thermal purposes. This simultaneous production of heat and electricity makes CHP systems extremely energy-efficient, with overall efficiencies frequently reaching 85-90% (Bagheri et al., 2023; Bora et al., 2020; Ganesapillai et al., 2023).

The elimination of impurities, such as hydrogen sulfide, from biogas prior to combustion is a crucial step in the upgrading process. This is typically achieved through a desulfurization process that may be chemical, biological, or physical in nature. A failure to effectively purify biogas can result in the formation of sulfur oxides during combustion, which can contribute to air pollution and corrosion of equipment (Hemmati & Abedzadegan, 2019; Mukawa et al., 2022).

Despite its challenges and limitations, biogas upgrading provides significant benefits in terms of energy recovery and greenhouse gas emission reductions. Due to their high overall energy efficiency, CHP systems are ideally suited for converting biogas to heat and electricity, thereby maximizing the use of this renewable energy source in a sustainable manner.

CHP systems allow for the simultaneous production of heat and electricity from a single energy source, resulting in a high energy efficiency overall. The heat generated by this process, which would otherwise be lost, is recovered, and used for thermal purposes. CHP systems are extremely energy-efficient, with aggregate efficiencies often reaching 85-90% (Bagheri et al., 2023; Bora et al., 2020; Ganesapillai et al., 2023).

3.6.4.1 Theoretical Estimation of energy output

The estimation of the energy quantity and quality derived from upgraded biogas from sludge requires the consideration of multiple formulas, parameters, and factors. Physical and chemical properties, operational conditions, and conversion efficiencies are the main categories into which they can be clusters.

The physical and chemical characteristics are the first category and encompass the sludge's organic content, also known as the volatile solids (VS) content. The theoretical methane potential (B0) of the sludge, which represents the optimal amount of methane that can be produced from organic materials under ideal conditions, forms a crucial factor. Additionally, the biodegradability of the organic content can affect the resulting methane production. In addition, the calorific value of biogas, which is derived from methane, can be estimated based on its constituent fractions, such as CH4 and CO2.

Operational conditions form another essential category, comprising factors like the temperature and the digestion process's retention time. The pH level and the presence of inhibitory substances also have a significant impact on the activity of methanogenic bacteria.

The third category is conversion efficiencies. Due to practical constraints, the efficiency of the digestion process is often below its theoretical maximum. Similarly, the efficiency of the biogas upgrading process, which is highly dependent on the employed technology, and the efficiency of the combined heat and power (CHP) system or alternative energy conversion system all contribute to the overall conversion efficiencies.

To calculate the produced energy, the following formula can be used:

$\mathbf{E_p = Q_s * T_{mp} * C_{ef} * C_{vm}}$, where E_p represents the produced energy, Q_s the quantity of sludge, T_{mp} the theoretical methane potential, C_{ef} the conversion efficiency (the sum of the digestion, upgrading, and CHP efficiencies), and Cvm represents the calorific value of methane.

$$\mathbf{E_p = Q_s * B_Y * M_c * E_{cm} * CHP_{ef}}$$

The quantity of sludge (Q_s) refers to the amount of sludge available for energy production. The potential for energy production from sludge is proportional to the amount of sludge (Bagheri et al., 2022). The biogas yield (B_Y) is the volume of biogas produced per unit weight/volume of sludge through the anaerobic digestion of sludge. It is determined by the organic content of the sludge and the efficiency of the digestion process (Enebe et al., 2023). The methane content (M_c), constituting 50-70% of the biogas with the remainder being carbon dioxide and other trace gases, primarily defines the biogas's energy content (Lima et al., 2023). The energy content of methane (E_{cm}) is approximately 50-55.5 MJ/kg or 39.82 MJ/m3 (Tanigawa, 2017). The CHP efficiency (CHP_{ef}), a crucial factor, typically ranges between 75 and 80 percent (Capodaglio & Callegari, 2020).

The precise values for these parameters will vary depending on the characteristics of the sludge and the specifics of the treatment process and must be determined experimentally for each unique case (Bagheri et al., 2022).

Note that these calculations are estimates, and actual outcomes may deviate due to variances in sludge characteristics and treatment process efficiency. In addition, the economic and environmental effects of the sludge treatment and energy production process must be examined (Mills et al., 2014).

3.6.4.2 Theoretical Estimation of Energy Production and Sale Prices

Estimating the cost of producing energy or heat from biogas and determining its selling price involves multiple factors, parameters, and calculations. These factors can be grouped into four main categories: capital costs (CapEX), operational costs (OpEX), revenue from the sale of energy or heat produced, and regulatory and environmental considerations (Bagheri et al., 2022; Zaharioiu et al., 2021; Venkatesh & Elmi, 2013).

CapEX includes the costs of investment including land acquisition (C_p), infrastructure including plant construction (Ci), and equipment including installation (C_e).

$$\mathbf{CapEX} = \mathbf{C_p} + \mathbf{C_i} + \mathbf{C_e}$$

OpEX comprises the day-to-day operational costs of the biogas plant. It includes maintenance (C_m), labour (C_l), feedstock (C_f), utilities (C_u), and insurance (C_{ins}) expenses.

$$\mathbf{OpEX} = \mathbf{C_m} + \mathbf{C_l} + \mathbf{C_f} + \mathbf{C_u} + \mathbf{C_{ins}}.$$

Revenue from the sale of the produced energy or heat (Re) can be determined by the quantity of energy or heat produced (Q_{ep}) and the unit market price of energy or heat (P_{ue}).

$$\mathbf{R_e} = \mathbf{Q_{ep}} * \mathbf{P_{ue}}.$$

Regulatory and environmental considerations: Various regulations and environmental policies can affect the production cost and selling price of biogas. For instance, certain regulations may necessitate the purchase of additional equipment (C_{ac}) to reduce environmental impacts, thereby increasing production costs. Additionally, government incentives (G_{icv}) for renewable energy production, such as tax credits, tax increment financing (TIF), or environmental subsidies, can reduce production costs and impact selling prices (Scholten & Bosman, 2016).

Regulatory costs (**C_R**) = **Cost additional equipment** (**C_{ae}**) + **Cost compliance** (**C_c**).

Using the following formulas (Salomon et al., 2011; Mukawa et al., 2022), stakeholders can estimate the total cost (TC), the desired profit (P_d), and the selling price of the energy after evaluating the aforementioned costs and the quantity of energy produced (Q_{ep}):

Total cost (**TC**) = **CapEX** + **OpEX** + **C_R** - **G_{icv}**

Selling price (**SP**) = $\frac{TC}{Q_{ep}} + P_d$

The type and quality of feedstock, the efficiency of the biogas production process, and market conditions can all influence these costs and revenues (Lema & Suarez, 2017; Moreno et al., 2017). Moreover, it may be advantageous to consider the social cost of carbon and the monetary value of environmental benefits when determining the selling price (Hannon & Bolton, 2021; Johnstone & Haščič, 2013).

3.6.5 Biogas upgrading to hydrogen

Hydrogen derived from biogas is a renewable energy source produced by converting organic materials, predominantly methane, and carbon dioxide into hydrogen and carbon dioxide (Farghali et al., 2022). Methane and carbon dioxide constitute the largest percentage of biogas's components. The upgrading of biogas to hydrogen involves a series of processes, including purification and reforming, that convert biogas into a fuel that can be used in a variety of applications, such as fuel cells (Kumar et al., 2022).

The primary benefit of converting biogas to hydrogen is that hydrogen has a higher energy density, making it a more efficient fuel. When used as a fuel, hydrogen produces no harmful emissions, only water, which contributes to the reduction of greenhouse gas emissions (Angelidaki et al., 2018). In addition, hydrogen can be easily stored and transported, allowing its use in a variety of applications, including transportation, power generation, and industrial processes (Farghali et al., 2022).

However, the process of upgrading has some limitations. The cost, which includes both the capital and operating costs of the conversion equipment, seems the most significant factor (Hauser, 2017). In addition, the process may generate carbon dioxide, a greenhouse gas, as well as other potential contaminants (González-Arias et al., 2022). Additionally, the technology for producing hydrogen from biogas is still in development, and there may be technical barriers that need to be overcome (Ghafoori et al., 2022).

Several techniques are used to convert biogas to hydrogen, such as steam reforming (SMR), dry reforming (DMR), dual reforming (DLMR), and tri-reforming (TRM) of methane (Minh et al., 2018). Methane reacts with steam in steam reforming (SMR) to produce hydrogen and carbon monoxide. The carbon monoxide is then reacted with additional steam to generate more hydrogen and carbon dioxide (Mahmoudi et al., 2022). Dry reforming (DMR) is the process of converting methane and carbon dioxide into hydrogen and carbon monoxide (Hrycak et al., 2023). Dual and tri-reforming are more intricate procedures that combine steam and dry reforming.

The steam reforming (SMR) method is generally seen as the most suitable process for upgrading biogas to hydrogen due to its high hydrogen yield and well-established technology (Minh et al., 2018). However, this method requires high energy input, making it less energy-efficient than some other methods. Methane, the primary component of biogas, is reacted with steam over a catalyst to produce hydrogen and carbon monoxide. This reaction occurs at high temperatures, typically between 800 and 1000 degrees Celsius (Hrycak et al., 2023). In the second phase known as the water-gas shift reaction, the carbon monoxide produced in this reaction is reacted with steam to produce additional hydrogen and carbon dioxide (Mahmoudi et al., 2022). After cooling the resulting gas mixture, hydrogen is separated from carbon dioxide and any remaining steam. The process involves the Purification of biogas to remove impurities, the steam reforming to convert methane into hydrogen and carbon monoxide, the water-gas shift reaction to convert carbon monoxide into additional hydrogen and carbon dioxide, the cooling and separation of the gas mixture to extract pure hydrogen (Minh et al., 2018).

The most suitable technique for upgrading biogas depends on the source's specific conditions and the hydrogen's intended application. Despite recognizing that steam reforming is the most common procedure, other methods may be more appropriate in certain situations. For instance, when a biogas source has a high carbon dioxide content, dry reforming (DMR) can be a more efficient method because it utilizes carbon dioxide as a reactant rather than producing it as a byproduct (Gong et al., 2023). Tri-reforming (TRM), which incorporates steam, dry, and partial oxidation (POX) reforming, has the potential to increase overall efficiency and carbon dioxide utilization (Minh et al., 2018). Moreover, advancements in catalyst technology, such as the use of Ni-doped activated carbons, have been shown to increase the efficacy of methane decomposition and thus, the generation of hydrogen (Mahmoudi et al., 2022). This, combined with the optimization of the process, could increase the economic viability of biogas upgrading to hydrogen (Ghafoori et al., 2022).

Several studies have also investigated additional biogas upgrading techniques, such as adsorption and biogas recirculation. Adsorption techniques, for example, can selectively remove carbon dioxide from biogas, thereby improving the methane's purity (Vivo-Vilches et al., 2017). In contrast, biogas recirculation is the practice of reintroducing a portion of the produced biogas back into the anaerobic digestion system to stimulate microbial activity and increase the overall biogas yield (Yuan et al., 2021).

However, despite the potential benefits and the ongoing advancements in upgrading technologies, the commercial scale of these methods requires additional research due to the potential environmental impacts, high capital costs, and technical complexities involved (Hauser, 2017; Ghafoori et al., 2022).

3.6.5.1 Theoretical Estimation hydrogen output

The production of hydrogen from biogas via the upgrading process is a complex procedure requiring consideration of multiple variables and parameters. The following formulas provide a fundamental comprehension of the arithmetical calculations involved in estimating the quantity and quality of refined hydrogen from sludge-derived biogas. It is essential to note, however, that the specific calculations may differ depending on the hydrogen production pathway, process conditions, and other variables. Detailed analytics models and simulations can be developed to provide more precise estimates based on particular parameters and conditions. Please note that the provided formulas are generalizations, and it is recommended to consult professional or specific research papers and literature for more detailed and accurate models relating to the biogas-to-hydrogen upgrade (Kumar et al.,2022; Minh et al., 2018; Farghali et al., 2022; Giannakou, 2015).

The following equation can be utilized to illustrate the conversion of methane (CH_4) in biogas to hydrogen (H_2): $\mathbf{CH_4 \rightarrow 2H_2}$

The stoichiometric equation for Steam methane reforming (SMR) reaction is (Minh et al., 2018; Farghali et al., 2022; Giannakou, 2015):

$$\mathbf{CH_4 + H_2O \rightarrow CO + 3H_2 \text{ or } CH_4 + H_2O \leftrightarrow CO + 3H_2 \quad \Delta H°_{298K} = 206.2\ kJ/mol}$$

The percentage of methane (CH_4) in biogas, which affects the energy content and efficacy of hydrogen production, can be converted to an energy value using (Enebe et al., 2023):

Methane Energy Content (kWh/m^3) = **Methane Percentage** (%) $*$ **Methane Heating Value** (kWh/m^3). The heat value, also known as energy or calorific value, of methane is the quantity of heat emitted during its combustion and ranges between 50 - 55 MJ/kg.

Several significant variables must be considered when trying to estimate the quantity and purity of hydrogen that can be extracted from sludge-derived biogas at a municipal WWTP or WTP. These variables include the quantity and composition of the biogas, the efficiency of the reforming process, and the purity of the hydrogen produced.

The following formula can be used to calculate the theoretical **Quantity of hydrogen** (Q_{H2}) that can be produced from a specified volume of biogas (Minh et al., 2018). As indicated by the stoichiometric equation for SMR, the formula implies that each mole of methane in biogas can produce three moles of hydrogen. Typically, the CH_4 molar composition in raw biogas ranges between 50 and 75% (Farghali et al., 2022). It is crucial to note, however, that not all CH_4 can be converted into hydrogen, the actual quantity of hydrogen produced can be 5 to 20% lower than the stoichiometric prediction due to the limitations of reaction kinetics, the presence of other components in the biogas, and inefficiencies in the reforming process. To modify the estimation, the conversion efficiency of the steam reforming process must be considered (Farghali et al., 2022).

Quantity of hydrogen (moles) = **Biogas Volume** (m^3) $*$ **CH4 Molar Fraction in Biogas** $*$ **3**

Hydrogen Yield (Y_{H2}), also known as the conversion efficiency of the reforming process, is an additional crucial aspect to consider. It can be calculated using the following formula and represents the percentage of hydrogen produced from the available methane in the biogas (Minh et al., 2018). The real amount of hydrogen moles produced can be determined experimentally, while the amount of theoretical moles is derived from the stoichiometric equation.

$$\textbf{Hydrogen Yield}\ (\%) = \left(\frac{\textbf{Actual mol H2 produced}}{\textbf{Theoretical mol H2 produced}}\right) * \textbf{100}$$

$$\textbf{Biogas Flow Rate}\ (m^3/s) = \frac{\textbf{Volume of Biogas Produced}\ (m^3)}{\textbf{Theoretical mol H2 produced}\ (s)}$$

Hydrogen Production Rate (m^3/s) = **Biogas Flow Rate** (m^3/s) $*$ **Hydrogen Yield** (%), or

Hydrogen Production Rate (kg/day) = $\left(\frac{\textbf{Mol H2 Produced}}{\textbf{Mol CH4 in Upgraded Biogas}}\right) * $ **Upgraded Biogas Output (m^3/day)** $*$ **CH4 Molar Mass** (kg/mol)

The upgraded **Hydrogen's Purity** is an essential criterion for evaluating its quality. Typically, it is determined by the volume fraction of hydrogen remaining in the gas mixture after reforming. The purity can be determined using the following formula (Kumar et al., 2022):

Hydrogen Purity (%) = $\left(\frac{\textbf{Volume of H2}}{\textbf{Total volume of gas mixture}}\right) * \textbf{100}$

The mass of hydrogen and its higher heating value (HHV), which is approximately 142 MJ/kg, can be used to estimate the **Energy Content** of the produced hydrogen. Hydrogen's mass can be determined using the ideal gas law, **PV = nRT**, where P is pressure, V is volume, n is the number of moles, R is the ideal gas constant, and T is the temperature (Mahmoudi et al., 2022):

Energy Content of H2 (MJ) = **Mass of H2** (kg) $*$ **HHV of H2** (MJ/kg)

The **Efficiency of hydrogen production** process can be affected by the technology employed, such as steam methane reforming (SMR) and water electrolysis. The following formula can be used to calculate the SMR process's efficiency (Minh et al., 2018):

SMR Efficiency (%) = $\left(\frac{\textbf{Hydrogen Energy Content}}{\textbf{Biogas Energy Content + Steam Energy Input}}\right) * \textbf{100}$

Energy Consumption refers to the energy required for biogas refining and hydrogen production processes, including heat and electricity input (Maktabifard et al., 2018).

Energy Consumption for Hydrogen Production (kWh/day) = **Hydrogen Production Power Demand** (kW) $*$ **Operating Time** (h/day)

To maximize the economic and environmental benefits of biogas upgrading, it is essential to manage and optimize the factors and parameters listed above. In addition, it is essential to consider other variables, such as the specific reforming technology, operating conditions, catalysts used, and presence of contaminants (Farghali et al., 2022; Hrycak et al., 2023; Minh et al., 2018).

3.6.5.2 Theoretical Estimation of Hydrogen production and sales prices

In a typical techno-economic analysis, several variables are considered. Among these variables are the biogas production rate, the methane content, the composition of the biogas, the energy consumption for the upgrading and hydrogen production processes, the capital investment required (CapEX), the operation and maintenance costs (OpEX), the regulatory costs (C_R), the government incentives (G_{icv}), other financial incentives, and market factors (SEAI, 2017; Johnstone & Haščič, 2013; Gong et al., 2023). Importantly, the equations that followed are simplifications and may not account for all costs and complexities of a real-world biogas-to-hydrogen production system because they are generalized and may need to be adjusted according to the specific context, application, or study scenario (Bagheri et al., 2022; Ganesapillai et al., 2023). Costs and profitability of hydrogen production from biogas are highly dependent on project specifications, location, employed technology, and market conditions (Johnstone & Haščič, 2013; Gong et al., 2023). Therefore, a comprehensive feasibility study and analysis are required for accurate cost estimation.

The equation for estimating the cost of producing hydrogen from biogas via steam methane reforming (SMR) can be:

$$\textbf{Cost of hydrogen}\ (C_{SMR}) = \frac{\textbf{Cost of biogas} + \textbf{Cost of steam} + \textbf{Cost of catalyst}}{\left(\frac{\textbf{mol H2 produced}}{\textbf{mol CH4 in biogas}}\right)}$$

OpEX (currency/year) = **Initial Investment Cost** (currency) $*$ **Operation and Maintenance Cost Percentage** (%)

Initial Investment Cost (currency) = **Cost of Biogas Upgrading System** (in currency) + **Cost of Hydrogen Production System** (in currency)

The equation for the cost of hydrogen (C_{SMR}) includes the costs of biogas and steam based on local market prices, as well as the catalyst, which can vary depending on its specific type and the amount of biogas processed. From the output of the SMR process, the molar amounts of hydrogen produced and methane present in biogas are experimentally determined (Farghali et al., 2022).

Due to the additional cost of generating the biogas feedstock and the energy required to generate the steam, the cost of producing hydrogen via SMR is typically greater than the cost of producing hydrogen from fossil fuels (Hauser, 2017). Other important factors that can affect the total cost of producing hydrogen from biogas include biogas quality, capacity utilization, CO2 emissions, hydrogen market demand, and government incentives. Higher impurity levels, such as CO2 and sulfur compounds, can increase the cost of hydrogen production via SMR (Angelidaki et al., 2018).

Total cost (TC) = **CapEX** + **OpEX** + **C_R** – **G_{icv}**, where C_R is the regulatory costs and G_{icv} is government environmental incentives subsidies.

Market demand (market factors) reveals the circumstances under which the demand for hydrogen can affect the selling price and profitability. The selling price can vary considerably based on the project, location, technology, and market conditions; consequently, a comprehensive feasibility study and analysis are necessary. Nevertheless, the selling price of hydrogen can be determined by factoring in the cost of hydrogen production, market demand, transport (distribution), and intended profit margin:

Selling Price of Hydrogen = **Total Cost of Hydrogen** + **Desired Profit Margin**, or

Selling Price of Hydrogen (currency/kg) = **Production Cost** (currency/kg) + **Distribution Cost** (currency/kg) + **Desired Profit Margin** (currency/kg)

Despite the associated challenges in terms of cost and technical feasibility, the transition from biogas to hydrogen represents a promising path toward a more sustainable energy system (Farghali et al., 2022; Kumar et al., 2022; Mahmoudi et al., 2022). To make well-informed decisions regarding investments and policies in this sector, it is essential to fully understand the complex interactions of factors influencing the economics of biogas-based hydrogen production.

3.7 Biochar

Biochar has garnered considerable interest as a prospective remedy from sludge treatment, thereby facilitating resource recovery and promoting sustainable practices in waste management. This chapter aims to provide a comprehensive analysis of the utilization of sludge to produce biochar. It encompasses various aspects such as the definition of biochar, its distinguishing characteristics from other carbonaceous materials, effective methods for its production, the conventional process of producing biochar using sludge as a raw material, factors influencing the production of biochar from sludge, potential pollutants present in biochar derived from sludge, disparities between biochar produced from Water Treatment Plants (WTP) and Waste Water Treatment Plants (WWTP), areas of application for biochar, potential for biochar reuse, the role of biochar in preserving surface and groundwater quality, techno-socio-economic-environmental benefits associated with biochar utilization, both positive and negative contributions of biochar to the green shift and circular economy, the potential for generating revenue from biochar at WTP and WWTP, and the implementation of a biochar utilization strategy in municipalities.

Biochar in Sludge Treatment for Resource Recovery

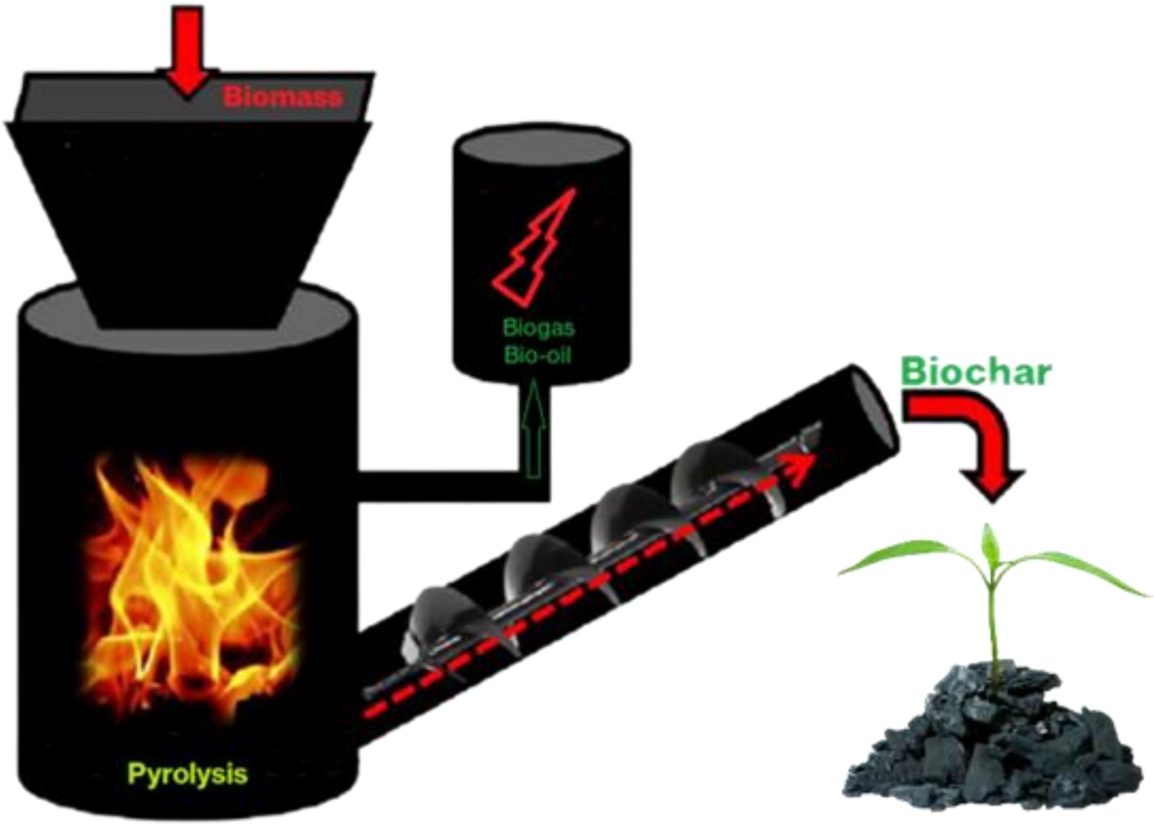


Figure 16: Biochar production from pyrolysis. Source: Unknown, retried online

Biochar has emerged as a significant product in the field of sludge treatment, derived from resource recovery, with the potential to facilitate sustainable waste management. The sludge, which is a residue produced by WWTPs and WTPs, contains organic matter and various other components that can be efficiently transformed into biochar through pyrolysis or gasification methods. The incorporation of biochar into waste treatment protocols offers a viable approach to transforming sludge, traditionally considered a waste product, into a valuable resource while minimizing adverse environmental impacts. The aforementioned conversion presents a range of potential applications, including but not limited to soil improvement, the capture and storage of carbon, the generation of energy, and the remediation of environmental issues. These applications are in line with the goals of sustainable development and waste management (Regjeringen, 2022; Ghorbani et al., 2022).

Furthermore, the use of biochar in sludge treatment can serve as a cornerstone for resource recovery, allowing the organic matter and nutrients stored in the sludge to be reused. Multiple uses are made possible by these important components, which are harnessed throughout the biochar conversion process. These applications extend from promoting agricultural fertility to serving as renewable energy sources, thereby endorsing environmentally friendly and sustainable (Nibio, 2021b; Nibio, 2022b).

Difference Between Biochar, Charcoal, Coal, GAC, and Other Types

Biochar, like charcoal, coal, granulated activated carbon (GAC), and other carbonaceous materials, has characteristics in common, but each has distinct features and applications. To properly appreciate the significance of biochar in sludge treatment, it is critical to decouple it from other carbonaceous compounds often used in various industrial sectors. The distinction is found not only in their manufacturing processes and carbon content but also in their physiochemical qualities and the variety of applications in which they serve.

Biochar occupies a unique position in the context of sludge treatment due to its inherent potential for resource recovery, sustainable waste management, and environmental conservation. The pyrolysis or gasification of biomass under oxygen-deprived conditions is used to produce biochar, especially from sludge. This technique generates a carbon-dense material that keeps the original biomass's structure, boosting its application in soil amendment, carbon sequestration, and energy generation (EBC, 2023; Ganesapillai et al., 2023).

Charcoal production, on the other hand, requires the pyrolysis of wood or organic materials in an oxygen-free atmosphere, providing a product that is often used as a fuel source for heating and cooking. Furthermore, charcoal has a higher heating value than biochar, making it a good option for industrial uses such as metallurgy and activated carbon production (Nibio, 2020a; Bandyopadhyay et al., 2021).

Coal, unlike biochar and charcoal, is a fossil fuel generated over geologic periods from plant remnants. Coal is a popular choice for power generation and a variety of industrial activities due to its high carbon content and energy-rich composition. However, it is important to remember that coal is not the result of pyrolysis or gasification, but of geological processes that have occurred over millions of years (Gong et al., 2023; Hrycak et al., 2023).

Granulated activated carbon (GAC), is a kind of activated carbon made by activating different carbonaceous materials. Activated carbon has a high adsorption capability when granulated, making it an excellent alternative for water and air purification applications (Thomas et al., 2021; Zhao et al., 2023a).

3.7.1 Biochar production process and quality

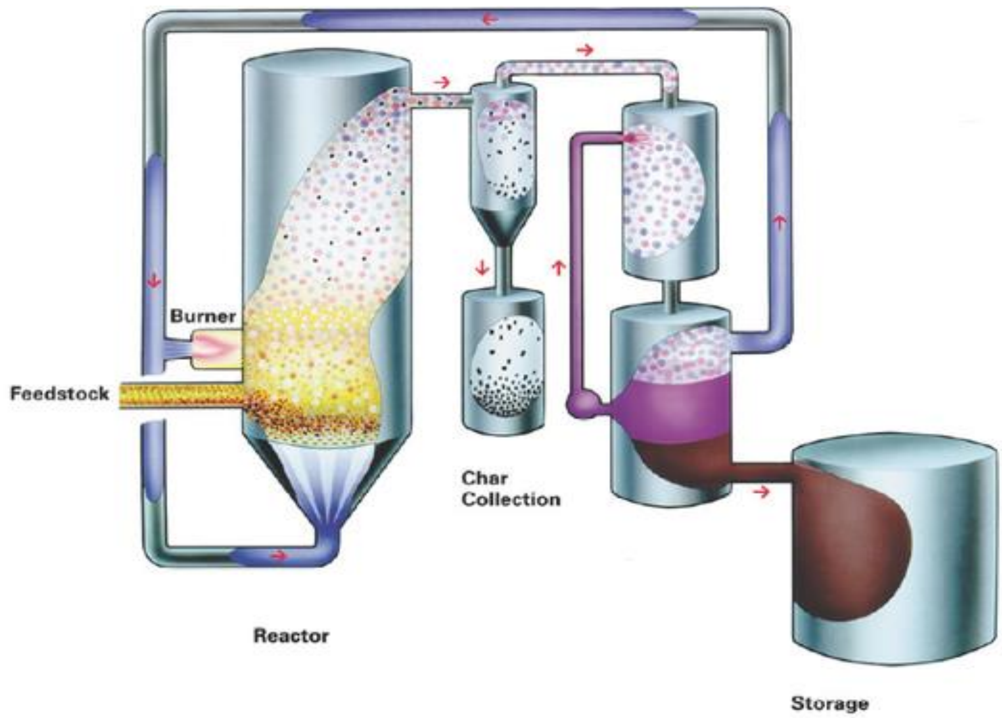


Figure 17: Biochar production process. Source: https://www.cleantechloops.com/carbon-sequestration-and-biochar/

Multiple techniques facilitate the production of biochar from WTP and WWTP sludge. Several factors, including the efficiency of the process, safety considerations, cost-effectiveness, and the desired properties of the final biochar product, influence the selection of an appropriate method. For the production of biochar from sludge, pyrolysis, and gasification are the two most prevalent techniques (Ghorbani et al., 2022). Despite its complexity, hydrothermal carbonization (HTC) is also a plausible alternative. The fundamental principle underlying these techniques is to subject the sludge feedstock to thermal decomposition in an oxygen-free or oxygen-limited environment.

3.7.1.1 Hydrothermal Carbonization (HTC)

Hydrothermal carbonization (HTC) is a thermally intensive process that converts sludge into biochar in a high-pressure, high-temperature, water-rich environment. HTC has the advantage of reduced processing times and the ability to produce biochar with desirable properties compared to other methods. Nonetheless, this method necessitates significant investments in energy and meticulous management of process parameters (Zhou et al., 2018; Shen et al., 2015).

3.7.1 .2 Pyrolysis

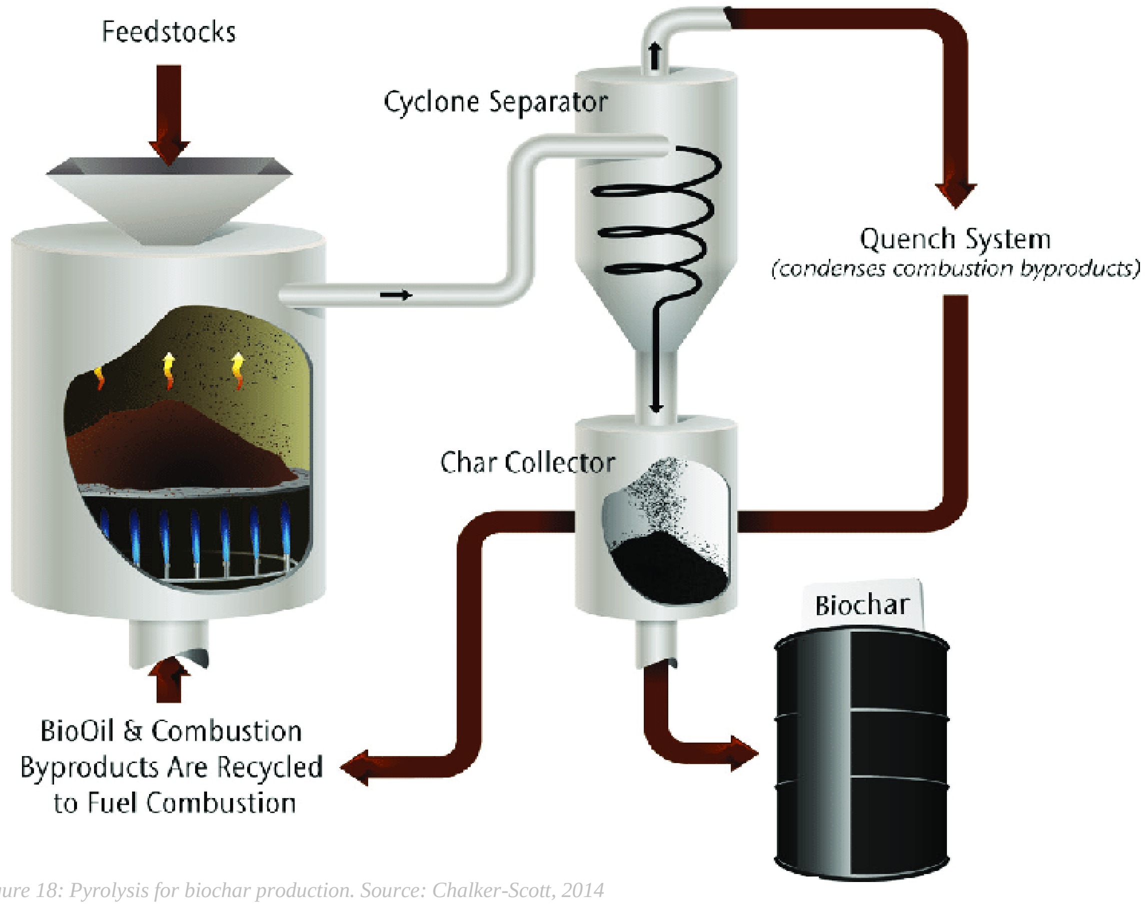


Figure 18: Pyrolysis for biochar production. Source: Chalker-Scott, 2014

As a method for biochar production, pyrolysis can be divided into two distinct categories: slow and fast pyrolysis.

Slow pyrolysis is a process characterized by a pyrolysis temperature between 300 and 500°C. The design of the method permits longer residence times, which increases the production of biochar with superior carbon content and stability. In addition, slow pyrolysis is preferable for preserving the nutrient content of sludge and reducing the emission of harmful byproducts (Paz-Ferreiro et al., 2018; Méndez et al., 2017; Cong et al., 2022; Elkhalifa et al., 2022).

Fast pyrolysis, on the other hand, involves rapid heating of the sludge feedstock (substrate) to temperatures greater than 500°C. This technique yields biochar, bio-oil, and syngas as a result of higher heating rates and reduced residence times. Fast pyrolysis is notably desirable for bioenergy applications due to its capacity to generate biochar with high bio-oil yields (Younis & Kim, 2022; Gong et al., 2019; Mohamed et al., 2022; Chiappero et al., 2021).

3.7.1.3 Gasification

As a method for biochar production, gasification entails the controlled heating of sludge feedstock to temperatures between 800 and 1200°C in the presence of oxygen or steam. The process facilitates the conversion of organic matter within the sludge into a gaseous mixture known as syngas. The syngas can then be utilized to produce biochar and other valuable byproducts. Gasification is effective in terms of conversion, and the composition of the resulting syngas can be controlled, rendering the process flexible for a wide range of applications (Kumar et al., 2021; Atukunda et al., 2022; Luo et al., 2020).

The gasification process can be recognized for its safety, cost-effectiveness, and efficacy in the production of biochar from sludge. Several factors contribute to gasification's effectiveness:

i. **Energy Recovery**: The process permits the energy contained in the sludge substrate to be recovered as syngas. This recovered energy can be used to generate heat and electricity, promoting energy sustainability, and decreasing reliance on fossil fuels (Ganesapillai et al., 2023; Kumar et al., 2021).
ii. **Sludge Volume Reduction**: Gasification significantly reduces sludge volume by converting organic matter into syngas and biochar. This volume reduction reduces the need for large storage and disposal facilities, resulting in cost savings and enhanced waste management practices (SINTEF, 2017; Ghorbani et al., 2022).
iii. **Syngas Utilization**: The syngas generated during the gasification process can be harnessed for multiple purposes, including the production of biofuels and valuable chemicals, in

addition to heat and electricity generation. These applications boost the economic viability of biochar production (Gong et al., 2019; Atukunda et al., 2022).

iv. **Flexibility and Control**: Gasification permits fine-tuning of several process parameters, such as temperature, residence time, and feedstock composition. This form of control enables the production of biochar with tailorable properties for specific applications, such as soil amendment or environmental remediation (Ganesapillai et al., 2023; Cong et al., 2022).

v. **Environmental Benefits**: The gasification process has the potential to reduce GHG emissions in comparison with traditional sludge disposal methods. It allows for carbon sequestration and mitigates the release of methane, a potent GHG from sediment (Ghorbani et al., 2022; Luo et al., 2020).

3.7.1.4 Conventional Method for Producing Biochar from Sludge

Conventional biochar production requires careful selection of thermal methods, typically pyrolysis or gasification, as well as optimization of process variables and subsequent processing steps. This is done to ensure the production of biochar of superior quality and with the intended properties. As mentioned previously, gasification is widely utilized due to its safety measures, cost-effectiveness, and enhanced energy recovery capabilities. The typical biochar production process, which utilizes sludge as raw material, includes the preparation of feedstock, pyrolysis or gasification, quenching and cooling, post-processing and quality assurance, storage and packaging, and eventually, disposal. Biochar produced from sludge can be used in a wide range of applications if the aforementioned steps are followed. To produce high-quality biochar and maximize the recovery of resources from sludge, each step in this conventional biochar production procedure must be meticulously optimized and monitored (Ghorbani et al., 2022; Kumar et al., 2021).

In trying to provide more insight, the details that follow outline each phase of the traditional biochar production process using sludge as source material:

Collection and Pre-treatment of Sludge: sludge is collected from WWTPs or WTPs and subjected to dewatering and drying as part of preliminary treatment. This is done to reduce the amount of moisture, thereby increasing the effectiveness of the process.

Feedstock Preparation: The pre-treated sludge undergoes additional processing to attain the necessary feedstock characteristics. In this initial phase, sludge feedstock is subjected to a variety of processes to remove remaining water, moderate moisture content, and increase its suitability for the following pyrolysis or gasification process (Shen et al., 2013; Czech & Oleszczuk, 2018).

Pyrolysis/Gasification: The prepared sludge feedstock is put through pyrolysis or gasification under regulated conditions. Here, process variables such as temperature, heating rate, and residence time are meticulously monitored in order to optimize biochar production (Ghorbani et al., 2022; Gong et al., 2019).

Quenching and Cooling: The resultant biochar is extracted from the pyrolysis or gasification system, cooled, crushed, and sieved to obtain the desired particle size and remove any remaining impurities. After the phase of pyrolysis or gasification, biochar, and syngas are separated. Typically, the syngas is cooled and then subjected to additional purification or utilization procedures. The biochar is quenched and quickly cooled to inhibit further thermal decomposition and ensure its stability and desired properties (Ghorbani et al., 2022; Gong et al., 2019).

Post-Processing and Quality Control: The biochar produced is subjected to additional processing steps to remove any remaining impurities and ensure its quality and safety. Post-processing may include sieving or grinding biochar to a desired particle size, washing to remove water-soluble contaminants, and carrying out quality control tests to determine its physical and chemical properties. To ensure its suitability for specific applications, biochar is characterized by its properties, including carbon content, nutrient content, stability, and contaminant levels (Gong et al., 2019; Ganesapillai et al., 2023).

Storage and Packaging: The final step entails preserving biochar in suitable containers or packaging materials to maintain its quality and prevent contamination. Adequate storage conditions, such as preventing exposure to excessive moisture and heat, are required to conserve the biochar's properties until its application (Gong et al., 2019; Ganesapillai et al., 2023).

3.7.1.5 Factors Impacting the Production of Biochar from Sludge

The production of biochar from sludge is a multifactorial process dependent on a variety of influencing parameters, such as feedstock characteristics, pyrolysis or gasification conditions, variable process parameters, and the application of anaerobic digestion. The presence of contaminants in the resulting sludge-derived biochar can present environmental and health concerns, necessitating risk-mitigation strategies (Paz-Ferreiro et al., 2018; Gong et al., 2019).

Moreover, distinguishing characteristics between biochar derived from drinking water treatment plant sludge (WTP sludge) and wastewater treatment plant sludge (WWTP sludge), including differences in feedstock composition, contaminant profiles, and overall properties, require a comprehensive understanding for the evaluation of biochar's suitability and potential risks upon various applications (Younis & Kim, 2022; Méndez et al., 2017). For the production and use of sludge-derived biochar to be secure and sustainable, it is essential that rigorous but flexible regulations, àjour (update) guidelines, and continual investigations and research strategies are developed.

Delving further into the influencing factors, the following details highlight the importance of their meticulous optimization to achieve the desired biochar properties and maximize the resource recovery potential of sludge:

Feedstock Characteristics: The composition of sludge, which includes attributes such as moisture content, organic content, and nutrient content, is key in determining biochar production. Typically, the biochar yields of sludge enriched with organic matter are preferable. In addition, the presence of contaminants and heavy metals in the sludge can significantly impact the biochar's quality (Paz-Ferreiro et al., 2018; Gong et al., 2019).

Conditions of Pyrolysis/Gasification: The operational conditions during pyrolysis or gasification, such as temperature, heating rate, residence time, and reactor type, have a significant impact on the properties of biochar. Higher temperatures and longer residence times usually produce biochar with higher carbon content and greater stability. The rate of heating affects the biochar yield and the formation of byproducts, such as bio-oil and syngas (Younis & Kim, 2022; Méndez et al., 2017).

Process Parameters: Multiple process parameters, including feedstock particle size, moisture content, and reactor atmosphere, have a significant impact on biochar synthesis. Reduced moisture content and smaller particle diameters can facilitate heat transfer and increase biochar yield. The presence of oxygen during the process can lead to the formation of ash, which impacts the biochar's properties (Shen et al., 2013; Liu et al., 2022).

Anaerobic digestion: is as mentioned above a process that involves the breakdown of organic matter by microorganisms in oxygen-deprived conditions, resulting in the production of biogas and digestate. The digestate characteristics, such as nutrient content and digestate-to-sludge ratio (VS/TS ratio), can influence the subsequent biochar production process (Atukunda et al., 2022).

3.7.1.6 Pollutants in Sludge-derived Biochar and Remediation

Pollutants

In the absence of effective management, sludge-derived biochar may harbor a variety of pollutants that pose significant environmental and health hazards. Common contaminants located in sludge-derived biochar include:

Heavy Metals: These may be present in sludge due to the accumulation of metals from wastewater and industrial effluents. Pyrolysis or gasification can concentrate heavy metals within biochar. When applied to soil, biochar containing elevated levels of heavy metals bears the risk of leaching into groundwater or being absorbed by plants, thereby potentially entering the food chain. Such incidents can have negative impacts on ecosystems and human health (Czech & Oleszczuk, 2018).

Persistent Organic Pollutants (POPs): POPs are organic compounds with resistance to degradation and potential environmental accumulation. POPs may be present in sludge from industrial and domestic sources. Inadequate treatment during biochar production may result in the transfer of these compounds to the biochar, thereby increasing the risk of environmental contamination (Ganesapillai et al., 2023).

Pathogens: Sludge may contain pathogens such as bacteria, viruses, and parasites, particularly when derived from wastewater treatment facilities. Inadequate temperature and residence time during pyrolysis or gasification may enable pathogens to persist in biochar, posing threats to human health and the environment (Gong et al., 2023).

Pharmaceutical Residues: Sludge may also contain pharmaceutical residues as a result of human and animal drug excretion. These residues could be transferred to biochar during its production, and if applied to soil, they may present a threat to ecosystems, such as the development of antibiotic resistance (Gong et al., 2023).

Remediation of Pollutants

Multiple remediation strategies can reduce the prevalence of contaminants in sludge-derived biochar. These can include feedstock screening, pre-treatment processes, optimization of pyrolysis/gasification conditions, post-processing measures, quality control initiatives, and the implementation of detailed soil application guidelines (Czech et al., 2021; Gong et al., 2023). It is essential to prioritize the safe and responsible production and application of sludge-derived biochar in order to mitigate the potential negative effects of pollutants on the environment and human health.

Screening of Feedstock: Effective screening and characterization of sludge feedstock may be helpful in identifying potential pollutant sources and selecting feedstocks with reduced pollutant levels (Gong et al., 2023).

Pre-treatment: Prior to the biochar production procedure, pathogen and organic pollutant levels in sludge can be reduced through pre-treatment procedures such as composting and digestion (Nibio, 2021a).

Pyrolysis/Gasification Conditions: By optimizing pyrolysis or gasification conditions, such as high temperatures and extended residence times, pathogens and organic pollutants can be eliminated during the biochar production process (Cong et al., 2022).

Post-processing and Quality Control: Post-processing steps such as washing, sieving, and quality control can aid in the removal of impurities and ensure the final biochar meets quality standards and regulatory requirements (Gong et al., 2023).

Detailed Guidelines for Soil Application: Clear formulation and implementation of appropriate detailed guidelines and up-to-date regulations for biochar application in the soil can assist in mitigating risks associated with pollutants. This may involve the restriction of biochar application rates, the selection of suitable soil types, and the consistent monitoring of the presence of pollutants in the environment (Czech et al., 2021).

3.7.1.7 Difference in Biochar from WTP-Sludge and WWTP-Sludge

Biochars produced from WTP-Sludge and WWTP-Sludge can exhibit significant variations. This is predominantly due to the unique composition and characteristics of the feedstock used in each process. A comprehensive analysis of these distinctions is essential to ensure the safe and sustainable use of sludge-derived biochar. This knowledge also aids in mitigating the potential threats posed by the pollutants contained within these products.

As previously mentioned, sludge derived from the WTP typically contains a more significant concentration of minerals than sludge sourced from WWTP. This disparity is due to the predominately inorganic composition of WTP sludge extracted during the drinking water treatment process. As a result, biochar derived from this type of sludge frequently has a high ash content. In contrast, WWTP sludge is characterized by a higher concentration of organic matter, including residual sewage solids. This increased organic content contributes to a larger carbon footprint in the biochar that results (Nibio, 2021b; Elkhalifa et al., 2022).

Furthermore, the contaminant profile differs substantially between WTP sludge and WWTP sludge, depending on the character of the source and the applied treatment methods. For instance, WTP sludge may contain higher concentrations of inorganic contaminants, such as heavy metals. This elevated contamination is due to the prevalence of industrial effluents in the water supply. In distinct contrast, WWTP sludge is likely to contain a higher concentration of organic contaminants, including residues from pharmaceutical products and disease-causing microorganisms. Typically, these contaminants come from domestic wastewater (Gong et al., 2019; Ganesapillai et al., 2023).

Variations in feedstock composition and associated contaminant profiles have a substantial effect on the properties and potential applications of biochar derived from WTP and WWTP sludge. Therefore, these distinguishing characteristics must be considered when assessing the suitability of biochar for various applications, such as soil amendment and environmental remediation, and identifying potential threats associated with its use.

3.7.2 Biochar usage areas

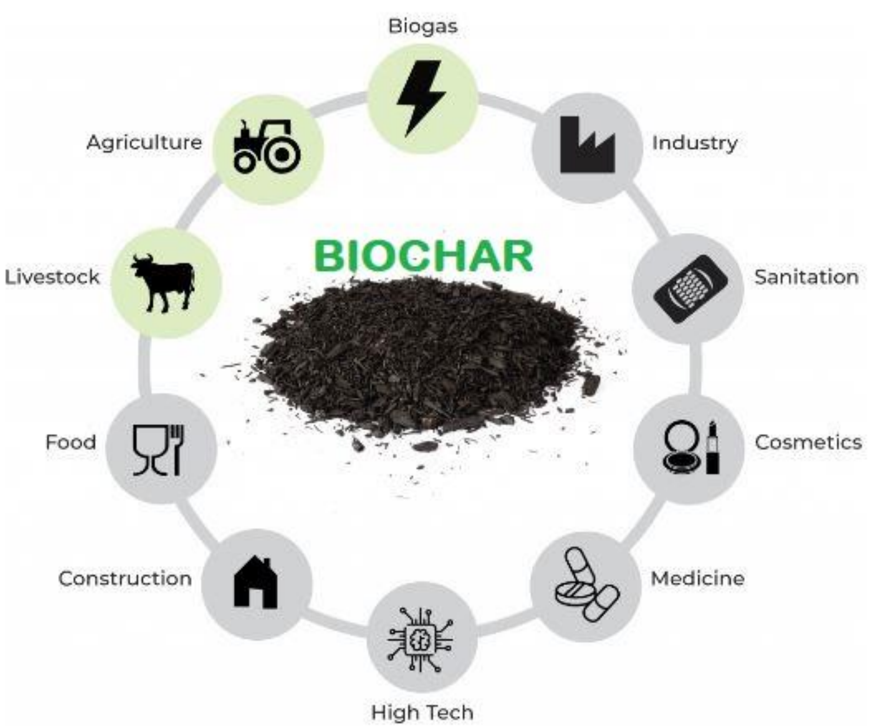


Figure 19: Biochar as a material with exceptional proprieties. Source: EBI, 2023

Due to its unique properties and wide range of applications, biochar can be used in a variety of industries, including industry, sanitation, cosmetics, medicine, pharmaceuticals, advanced technology, construction, agriculture, food production, energy production, and water treatment facilities. Implementing biochar in these sectors promotes sustainability, mitigates environmental degradation, and advances a circular and resource-efficient economy (Nibio, 2021b; EBI, 2023).

Agriculture and Soil Amendment

As previously stated, biochar is primarily utilized in the agricultural sector as a soil amendment to improve soil fertility, structure, and nutrient retention capacity (Nibio, 2021b; Nibio, 2020a; Bu et al., 2022). It offers an environmentally favourable solution to problems like climate change, soil health, and food security (Nibio, 2022a; EBI, 2023). Biochar can considerably improve soil water retention, allowing farmers (agriculture) to save water. It accomplishes this by increasing soil porosity, which allows the soil to retain more water. The precise quantity of water saved can vary greatly based on factors such as the type of soil, the crop being grown, and the volume and type of biochar employed. However, some studies suggest that biochar can increase water-holding capacity by 18 to 80 percent, potentially resulting in irrigation savings of the identical amount. This suggests that producers may need to irrigate less frequently, thereby conserving water and energy.

Biochar has demonstrated significant potential as an agricultural soil amendment. However, one of the most significant threats associated with this solution can be the possibility of soil contamination by heavy metals present in biochar. This issue can be remedied by performing a comprehensive characterization of biochar prior to application, ensuring low metal content in the feedstock, implementing quality control measures during production, and conducting soil testing and monitoring to guarantee safe application levels (Nibio, 2020b; Gong et al., 2019).

Carbon Sequestration and Climate Change Mitigation

As previously mentioned, biochar's function in Carbon Sequestration extends to mitigating climate change by sequestering carbon in the soil matrix for extended periods of time (Bu et al., 2022; Nibio, 2022b; Ghorbani et al., 2022). Consequently, it provides a sustainable strategy for reducing the carbon footprint of various sectors and facilitates the achievement of carbon neutrality objectives.

Employing biochar for carbon sequestration and climate change mitigation is a potentially effective strategy. However, the potential release of greenhouse gases during biochar production and application can present a threat to this solution. To address this, it is crucial to optimize pyrolysis conditions to minimize emissions, adopt sustainable feedstock procurement practices, and consider the entire process's life cycle analysis (Bu et al., 2022; Czech & Oleszczuk, 2018).

Environmental Remediation and Water Treatment

As stated earlier, biochar demonstrates remarkable environmental benefits. Its adsorption properties enable its use in environmental remediation and water treatment applications, thereby enhancing water quality, and nutrient removal, and mitigating environmental impact (Thompson et al., 2016; Vivo-Vilches et al., 2017).

Biochar can be beneficial for environmental remediation and water treatment, but it can also pose a risk of contaminant leaching. Various strategies, including the use of activated biochar with enhanced sorption properties, thorough characterization of the biochar and the target contaminants, and implementation of appropriate filtration and treatment processes, can be employed to mitigate this risk (Czech et al., 2021; Huber, 2021).

Energy Generation

Biochar is a renewable energy source that can be utilized through combustion or gasification in the domain of Energy Production. As a solid fuel, biochar provides an eco-friendly alternative to fossil fuels by generating heat and electricity (Hauser, 2017). It provides opportunities for the production of clean and sustainable energy in industries, homes, and communities. The production of biochar-based energy supports decentralized energy systems and reduces reliance on non-renewable energy sources (Thomas et al., 2021).

Through biogas production and pyrolysis, biochar can be used as a source of renewable energy. However, the minimal energy content of the biochar produced from WTP or WWT sludge can pose a risk to this solution. Co-pyrolysis of sludge and other biomass feedstocks can be used to increase the energy content and optimize the process parameters (Atukunda et al., 2022; Liu et al., 2022).

Livestock and Animal Husbandry

In animal husbandry and livestock production, biochar serves as a feed additive. Its incorporation into animal feed enhances nutrient utilization, promotes digestive health, and reduces livestock operations' environmental impact. It has been demonstrated that biochar reduces odor emissions and improves manure management. Biochar offers sustainable solutions in this field by enhancing animal welfare, reducing pollution of the environment, and optimizing resource utilization (Nibio, 2022b; Yoo et al., 2021).

Utilizing biochar in livestock and animal husbandry has a number of advantages. In this application, however, the potential presence of contaminants that can negatively impact animal health presents a threat. To address this issue, strict quality control measures and comprehensive characterization of biochar are required to ensure its safety for animal consumption (Nibio, 2022a; Paz-Ferreiro et al., 2018).

Building Materials, Road Construction, and Infrastructure

The construction industry can incorporate biochar into building materials such as bricks, and tiles, which leads to improved thermal properties, reduced carbon emissions, and increased energy efficiency. By substituting conventional building materials with alternatives based on biochar, the construction industry can reduce its environmental impact and contribute to sustainable building practices (Zhou et al., 2018; Dickinson et al., 2015)

In the sphere of road construction and infrastructure, biochar can be incorporated into road construction and infrastructure to improve their performance and sustainability. Asphalt and concrete modified with biochar reveal superior mechanical properties, decreased fracture, and increased resistance to deformation (Gong et al., 2023). Applying biochar in road construction can result in infrastructure that is more durable and environmentally beneficial, reducing maintenance costs and carbon emissions.

The incorporation of biochar into building materials, road construction, and infrastructure applications can, as mentioned, improve the mechanical properties and sustainability of these materials. However, the potential leaching of contaminants from biochar can compromise the structural integrity of the materials in this solution. Appropriate treatment and modification of biochar to reduce leachability, adherence to relevant regulations and standards, and long-term durability testing are remedies for this issue (Kapoor et al., 2022; Zhao et al., 2023b).

Cosmetics and Personal Care Products

In hygiene products such as face masks, cleansers, and exfoliants, the cosmetic and personal care industry takes advantage of the adsorption properties of biochar. It facilitates the removal of impurities, toxins, and excess sebum, thereby promoting a healthy complexion. Biochar-based cosmetics provide sustainable alternatives to conventional products, meeting the increasing demand for eco-friendly beauty products (Ganesapillai et al., 2023; EBI, 2023).

Applying biochar in cosmetics and personal care products can have multiple benefits. However, the potential presence of toxic compounds in biochar can present an imminent danger to human health and puts a risk to this solution. To mitigate this, stringent quality control measures, including testing for contaminants, should be implemented, and biochar should comply with pertinent safety regulations and guidelines (Thomas et al., 2021; Vivo-Vilches et al., 2017).

Pharmaceutical and Medical Applications

Biochar's potential extends to pharmaceutical and medical applications. It has been examined for wound healing, antimicrobial activity, and detoxification (Zhao et al., 2023a; Elkhalifa et al., 2022). Due to its biocompatibility and adsorption properties, biochar-based materials are used in medical devices such as implants and wound dressings (Zhao et al., 2023b; EBI, 2023).

The pharmaceutical and medical applications of biochar are very promising. However, the potential cytotoxicity of biochar can pose a risk in this application and may limit its safe application. This problem can be remedied by conducting a comprehensive toxicity assessment of biochar, modifying its surface to reduce cytotoxicity, and adhering to stringent regulatory requirements (Chiappero et al., 2021; Méndez et al., 2017).

Laboratory and High-Tech Applications

In laboratory research, high-tech industries, and advanced material science, biochar is used as a support material for catalytic reactions, providing a stable matrix for catalysts and increasing reaction efficiency (Younis & Kim, 2022). It has the potential to be utilized in energy storage, electronic devices, and sensor technologies (Atukunda et al., 2022). Biochar's unique physicochemical properties make it suitable for a variety of high-tech applications, including carbon-based nanomaterials, water filtration membranes, and environmental sensors (Younis

& Kim, 2022; EBI, 2023). Biochar-derived materials have the potential to advance a variety of disciplines, including electronics, nanotechnology, and sustainable materials.

As stated above, biochar has a useful contribution to laboratories and high-tech industries. However, the potential interference of impurities present in biochar with sensitive analytical techniques or device performance can represent a threat in this application. To address this issue, high-purity biochar should be produced using high-quality feedstocks and rigorous purification techniques, and its potential impact on analytical results or device performance should be extensively evaluated (Cong et al., 2022; Shen et al., 2013).

Food and Food Processing

Biochar is utilized in the food industry to enhance the quality and expiration life of food products. It has been investigated for its potential to decrease food degradation, inhibit microbial growth, and enhance food safety (Bandyopadhyay et al., 2021). In addition, biochar-amended soils increase crop yields and enhance the nutrient content of food crops (Nibio, 2020b; EBI, 2023). Hence, the application of biochar in the food industry can contribute to sustainable agriculture, waste reduction, and improved food security.

Using biochar in food and food processing has the potential to provide benefits. However, the potential transfer of contaminants from biochar to the food chain can represent a risk for this usage. To mitigate this risk, biochar should be subjected to stringent quality control checks, including contaminant testing, and comply with applicable food safety regulations and standards (Nibio, 2021a; Zhou et al., 2018).

3.7.2.1 Biochar Reutilization

The concept of biochar reutilization has garnered increased interest as a result of the potential benefits it may confer across a wide range of applications. Yet, with the augmentation in the usage of biochar, concerns have been raised regarding the feasibility of biochar reutilization, the benefits and potential risks involved, and the procedures necessitated for such reutilization. The improvement and optimization of biochar reutilization techniques, with an emphasis on mitigating potential threats, requires additional research and technological development. This can facilitate the sustainable implementation of biochar in a broader range of industries.

Addressing the potential for biochar reutilization in a variety of applications, many different factors can impact the process. These include the biochar's physical and chemical properties, the specific requirements for each application, and the potential presence of contaminants within the biochar. Reutilization is supported by several benefits, including the conservation of resources, the reduction of waste, and the possibility of cost savings.

In agricultural applications, the viability of biochar reuse as a fertilizer is largely determined by its nutrient content, stability, and suitability for specific crop and soil conditions (Nibio, 2020b; Nibio, 2021b). Similarly, the reutilization of biochar in anaerobic digestion systems for the production of biogas is dependent on its stability, adsorption capacity, and effects on microbial activity and digestion performance (Luo et al., 2020; Liu et al., 2022).

It is also possible to reuse biochar in the treatment of water and wastewater. This depends on biochar's adsorption capacity, porosity, surface chemistry, and regeneration potential of biochar (Gong et al., 2023; Zhao et al., 2023b). In the context of biogas upgrading, biochar can serve as a CO2 adsorbent, contributing to the increase of methane content in biogas and the improvement of biomethane quality (Yuan et al., 2021; Shen et al., 2015; Vivo-Vilches et al., 2017).

Despite all of the advantages conferred by biochar reutilization, there are potential risks. Accumulation of contaminants such as heavy metals or organic pollutants may occur during its initial use (Gong et al., 2019; Mohamed et al., 2022). In addition, the repeated application of biochar to soil or ecosystems may modify soil properties, nutrient cycling, microbial communities, and the wellness of ecosystems overall (Czech & Oleszczuk, 2018; Ghorbani et al., 2022).

In order to ensure the safety and efficacy of biochar reutilization, it is essential to implement suitable processing techniques. These can include washing and sieving to remove water-soluble contaminants and impurities (Gong et al., 2023; Gong et al., 2019), thermal treatment such as high-temperature heating or pyrolysis to eliminate potential pathogens or contaminants (Cong et al., 2022; Czech et al., 2021), and chemical treatment such as acid or base washing to remove specific contaminants or modify surface properties (Zhao et al., 2023a; Goldan et al., 2022). In addition to these processing methods, quality control measures, such as routine testing and monitoring, are essential for determining the reusability of biochar (Paz-Ferreiro et al., 2018; EBC, 2023). Thus, the combination of advanced processing techniques and stringent quality control measures can assure the safe and sustainable reuse of biochar in a variety of applications.

3.7.3 Biochar Contribution to the Ecosystem and Society

Biochar offers many benefits and can contribute a lot to the well-being of the ecosystem and the local community. It requires an expanded understanding of how to take advantage of these benefits and avoid the potential threats that can arise from negligence.

3.7.3.1 Contribution of Biochar to Ecosystem Function and Stability

Biochar is a promising product for enhancing the well-being of surface water systems, groundwater, biodiversity, and the environment as an ensemble. It has the potential to significantly enhance water quality, nutrient sequestration, and water-holding capacity in a variety of ecosystems, including lakes, catchments, and peatlands. To harness these benefits and minimize potential risks, it is essential to consider the specific environmental conditions and contexts in which biochar is used. The source of the feedstock and the production processes must be thoroughly examined. More importantly, continuing research and pilot projects are essential for determining the long-term effects of biochar on the environment and developing guidelines for its sustainable and responsible use.

Biochar's impact on Surface Water Systems

Lakes and Catchments

Biochar has been shown to enhance water quality by adsorbing and neutralizing pollutants such as heavy metals and organic contaminants, thereby decreasing their bioavailability and potential toxicity to aquatic organisms (Gong et al., 2019; Huber, 2021). In addition, biochar-amended soils can increase nutrient sequestration, which reduces nutrient discharge into lakes and catchments. Incorporation of biochar into soils encircling water bodies can improve soil structure and water retention capacity, thereby reducing erosion and nutrient runoff into surface water. Thus, water quality is preserved, and the risk of eutrophication is reduced or controlled (Gong et al., 2019; Zhao et al., 2023b). In addition, biochar has the capacity to improve soil water-holding capacity, resulting in decreased surface runoff and increased infiltration, thereby maintaining water levels in lakes and catchments during periods of low rainfall. These effects collectively contribute to the total well-being and long-term sustainability of surface water systems (Elkhalifa et al., 2022; Goldan et al., 2022; Regjeringen, 2022; Nibio, 2021b).

Biochar's Function in Peatland Ecosystems

Peatlands are essential ecosystems that play crucial roles in carbon sequestration and biodiversity conservation. Utilizing biochar in peatlands can yield significant benefits. Biochar insertion into peat soils has been shown to increase carbon sequestration by increasing soil organic carbon content and slowing down the decomposition rate of organic matter (Paz-Ferreiro et al., 2018; Nibio, 2020b). This capability has significant implications for reducing GHG emissions and advancing strategies to mitigate climate change. Additionally, the improvement of water retention capacity in biochar-amended peatlands can reduce the risk of peatland degradation, such as soil subsidence and erosion (Méndez et al., 2017; Gong et al., 2019). Additionally, enhanced water retention contributes to the preservation of peatland ecosystems and the associated biodiversity (Gong et al., 2019; Nibio, 2020b).

Biochar's Effect on Groundwater Systems

Biochar has demonstrated positive effects on the quality and management of groundwater. When applied to agricultural soils, biochar can increase water infiltration and reduce nutrients and pollutants leaching into groundwater (Luo et al., 2020; Nibio, 2021a). Biochar's large surface area and porosity facilitate the absorption and retention of pollutants, thereby preventing their downward migration into groundwater resources (Gong et al., 2019; Xiao et al., 2022). Furthermore, biochar-enriched soils can improve soil structure by reducing soil compaction and fostering the formation of macropores, which improves water percolation (Gong et al., 2019; Nibio, 2021b). These effects contribute to the protection and maintenance of the integrity of groundwater.

Biochar's Role in the Conservation of Biodiversity

Biodiversity refers to the multitude of life forms within ecosystems and is essential for ecosystem stability and function. Various biochar applications can contribute to the conservation of biodiversity. First of all, biochar-enriched soils can boost fertility and encourage the growth of beneficial bacteria and fungi, both of which play a crucial role in the nutrient cycle and plant well-being. Beneficial soil microorganisms are assisted by biochar, which improves nutrient cycling and ecosystem health (Gong et al., 2019; Thompson et al., 2016; Méndez et al., 2017; Nibio, 2021b; Nibio, 2020a; Huber, 2021). As a result, plant growth is boosted and diverse plant communities are sustained, which contributes to an increase in biodiversity (Ghorbani et al., 2022; Gong et al., 2019; Nibio, 2022a; Méndez et al., 2017;

Mohamed et al., 2022). Second, biochar-enriched soils can enhance soil water-holding capacity, especially in arid or degraded ecosystems, thereby enhancing plant establishment and survival (Gong et al., 2019; Nibio, 2021a). Third, the addition of biochar to degraded or contaminated soils can improve soil conditions and restore habitat quality, thereby facilitating the recovery of native flora and fauna (Gong et al., 2019; Goldan et al., 2022). Biochar's favorable effects on soil fertility, water availability, and habitat quality collectively contribute to the promotion and conservation of biodiversity. Importantly, the variety of biochar and its application rate should be carefully considered to ensure compatibility with local ecosystems and to minimize any unintended ecological effects (Goldan et al., 2022).

3.7.3.2 Contribution of Biochar to the Local Community's Well-Being

Biochar's diverse applications provide a variety of socioeconomic benefits that empower local communities and promote societal well-being. These benefits span multiple domains, including agriculture, climate change mitigation, resource management, and economic diversification, thereby paving the way for a prosperous and resilient future (Bu et al., 2022; Regjeringen, 2022; Gong et al., 2019; Nibio, 2020a; Hauser, 2017; Seman-Varner et al., 2022; Nibio, 2022b).

Biochar, as mentioned repeatedly, has demonstrated efficacy as a soil enhancer, increasing soil fertility and water-holding capacity, which bolsters crop yield and agricultural productivity overall. This improvement increases food security and contributes to the stability and diversity of the local food supply. The function of biochar in decreasing reliance on synthetic fertilizers contributes to sustainable agricultural practices (Nibio, 2021b; Nibio, 2020a; Bu et al., 2022).

In addition, as aforementioned, biochar is essential for carbon sequestration, thereby assisting communities in attaining carbon neutrality by lowering atmospheric carbon dioxide levels. It also contributes significantly to environmental remediation by absorbing contaminants and heavy metals to reduce soil and water contamination (Bu et al., 2022; Regjeringen, 2022; Gong et al., 2019).

In the context of sustainable resource management, biochar is essential for enhancing agricultural water availability and fostering water efficiency. In addition, biochar-based energy production provides a renewable energy source, thereby contributing to local energy security and decreasing reliance on fossil fuels (Nibio, 2020a; Hauser, 2017).

The adoption of biochar also stimulates job creation and local entrepreneurship. The biochar value chain, from the collection and processing of biomass to its application, necessitates a diverse workforce, thereby generating new job opportunities. It also offers a platform for local enterprises to create innovative biochar-based products and services (Seman-Varner et al., 2022).

The incorporation of biochar into local communities stimulates innovation and facilitates the transmission of knowledge. The execution of biochar initiatives necessitates collaboration between various stakeholders, facilitating an exchange of knowledge and expertise. This collaboration encourages the development of biochar solutions particular to a region and sustainable development (Nibio, 2022b).

Finally, biochar utilization can stimulate economic diversification and resilience in local communities. It creates new revenue streams, reduces reliance on traditional industries, and promotes sustainable economic growth. The incorporation of biochar into various sectors, such as agriculture, energy, and water treatment, creates an economy that is more resistant to external disruptions (Seman-Varner et al., 2022).

3.7.3.3 Contribution of Biochar to Industrial Symbiosis

It is now understood that sludge generated by WWTPs and WTPs poses disposal and environmental impact challenges. As previously stated, sludge is one of the persistent wastes that will continue to increase as the demand for water and wastewater treatment increases alongside the global population. So far, it has been demonstrated that this issue can be resolved by transforming sludge into a precious resource such as biochar production. By strategically implementing biochar in an industrial symbiosis for its use across multiple sectors, the revenue potential of WTPs and WWTPs can be enhanced, thereby contributing to their financial viability. Biochar can be utilized in agriculture as a soil amendment, in energy production, water and air filtration, construction materials, and animal feed additives (PYREG, 2022; Shen et al., 2015; Thomas et al., 2021; Nibio, 2022b).

Several strategies can be implemented to increase the production and sales of sludge-derived biochar:

(1) **Optimization of Sludge Treatment Processes**: Beneficial and productive sludge treatment processes, such as anaerobic digestion, can maximize biochar production and quality (Yuan et al., 2021; Luo et al., 2020).

(2) **Process Integration**: Integrating the biochar production process with existing sewage or sludge treatment infrastructure can reduce costs and improve the system's overall performance. Combining anaerobic digestion with pyrolysis/gasification, for instance, can result in the co-production of biogas and biochar (Shen et al., 2015; Atukunda et al., 2022).

(3) **Quality Control and Certification**: Implementing quality control measures and acquiring certifications, such as the European Biochar Certificate (EBC), can increase the marketability and value of sludge-derived biochar (EBC, 2023; Bandyopadhyay et al., 2021).

(4) **Market Development and Collaboration**: Developing robust market networks, engaging with potential consumers, and fostering collaborations with stakeholders can open up new sales channels for biochar products. This may involve collaborations with farmers, horticulturists, waste management companies, and other industries (Seman-Varner et al., 2022; Ganesapillai et al., 2023).

To increase the revenue and sustainability of WTPs and WWTPs through biochar as a commercialization product, there is a need for the following biochar implementation strategies:

(1) **Collaboration with Agriculture Sector**: Agriculture (farmers) are the primary prospective biochar consumers. Collaboration with the agriculture industry can facilitate biochar's use as a soil amendment. This can be accomplished through partnerships, the sharing of knowledge, and the establishment of incentives for farmers to incorporate biochar into their agricultural practices (Nibio, 2021a; Zhao et al., 2023b).

(2) **Development of Value Chains**: Establishing comprehensive value chains for biochar, including production, distribution, and marketing, can increase its commercial viability and establish a sustainable market (Nibio, 2021b).

(3) **Pilot Projects and Research**: Conducting pilot projects and research studies on the effectiveness and beneficial effects of biochar utilization can generate valuable data and evidence, thereby supporting the adoption of biochar and attracting additional investment (González-Arias et al., 2022; Nibio, 2022a).

(4) **Policy and Regulatory Support**: Governments should provide policy and regulatory support, such as incentives, subsidies, and standards, to encourage the adoption and use of sludge-derived biochar (Regjeringen, 2022).

3.7.4 Biochar to GAC for usage in water and wastewater treatment

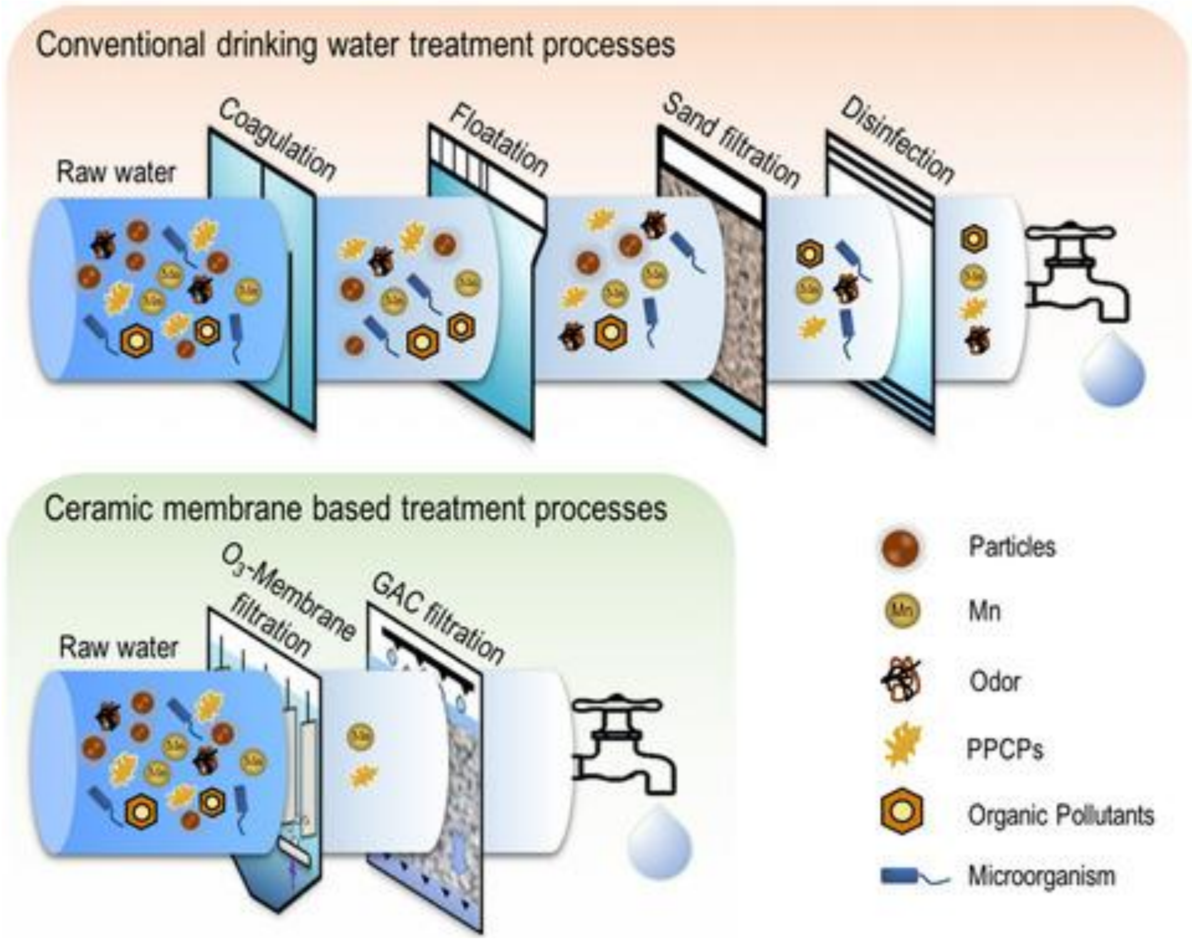


Figure 20: Using O3 Ceramic membrane and GAC filtration process. Source: Chen et al. 2020

Granular activated carbon (GAC) has emerged as a promising product for the treatment of water and wastewater. Studies have all proven the effectiveness of GAC filtration in minimizing the formation of disinfection by-products (DBP) and mitigating odor and taste concerns in the process of drinking water treatment (Hu et al., 2018; Chen et al., 2020; Total Water, 2016). Due to its specificity and efficiency in water treatment, the demand for GAC in the water sector is increasing. The transition from biochar to GAC can be an excellent strategy to ensure the availability of this unique product with multiple benefits:

(1) **Enhancement of Precursor Elimination**: An important benefit of biochar transition to GAC is its enhanced ability to eliminate precursors, which are crucial to the formation of regulated carbon-containing disinfection by-products (C-DBPs) and unregulated nitrogen-containing disinfection by-products (N-DBPs). Combining micro-ozone pretreatment with coagulation-sedimentation-filtration (CSF) and O3-GAC has shown significant efficacy in reducing chloroform (CF) and dichloroacetonitrile (DCAN) precursors, thereby decreasing total cytotoxicity (Hu et al., 2018; Total Water, 2016).

This is especially advantageous for the treatment of water originating from eutrophic or humic streams, where such precursors are abundant.

(2) **Reduction in Land Utilization**: GAC direct filtration is recognized as a viable method for conserving land, especially when designing water treatment installations in urban areas. Notably, the combination of ozone membrane filtration and GAC filtration reduces the need for large areas and, thus, decreases capital expenditures compared to the traditional coagulant dosage method (Chen et al., 2020; Total Water, 2016). This makes switching from biochar to GAC an attractive option for urban water treatment facilities.

(3) **Sustainability Impact**: The transformation of biochar to GAC can comply with the water industry's sustainability goals. Utilizing sludge-derived biochar as a resource promotes resource recovery and the circular economy philosophy. This strategy contributes to reducing waste production, mitigating environmental impacts, and enhancing the overall sustainability of the water industry (Kumi et al., 2022).

In addition to the aforementioned benefits, it is essential to consider the potential drawbacks of upgrading from biochar to GAC, including the cost implications. The conversion of biochar to GAC can have a significant economic impact, as it can accrue higher costs than the direct use of biochar. The processing phases in the upgrade sequence, such as activation and granulation, necessitate additional equipment, energy, and labor, which raises production costs (González-Arias et al., 2022). It is necessary to conduct a comprehensive cost-benefit analysis (CBA) of the upgrade procedure to determine its viability.

There are many methods to convert biochar to GAC, including physical activation, chemical activation, and thermal activation. Chemical activation offers greater control over activated carbon's pore structure and surface chemistry, thereby enhancing its adsorption properties (Gong et al., 2023). This process requires biochar to be impregnated with activating agents, which increases its reactivity and active areas for adsorption. In addition, chemical activation can be conducted at lower temperatures than physical activation, which helps to preserve the inherent properties of biochar and reduce energy consumption (Liu et al., 2022).

Several steps comprise the chemical activation procedure for transforming biochar into GAC:

(1) Biochar feedstock is prepared and characterized for its properties, including carbon content, ash content, and surface area. Biochar feedstock is typically derived from the pyrolysis of biomass or organic waste (Shen et al., 2013).

(2) The biochar is impregnated with an activating agent such as potassium hydroxide (KOH) or phosphoric acid (H3PO4), with methods such as incipient wetness impregnation or vacuum impregnation ensuring homogenous distribution on the biochar surface (Zhao et al., 2023b).

(3) Thermal treatment under controlled conditions is applied to the biochar that has been impregnated. This process, which involves heating impregnated biochar to temperatures between 400 to 900 oC in an inert atmosphere such as nitrogen or argon, induces chemical reactions between the activating agent and the biochar, resulting in the formation of a porous structure (González-Arias et al., 2022).

(4) Following activation, the newly formed GAC is washed to remove any residual activating agents and impurities, typically with deionized water or acid solutions, and then completely dehydrated to eliminate moisture (Shen et al., 2013).

(5) Finally, the GAC is granulated with an appropriate particle size distribution for specific applications. Through sieving and classification, uniform granule size is attained. The final GAC product is packaged and prepared for use in water and wastewater treatment systems.

Upgrading biochar to GAC has many advantages. However, it remains essential to consider possible disadvantages. Chemical activation provides the most efficient pathway for upgrading biochar to GAC, enabling control over pore structure and surface chemistry, and resulting in GAC with superior adsorption properties.

3.7.5 Estimation of biochar potential and price

The quantitative prediction of sludge-derived biochar output needs the examination of several mathematical frameworks, influential factors, and parameters. A comprehensive review of the key elements involved in determining the quantity and quality of biochar produced from sludge at either a WWTP or a WTP is required.

3.7.5.1 Theoretical Biochar Yield Estimation

The quantification of converted dry sludge solids can be used to predict the probable production of biochar. This estimate is represented by the following equation:

Biochar quantity (kg/day) = **Dry sludge solids production** (kg/day) ∗ **Biochar yield** (%)

The term 'dry sludge solids production' refers to the daily dry sludge solids yield at a WWTP or WTP, as determined by quantifying dry sludge solids content and total sludge output. The term 'biochar yield' refers to the percentage of dry sludge solids that can be converted into biochar through pyrolysis or other conversion techniques.

Elements Influencing Biochar Yield

Several factors can influence biochar yield, including:

1. **Feedstock Characteristics**: The moisture content, organic carbon concentration, and elemental composition of sludge can all affect biochar output. Higher biochar yields are produced by sludge that has been enriched with organic carbon and has a lower moisture grade.
2. **Pyrolysis Conditions**: The heat rate, temperature, dwell time, and environment during pyrolysis all have a large impact on the biochar output. To optimize biochar output, the best pyrolysis conditions must be empirically discovered or predicted through process modelling.
3. **Pretreatment Techniques**: Specific pretreatment methods, such as drying, palletisation, or chemical treatment, can increase biochar output by lowering moisture content, amplifying sludge density, or altering sludge characteristics.
4. **Pyrolysis Technology**: Different pyrolysis methods, such as slow pyrolysis, fast pyrolysis, or hydrothermal carbonization, produce varying quantities of biochar. When choosing a pyrolysis technique, it is important to consider variables such as process scalability, energy efficiency, and environmental effect.

Parameters for Evaluating Biochar Quality

In addition to quantity, determining the quality of biochar is critical for determining its suitability for various purposes. The following parameters are typically considered:

1. **Carbon Content**: Biochar's carbon content reflects its stability and potential for carbon sequestration. A greater carbon percentage indicates a more stable biochar product.
2. **Elemental Composition**: The elemental composition of biochar, which includes nitrogen, phosphorus, and potassium levels, can influence its nutrient retention and release properties, which are important for agricultural applications.
3. **Surface Area and Porosity**: Biochar's surface area and porosity can impact its water-holding ability, adsorption capacity, and potential to improve soil fertility and microbial activity.

4. **pH and Electrical Conductivity**: Because biochar's pH and electrical conductivity can alter soil pH and nutrient availability, they should be considered when estimating biochar application rates in different soil types.
5. **Contaminant Concentrations**: Sludge-derived biochar may include residual contaminants such as heavy metals or organic pollutants. These pollutant concentrations must be analysed to assure biochar safety and to reduce any environmental hazards.
6. **Stability**: Biochar's stability is measured by its resistance to decomposition over time. Stable biochar can provide long-lasting benefits for soil or water treatment.

The quality factor (%) is typically derived from the biochar's properties and can be calculated using several different methods. Commonly, the carbon content of biochar is used as a basis for determining its quality. As an example, the quality factor can be estimated as follows:

$$\textbf{Quality factor} = \left(\frac{\textbf{Biochar carbon content}}{\textbf{100}}\right) * (\textbf{pH factor}) * (\textbf{nutrient factor}) * (\textbf{stability factor})$$

The aforementioned aspects are critical in improving biochar production processes and assuring its safe and effective use in a variety of applications, hence verifying the project's and investment's feasibility.

3.7.5.1 Theoretical Estimation of Biochar value

The initiation of sludge-derived biochar production necessitates a thorough and deliberate economic analysis. This crucial stage includes a cost-benefit and sensitivity analysis to evaluate the potential effects and economic viability of various parameters and variables (EBC, 2023; Nibio, 2021b; Bandyopadhyay et al., 2021). In addition, a thorough understanding of quantitative concepts and variables is required to calculate the production cost and anticipated selling price of biochar.

Valuation of Biochar

The value of biochar is determined by its quality and demand in the regional market (Bandyopadhyay et al., 2021). The formula below can be utilized for estimating the biochar value:

Biochar value (currency/kg) = **Price of biochar per unit weight** (currency/kg) * **Biochar quality factor**

This price per unit weight reflects production costs and market demand, integrating components such as capital expenditure (CapEX), and operational and maintenance expenditures (OpEX). The quality factor includes properties such as carbon content, pH, nutrient content, and stability, which directly influence the value of biochar. In general, biochar with superior quality parameters, such as high carbon content and effective nutrient retention properties, is generally priced higher.

Estimation of Production Costs

The estimation of sludge-derived biochar production costs requires a good understanding of a range of key parameters (Bandyopadhyay et al., 2021):

1. **Feedstock Acquisition Costs**: The procurement costs include transportation, processing, and management expenses.
2. **Pyrolysis Equipment Costs**: Account for the required capital expenditure for pyrolysis equipment, which includes reactors, heating, and control systems.
3. **Energy Consumption**: It is essential to quantify the energy required for pyrolysis and associated processes, including sludge dewatering, and drying.
4. **Labour Costs**: It is necessary to include labour costs associated with the operation and maintenance of the biochar production system.
5. **Waste Disposal Costs**: The potential costs associated with discarding or utilizing any byproducts or residues generated during the procedure must also be considered.

The total production costs (TC) can be estimated using the following formula:

TC (currency/kg biochar) = **CapEX** + **OpEX** + **EniEX** + **WmEx** – $\mathbf{G_{icv}}$, where CapEX is the cost of capital (incl. equipment), OpEX is the cost of operations and maintenance (incl. feedstock and labour), EniEX is the cost of energy inputs (excl. from OpEX), WmEX is the cost of waste management and disposal (excl. from OpEX), and G_{icv} is government environmental incentives subsidies. However, these costs may differ considerably based on the technology employed, the scope of the operation, and the local economic climate.

Factors Influencing Selling Price Estimation

The estimation of biochar's selling price should consider (Bandyopadhyay et al., 2021):

1. **Market Demand**: Taking into consideration the availability of alternative products and consumer preferences, local market demand has a significant impact on biochar's price.
2. **Biochar Quality**: The biochar's physical and chemical properties that influence its market value. Biochar of superior quality encourages a premium price.

3. **End-Use Application**: The intended application for biochar, such as soil amendment, water treatment, or energy production, can impact its selling price.
4. **Market Competition**: The number of suppliers and market competition can impact the retail price of biochar.

Market Analysis and Feasibility Study for Price Estimation

To determine prospective prices for biochar in a given region, it is essential to conduct a market and feasibility analysis. These evaluations must incorporate variables such as local market demand, product quality, market competition, and any applicable regulations and potential incentives (EBC, 2023; Bandyopadhyay et al., 2021). Government support mechanisms such as incentives, grants, and subsidies can have a substantial impact on the economic viability of biochar projects (EBC, 2023). For instance, in Norway, the estimated market price of untreated biochar in 2021 was over NOK 8 000 per tonne (Nibio, 2021b). However, due to market dynamics and differences in product quality, branding, and distribution channels, prices can fluctuate significantly over time. In 2023, a 3 kg package of biochar at the Norwegian retailer Plantasjen cost between NOK 75 and NOK 150.

Using the following formula, the theoretical selling price of biochar can be calculated:

Selling Price of Biochar = **Total Cost of Biochar** + **Desired Profit Margin**

or

Selling Price of Biochar (currency/kg) = **Production Cost** (currency/kg) + **Distribution Cost** (currency/kg) + **Desired Profit Margin** (currency/kg)

The valuation of biochar entails an evaluation of the price per unit weight, a quality factor that considers various properties, and production cost estimation parameters, which include CapEX, OpEx, and waste disposal costs. In addition, the estimation of the selling price should account for government incentives and subsidies, thereby monitoring the equilibrium between production costs and market dynamics. It is essential to conduct feasibility studies in order to evaluate the economic viability of biochar production initiatives and to determine prospective prices in particular regions. Adopting an industrial symbiosis strategy can therefore serve as a vital instrument for market penetration, resulting in the potential for increased revenue.

3.7.6 LCA, LCC, LCI, and LCIA of biochar

Various methodologies, such as Life Cycle Analysis (LCA), Life Cycle Costing (LCC), Life Cycle Inventory (LCI), and Life Cycle Impact Assessment (LCIA), are routinely employed when assessing the ecological effects of the production process of biochar derived from WTP or WWTP sludge. These analytical results provide producers, consumers, regulators, and investors with a valuable perspective, enabling them to assess the potential role of biochar in the transition to a sustainable and circular economic business model (EBC, 2023; Nibio, 2022a).

Life Cycle Analysis (LCA): the evaluation should include stages such as the collection of raw materials, such as sludge, the production process (pyrolysis), transportation, application as soil amendments, and various end-of-life scenarios. LCA permits the exhaustive quantification of variables such as energy consumption, emissions, and resource consumption at each stage. This provides an extensive understanding of environmental impacts, identifies problem areas, and enables informed decisions regarding the production and application of sludge-derived biochar (EBC, 2023; Nibio, 2020b).

Life Cycle Costing (LCC): this financial analysis should consider the costs associated with the acquisition of raw materials, production, transportation, application, and end-of-life scenarios for sludge-derived biochar. These expenses include OpEX and CapEX, energy consumption, waste management, and externalities. This analysis facilitates an evaluation of the economic viability and competitiveness of the production, enabling stakeholders to evaluate the cost-effectiveness of different technologies or scenarios and potentially identify cost-saving measures (EBC, 2023; Dickinson et al., 2015).

Life Cycle Inventory (LCI): this analytical procedure should include an inventory of raw materials, energy inputs, emissions, by-products, and waste streams throughout the entire lifecycle of sludge-derived biochar. This inventory serves as the basis for subsequent impact assessment and interpretation by describing the resources utilized and emissions produced (EBC, 2023; Thompson et al., 2016).

Life Cycle Impact Assessment (LCIA): requires meticulous consideration of impact categories such as climate change, eutrophication, acidification, ecotoxicity, and resource depletion. This assessment enables stakeholders to conduct comparative analyses of various environmental impacts, identify key contributors, and evaluate the overall sustainability of sludge-derived biochar production and utilization (EBC, 2023; Nibio, 2021b).

It is impossible to overstate the importance of LCA, LCC, LCI, and LCIA to stakeholders in sludge-derived biochar production. These tools enable various stakeholders, from producers to investors, to make informed decisions regarding production optimization, environmental impact reduction, cost-saving measures, the establishment of environmental standards, and the evaluation of the economic viability of biochar projects. Overall, these methodologies facilitate the adoption of sustainable practices and promote scientifically informed decision-making (EBC, 2023; Nibio, 2022a).

Examination frameworks such as LCA, LCC, LCI, and LCIA provide stakeholders with a holistic view of the environmental and economic performance of sludge-derived biochar, thereby informing decision-making processes associated with its adoption and implementation. The information derived from these analyses is crucial for numerous entities, including water and wastewater treatment facilities and investors, when establishing corporate social responsibility (CSR) reporting or evaluating environmental, social, and governance (ESG) criteria. The continued application and research of these methodologies are essential for the advancement of sustainable production and utilization of sludge-derived biochar, thereby facilitating the transition to a greener, circular economy.

3.8 Literature review

The water and wastewater industry faces significant challenges, including aging infrastructure, growing populations, and rigorous linear environmental regulations. In addition, the sector has the potential to play a significant role in promoting the circular economy, for example by utilizing sludge for the production of biogas and biochar. Determining the viability of such initiatives, therefore, requires a substantial body of research. Understanding our existing knowledge and identifying the discrepancies between theoretical propositions and empirical applications requires a comprehensive analysis of diverse literature related to these themes.

This literature review investigates the existing research on the implementation of the circular economy in the water and wastewater industry, with a focus on local biogas and biochar production and their potential for covering operational and maintenance costs for municipal treatment facilities. The literature review highlights and summarizes the most prevalent and pertinent conclusions from various studies related to the topics of this paper and provides an overview of the opportunities and challenges facing the water and wastewater industry. It analyses sludge, biogas and biochar production, pyrolysis of sludge, the benefits of resource recovery, and the challenges and strategies for implementing the circular economy in the water and wastewater industry.

Many studies have investigated the viability and potential of biogas and biochar production at water and wastewater treatment facilities in a broad range of contexts. The bibliography of this master's thesis contains more than 280 pieces of relevant literature that have been scrutinized to extract recurring findings and recommendations for bridging the gap between theoretical assertions and their practical application. In addition, the review endeavours to identify potential avenues for financial gain, to identify gaps in the literature, and to establish the basis for the research questions that will guide the empirical investigation.

The table that follows is a compilation of the findings and recommendations from various sources, structured according to specific keywords that pertain to the thesis's primary theme and problem statement.

Keywords	Findings	Recommendations	APA references
Sludge			
Options for optimal sludge treatment	Various sludge treatment technologies, such as anaerobic digestion, pyrolysis, and gasification, must be investigated continuously for their energy recovery potential from sewage sludge to establish a database for optimal sludge treatment for resource recovery.	Further research is needed to explore the techno-economic feasibility and environmental impact of different sludge treatment options.	Mirmasoumi et al., 2018; Mohamed et al., 2022; Oladejo et al., 2019; Rossetti et al., 2017; Samolada & Zabaniotou, 2014; Shen et al., 2015; Venkatesh & Elmi, 2013; Yan et al., 2020; Yu et al., 2018; Zaharioiu et al., 2021; Zhang et al., 2017.
Barrier for sludge optimization	Factors such as the presence of micropollutants, heavy metals, and recalcitrant organic contaminants in sludge pose challenges for its optimization and energy recovery.	Pre-treatment techniques and innovative process designs should be explored to address the barriers in sludge optimization.	Bioforsk, 2014; Liu et al., 2021a; Liu et al., 2021b; Liu et al., 2022; Maragkaki et al., 2018; Naqvi et al., 2021; Norsk Vann, 2010; Norsk Vann, 2016c; Venegas et al., 2021; Yuan & Zhu, 2016; Zhang et al., 2017;
Possibilities and benefits of Anaerobic digestion	Anaerobic digestion of sewage sludge has shown promise in terms of biogas production and energy recovery, leading to potential economic and environmental benefits.	Optimization of anaerobic digestion process parameters, co-digestion with other organic wastes, and utilization of the produced biogas should be explored for maximizing benefits.	Carbon Limits, 2019; Luo et al., 2020; Prabhu & Mutnuri, 2016; Rakić et al., 2023; Sapmaz & Kiliçaslan, 2019; Sarker et al., 2019; Scarlat et al., 2018; Trinomics, 2021; Tshemese et al., 2023; Xu & Lancaster, 2012; Yuan et al., 2021.
Biogas from sludge			
Possibilities to produce biogas from sludge	Anaerobic digestion of sewage sludge offers a viable option to produce biogas, which can be utilized as a renewable energy source.	Further research is needed to optimize the anaerobic digestion process parameters for maximum biogas production.	Sapmaz & Kiliçaslan, 2019; Sarker et al., 2019; Scarlat et al., 2018; Shen et al., 2013; Shen et al., 2015; Shuokr & Jwan, 2021; Tanigawa, 2017; Tshemese et al., 2023; Venkatesh & Elmi, 2013; Wang et al., 2019; Woo et al., 2022; Yuan et al., 2021; Zhang et al., 2017; Zubrowska-Sudol et al., 2022.
Advantages of producing biogas from sludge	Production of biogas from sludge offers multiple advantages such as renewable energy generation, waste reduction, and potential revenue generation.	Encouraging the implementation of anaerobic digestion systems in wastewater treatment plants and exploring co-digestion of other organic wastes to enhance biogas production.	Prabhu & Mutnuri, 2016; Sapmaz & Kiliçaslan, 2019; Sarker et al., 2019; Scarlat et al., 2018; Shao et al., 2021; Tanigawa, 2017; Tshemese et al., 2023; Venkatesh & Elmi, 2013; Yuan et al., 2021; Zhang et al., 2017; Zhao et al., 2023.
Disadvantages to produce biogas from sludge	Challenges associated with biogas production from sludge include the presence of inhibitors, process complexity, and operational issues that can affect overall efficiency and biogas yield.	Implementing effective pre-treatment techniques to mitigate inhibitory substances, optimizing process parameters, and ensuring proper maintenance and monitoring of anaerobic digestion systems.	Norsk Vann, 2010; Oladejo et al., 2019; Sapmaz & Kiliçaslan, 2019; Sarker et al., 2019; Scarlat et al., 2018; Shen et al., 2013; Shen et al., 2015; Tanigawa, 2017; Tshemese et al., 2023; Venkatesh & Elmi, 2013; Wang et al., 2019; Yuan et al., 2021; Zhang et al., 2017.
Challenges for enhancing circularity of biogas from sludge	Challenges for enhancing circularity of biogas from sludge include the need for efficient waste management systems, effective utilization of by-products, and addressing environmental and regulatory barriers.	Developing integrated waste management strategies that prioritize the circularity of biogas production and utilization.	Carbon Limits, 2019; Miljødirektoratet, 2020; Sapmaz & Kiliçaslan, 2019; Sauvé et al., 2021; Sgroi et al., 2018; Venegas et al., 2021; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zaharioiu et al., 2021; Zarei, 2020.
Possibilities and advantages of upgrading	Upgrading sewage-produced biogas can enhance its energy value and quality, allowing for wider applications such as injection into	Implementing cost-effective biogas upgrading technologies to improve the energy content and remove impurities from sewage-produced	Miljødirektoratet, 2020; Sauvé et al., 2021; Sgroi et al., 2018; Vivo-Vilches et al., 2017; Yuan et al., 2021; Zaharioiu et al.

sewage-produced biogas	natural gas grids or use as a vehicle fuel. It also reduces the environmental impact associated with biogas utilization.	biogas. Promote biogas upgrading technologies, invest in infrastructure, and support R&D	(2021); Zhang et al., 2017; Zhao et al., 2023a .
Pyrolysis of sludge			
Possibilities and advantages of pyrolysis/gasification of sewage sludge	Pyrolysis/gasification of sewage sludge offers the potential to convert the organic matter into biochar and produce bio-oil and syngas, which can be used for various applications. It also reduces the volume of sludge and contributes to resource recovery.	Exploring the technical and economic feasibility of pyrolysis/gasification processes for sewage sludge treatment and identifying suitable end uses for the biochar, bio-oil, and syngas produced.	Dzihora, 2021; Nibio, 2020a; Nibio, 2020; Nibio, 2021a; Shen et al., 2013; Shen et al., 2015; Shuokr & Jwan, 2021; Tanigawa, 2017; Thompson et al., 2016; Wang et al., 2019; Woo et al., 2022; Xiao et al. 2022; Yan et al. 2020; Younis & Kim 2022; Zewde et al., 2023.
.Disadvantages of pyrolysis/ gasification of sewage sludge	Disadvantages of pyrolysis/gasification of sewage sludge include the need for energy-intensive processes, potential emissions of harmful gases, and challenges in handling and storing the resulting biochar.	Developing efficient pyrolysis/gasification technologies with minimal energy consumption and optimized process parameters. Implement proper emission control measures.	Chen et al., 2021; Dzihora., 2021; Nibio., 2021a; Shen et al., 2013; Shen et al., 2015; Shuokr & Jwan, 2021; Tanigawa, 2017; Thompson et al., 2016; Woo et al., 2022; Xiao et al., 2022; Yan et al. 2020; Younis & Kim, 2022; Zewde et al., 2023.
Biochar from sludge			
Advantages of producing biochar from sludge	Producing biochar from sludge offers advantages such as reducing the volume of sludge, improving soil fertility and carbon sequestration, and providing a potential renewable energy source.	Exploring the use of biochar as a soil amendment and studying its effects on soil properties and plant growth. Developing efficient and sustainable biochar production techniques.	Ghorbani et al., 2022; Cong et al., 2022; Shen et al., 2013; Shuokr & Jwan, 2021; Tanigawa, 2017; Xiao et al., 2022; Yoo et al., 2021; Younis & Kim, 2022; Yu et al., 2018; Zhang et al., 2017; Zhao et al., 2023; Zubrowska-Sudol et al., 2022; Nibio., 2020a; Nibio., 2020b; Nibio., 2022a; Nibio., 2022b.
Disadvantages to produce biochar from sludge	Disadvantages to produce biochar from sludge include challenges in ensuring consistent feedstock quality, potential contamination of the biochar, and the need for proper disposal of the remaining ash.	Implementing stringent quality control measures for sludge feedstock. Developing appropriate treatment methods to minimize contaminant transfer to the biochar. Establishing protocols for safe and environmentally friendly disposal of ash residues.	Ghorbani et al., 2022; Nibio., 2021b; Nibio., 2022a; Nibio., 2022b; Shen et al., 2013; Shen et al., 2015; Shuokr & Jwan, 2021; Tanigawa, 2017; Xiao et al., 2022; Younis & Kim, 2022; Yu et al., 2018; Zhang et al., 2017; Zhao et al., 2023; Zubrowska-Sudol et al., 2022.
Challenges for enhancing circularity of biochar from sludge	Challenges for enhancing the circularity of biochar from sludge include the need for improved characterization and standardization, development of efficient production methods, and proper management of by-products and residues.	Establishing standardized protocols for the characterization and quality control of biochar from sludge. Developing advanced production techniques that optimize the biochar properties and yield. Implementing proper management strategies for the by-products and residues generated during the production process.	Cong et al., 2022; Ghorbani et al., 2022; Mukawa et al., 2022; Nibio, 2020a; Nibio, 2021b; Shen et al., 2013; Shuokr & Jwan, 2021; Tanigawa, 2017; Xiao et al., 2022; Yoo et al., 2021; Younis & Kim, 2022; Yu et al., 2018; Zhang et al., 2017; Zhao et al., 2023; Zubrowska-Sudol et al., 2022; Dzihora, 2021.
Possibilities and advantages of the use of sludge-produced biochar in drinking water treatment	The use of sludge-produced biochar in drinking water treatment offers advantages such as adsorption of contaminants, reduction of disinfection by-products, and enhancement of water quality. It can be employed in processes such as filtration, adsorption, and coagulation.	Exploring the use of biochar as an adsorbent or filtration media in drinking water treatment. Investigating the potential synergistic effects of combining biochar with other treatment technologies. Conducting comprehensive studies to assess the long-term performance, stability, and cost-effectiveness of biochar-based drinking water treatment systems.	Bioforsk, 2014; Ghorbani et al., 2022; Hu et al., 2018; Liu et al., 2022; Norsk Vann, 2012b; Shao et al., 2021; Yu et al., 2018; Zhang et al., 2017; Zhou et al. 2018.
Possibilities and advantages of the use of biochar in wastewater treatment	The use of biochar in wastewater treatment offers possibilities such as adsorption of pollutants, improvement of sludge dewaterability, and enhancement of treatment efficiency. It can be applied in processes such as adsorption, coagulation, and anaerobic digestion.	Evaluating the suitability of biochar for adsorption or coagulation in wastewater treatment processes. Investigating the potential for biochar-assisted anaerobic digestion and its impact on biogas production. Assessing the effects of biochar addition on sludge dewaterability and treatment performance. Exploring the combination of biochar with other treatment methods to achieve synergistic effects.	Carbon Limits, 2019; Ghorbani et al., 2022; Landbruksdirektoratet, 2014a; Liu et al., 2021a; Miljødirektoratet, 2020; Nibio, 2022a; Shao et al., 2021; Yoo et al., 2021; Yuan et al., 2021; Zhou et al., 2018.
Limitations of policy and rules on the use of sludge-produced biochar in water and wastewater treatment	Current policies and rules regarding the use of sludge-produced biochar in water and wastewater treatment vary across regions and may present limitations such as lack of standardization, insufficient regulatory frameworks, and uncertainty regarding the long-term impacts on water quality and treatment processes.	Develop standardized guidelines and regulatory frameworks for the use of sludge-produced biochar in water and wastewater treatment. Conduct comprehensive studies to assess the long-term effects of biochar application on water quality, treatment efficiency, and potential risks. Promote collaboration among stakeholders to establish best practices and guidelines for biochar implementation in water and wastewater treatment.	Cong et al., 2022; Ghorbani et al., 2022; Norsk vann, 2013b; Miljørettet helsevern IKS, 2022b; Shen et al., 2013; Shuokr & Jwan, 2021; Tanigawa, 2017; Xiao et al., 2022; Yoo et al., 2021; Younis & Kim, 2022; Yu et al., 2018; Zhang et al., 2017; Zhao et al., 2023; Zubrowska-Sudol et al., 2022.
Possibilities and advantages of the use of sludge-produced biochar in agriculture	The use of sludge-produced biochar in agriculture offers possibilities and advantages such as improved soil fertility, enhanced nutrient retention, carbon sequestration, and reduction of greenhouse gas emissions. It can be employed as a soil amendment, substrate, or carrier for beneficial microorganisms.	Promote the application of sludge-produced biochar as a soil amendment to enhance soil fertility and productivity. Conduct research to determine optimal biochar application rates and methods for different soil types and crops. Assess the long-term effects of biochar on soil quality, nutrient cycling, and greenhouse gas emissions. Raise awareness among farmers and	Ghorbani et al., 2022; Zhao et al., 2023; Ge & Huang., 2023; Liu et al., 2022; Shen et al., 2015; Shuokr & Jwan, 2021; Tanigawa, 2017; Wang et al., 2019; Woo et al., 2022; Xie et al., 2023; Yoo et al., 2021; Zhang et al., 2017; Zhao et al., 2023b; Bioforsk, 2014; Dzihora, 2021; Nibio, 2020a; Nibio, 2020b; Nibio, 2021a.

		stakeholders about the benefits and proper use of biochar in agriculture.	
Limitation of policy and rules on the use of sewage sludge-produced biochar in agriculture	Current policies and rules related to the use of sewage sludge-produced biochar in agriculture may pose limitations such as regulatory restrictions, concerns about heavy metal contamination, and uncertainty regarding the safety and quality of the biochar.	Establish clear guidelines and regulations for the production and use of sewage sludge-produced biochar in agriculture, considering factors such as feedstock selection, pyrolysis conditions, and contaminant removal. Conduct thorough risk assessments and monitoring to ensure the safety and quality of biochar-derived products. Promote research and development to address concerns related to heavy metal contamination and other potential risks. Enhance communication and collaboration among policymakers, researchers, and stakeholders to foster responsible and sustainable use of sewage sludge-produced biochar in agriculture.	Ge et al., 2023; Liu et al., 2022; Shuokr & Jwan, 2021; Tanigawa, 2017; Xiao et al., 2022; Yoo et al., 2021; Younis & Kim, 2022; Yu et al., 2018; Zhang et al., 2017; Zhao et al., 2023b; Zubrowska-Sudol et al., 2022; Landbruksdirektoratet, 2014a; Landbruksdirektoratet, 2014b; Mattilsynet, 2023.
Benefits from sludge			
Probability and advantages of the use of sewage sludge-produced biogas in construction and road engineering	The utilization of sewage sludge-produced biogas in construction and road engineering presents opportunities such as energy generation, reduction of greenhouse gas emissions, and sustainable waste management. Biogas can be utilized as a renewable energy source for various construction and road applications, including heating, electricity generation, and fuel for vehicles.	Promote the development and implementation of biogas plants in wastewater treatment facilities to maximize the production of sewage sludge-produced biogas. Encourage the use of biogas in construction and road engineering applications, such as heating systems, on-site power generation, and vehicle fuel. Conduct feasibility studies and cost-benefit analyses to evaluate the economic and environmental advantages of utilizing sewage sludge-produced biogas. Foster collaboration between wastewater treatment plants, construction companies, and road engineering authorities to explore innovative uses of biogas in the construction and road sector.	Liu et al., 2022; Scarlat et al., 2018; Shao et al., 2021; Tshemese et al., 2023; Umesh Ghimire et al., 2021; Venkatesh & Elmi, 2013; Woo et al., 2022; Yan et al., 2020; Yuan & Zhu, 2016.
Possibilities and advantages of the use of sludge-produced biochar in construction and road engineering	The utilization of sludge-produced biochar in construction and road engineering offers possibilities and advantages such as soil stabilization, improved road performance, carbon sequestration, and sustainable waste management. Biochar can be incorporated into construction materials, road pavements, and embankments to enhance their mechanical properties, reduce maintenance needs, and mitigate the environmental impact.	Conduct research and development to optimize the production and properties of sludge-produced biochar for construction and road engineering applications. Evaluate the potential benefits of incorporating biochar in construction materials, road pavements, and embankments in terms of performance, durability, and environmental impact. Promote the use of biochar-based additives and technologies in construction and road engineering projects. Develop guidelines and standards for the application of sludge-produced biochar in construction and road engineering, addressing aspects such as mixing ratios, compaction methods, and long-term performance monitoring. Collaborate with industry stakeholders, research institutions, and regulatory bodies to foster the adoption of biochar in construction and road engineering practices.	Bu et al., 2022; Liu et al., 2022; Sgroi et al., 2018; Shanmugapriya, 2022; Shao et al., 2021; Shen et al., 2013; Shen et al., 2015; Soares et al., 2017; Tanigawa, 2017; Thompson et al., 2016; Wang et al., 2019b.
Limitations of policy, rules, and techniques on the use of sludge-produced biochar in construction and road engineering	The utilization of sludge-produced biochar in construction and road engineering may face limitations related to regulatory frameworks, technical challenges, and lack of standardization. Policy and rules governing the use of biochar in construction and road applications need to be developed and harmonized to ensure safety, quality, and environmental sustainability. Technical challenges such as biochar production methods, material compatibility, and long-term performance require further research and standardization.	Establish comprehensive regulatory frameworks that address the use of sludge-produced biochar in construction and road engineering, considering aspects such as quality standards, material specifications, and environmental impact assessments. Develop technical guidelines and best practices for the production, characterization, and application of biochar in construction and road engineering projects. Foster collaboration among researchers, practitioners, and policymakers to address technical challenges and knowledge gaps related to the use of biochar in construction and road engineering. Promote information exchange, capacity building, and awareness-raising activities to enhance understanding and acceptance of biochar as a sustainable material in the construction and road sector.	Bu et al., 2022; Liu et al., 2022; Sgroi et al., 2018; Shanmugapriya, 2022; Shao et al., 2021; Shen et al., 2013; Shen et al., 2015; Soares et al., 2017; Tanigawa, 2017; Thompson et al., 2016; Wang et al., 2019b.
Possible energy recovery that can be obtained	Sludge-produced biogas can be utilized as a renewable energy source for various applications, such as heating, electricity	Promote the implementation of biogas plants in wastewater treatment facilities to maximize energy recovery from sludge-produced biogas.	Dzihora, 2021; Liu et al., 2022; Scarlat et al., 2018; Shao et al., 2021; Tshemese et al., 2023;

from sludge-produced biogas and biochar	generation, and vehicle fuel. The energy recovery from biogas can contribute to reduced greenhouse gas emissions and enhanced sustainability in the water and wastewater sector.	Explore opportunities for utilizing biogas in decentralized energy systems and off-site applications. Conduct feasibility studies and cost-benefit analyses to evaluate the economic viability of energy recovery from sludge-produced biogas. Enhance collaboration between wastewater treatment plants and energy stakeholders to facilitate the integration of biogas into energy systems.	Umesh Ghimire et al., 2021; Venkatesh & Elmi, 2013; Woo et al., 2022; Yan et al., 2020; Yuan & Zhu, 2016.
Possible economic benefits that could result from a circular water and wastewater treatment plant	A circular water and wastewater treatment plant can generate economic benefits through resource recovery, cost savings, and the creation of new business opportunities. The recovery of valuable resources from sludge, such as biogas, biochar, and nutrients, can contribute to revenue generation and reduced operational costs. The circular approach also promotes innovation and job creation in sectors related to resource utilization and sustainable development.	Implement circular economy principles in water and wastewater treatment plant design and operation to maximize resource recovery and economic benefits. Invest in research and development to explore new technologies and processes for resource extraction from sludge, such as biogas production, biochar utilization, and nutrient recovery. Foster public-private partnerships and collaborations to facilitate the commercialization and market development of circular products derived from sludge. Develop supportive policies and incentives that encourage the adoption of circular practices and promote the economic viability of resource recovery from sludge.	Scarlat et al., 2018; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Venegas et al., 2021; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster 2012; Zhang et al. 2017; Zhao et al. 2023a;
Possible environmentally friendly products that could arise from water and wastewater sludge	Water and wastewater sludge can serve as a valuable resource for producing environmentally friendly products. Sludge-derived biochar can be used as a soil amendment to enhance soil fertility, carbon sequestration, and pollutant immobilization. The utilization of sludge in constructing building materials, such as bricks and concrete, can contribute to resource conservation and reduced environmental impacts. The recovery of micropollutants from sludge can help mitigate water pollution and protect ecosystems.	Promote the development of technologies and processes for converting water and wastewater sludge into environmentally friendly products. Explore the use of sludge-derived biochar in agriculture to improve soil quality, crop productivity, and carbon storage. Support research and innovation in the application of sludge in construction materials, considering aspects such as material performance, durability, and environmental life cycle assessment. Implement advanced treatment methods to remove and recover micropollutants from sludge, minimizing their environmental impact. Enhance awareness and knowledge dissemination about the potential environmental benefits of utilizing sludge-derived products among stakeholders, policymakers, and the general public.	Chen et al., 2019; Dzihora 2021; Sauvé et al., 2021; Scarlat et al., 2018; Sgroi et al., 2018; Shuokr & Jwan, 2021; Tanigawa, 2017; Thompson et al., 2016; Vázquez-Fernández et al., 2022; Woo et al., 2022; Venegas et al., 2021; Yan et al., 2020; Yoo et al., 2021; Younis & Kim, 2022; Zaharioiu et al., 2021; Zhang et al., 2017; Zhao et al., 2023; Zubrowska-Sudol et al., 2022.
Circular economy water and wastewater sector			
Barriers to the implementation of the circular economy in the water and waste sector	Barriers to implementing the circular economy in the water and waste sector include lack of awareness and knowledge, regulatory and policy constraints, technological limitations, economic and financial challenges, and institutional barriers. These barriers hinder the adoption of circular economy practices and the transition towards more sustainable water and waste management systems.	Raise awareness and provide training and education on circular economy concepts and practices to stakeholders in the water and waste sector. Develop supportive policies and regulations that encourage the adoption of circular economy principles in water and waste management. Foster collaboration and partnerships between stakeholders, including government agencies, utilities, industries, researchers, and the community, to address technological and financial barriers and promote knowledge sharing and innovation. Establish incentive schemes and funding mechanisms to support investments in circular economy practices, such as resource recovery, recycling, and renewable energy generation. Strengthen institutional capacities and governance structures to facilitate the implementation of circular economy strategies and projects in the water and waste sector.	Carbon Limits., 2019; Klima- og miljødepartementet, 2020; Miljødirektoratet., 2020; Nordic Innovation., 2019. Sauvé et al., 2021; Scarlat et al., 2018; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Venegas et al., 2021; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zhang et al., 2017; Zhao et al., 2023a;
Collaboration model between stakeholders to boost sustainability in the water and wastewater sector	Collaboration among stakeholders in the water and wastewater sector is crucial for enhancing sustainability. Effective collaboration models involve close cooperation between water utilities, industries, government agencies, research institutions, and the community. Collaborative efforts can lead to improved resource management, knowledge sharing, innovation, and the development of integrated	Establish collaborative platforms and networks involving water utilities, industries, government agencies, research institutions, and community representatives to facilitate knowledge exchange, joint projects, and problem-solving. Promote partnerships and cooperation through formal agreements, memorandums of understanding, and public-private collaborations. Foster a culture of collaboration	Sauvé et al., 2021; Scarlat et al., 2018; Shuokr & Jwan, 2021; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Vázquez-Fernández et al., 2022; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zhang et al., 2017;

	solutions for sustainable water and wastewater management.	and mutual trust among stakeholders through regular meetings, workshops, and information sharing. Encourage the participation of stakeholders in decision-making processes related to water and wastewater management to ensure diverse perspectives and inclusiveness. Support research and development activities that address sector-wide challenges and promote innovative solutions for sustainable water and wastewater management.	Zhao et al., 2023a.
Financial incentives and support mechanisms to overcome financial constraints and promote investments in circular economy	Financial constraints are a significant barrier to implementing circular economy practices in the water and waste sector. Financial incentives and support mechanisms can help overcome these constraints and encourage investments in circular economy projects. Examples of financial incentives include grants, subsidies, tax benefits, and low-interest loans. Support mechanisms can involve capacity building, technical assistance, and knowledge sharing to facilitate project development and implementation.	Develop financial incentive programs, such as grants, subsidies, and tax benefits, to promote investments in circular economy practices in the water and waste sector. Establish revolving funds or dedicated financing schemes to support circular economy projects, including resource recovery, recycling, and renewable energy generation. Provide technical assistance and capacity building programs to help stakeholders develop viable business models and access funding opportunities. Facilitate knowledge sharing and best practices exchange related to financing circular economy projects in the water and waste sector through workshops, training events, and online platforms. Foster partnerships with financial institutions, private investors, and philanthropic organizations to mobilize additional funding for circular economy initiatives.	Sauvé et al., 2021; Scarlat et al., 2018; Shuokr & Jwan, 2021; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Venegas et al., 2021; Vázquez-Fernández et al., 2022; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zhang et al., 2017; Zhao et al., 2023.
Indicators for possible circularity in municipal water and wastewater treatment plants	Indicators can help assess and monitor the circularity of municipal water and wastewater treatment plants. Key indicators may include resource recovery rates, energy self-sufficiency, water reuse rates, pollutant removal efficiency, carbon footprint, and economic viability. These indicators provide insights into the effectiveness and sustainability of circular economy practices in water and wastewater management.	Develop standardized and comprehensive sets of indicators to assess the circularity of municipal water and wastewater treatment plants. Define specific indicators for resource recovery rates, energy self-sufficiency, water reuse rates, pollutant removal efficiency, carbon footprint, and economic performance. Establish monitoring and reporting systems to collect data on the identified indicators, enabling regular assessment of circular economy performance. Promote the use of life cycle assessment and other sustainability assessment tools to evaluate the environmental, social, and economic impacts of circular economy practices in water and wastewater management. Enhance data collection and knowledge sharing among water utilities and regulatory bodies to improve benchmarking and performance evaluation of circular economy initiatives.	Sauvé et al., 2021; Scarlat et al., 2018; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zhang et al., 2017; Zhao et al. 2023a.
Roadmap for a circular economic municipal water and wastewater treatment plant	Developing a roadmap is essential for guiding the transition towards a circular economic municipal water and wastewater treatment plant. The roadmap should outline clear objectives, strategies, and actions to integrate circular economy principles and practices throughout the entire water and wastewater management system. It should consider technical, economic, environmental, and social aspects and provide a step-by-step approach for implementation.	Establish a dedicated working group or task force involving relevant stakeholders to develop a roadmap for a circular economic municipal water and wastewater treatment plant. Conduct a comprehensive assessment of the current system, identifying potential circular economy opportunities and challenges. Define clear objectives and targets for resource recovery, energy efficiency, water reuse, and environmental performance. Develop a set of strategies and actions to implement circular economy practices, considering technical, economic, environmental, and social aspects. Ensure stakeholder involvement and engagement throughout the roadmap development process, seeking input and feedback from water utilities, government agencies, industry representatives, researchers, and the community. Monitor and evaluate progress regularly, adjusting strategies and actions as necessary to achieve the defined objectives.	Sauvé et al., 2021; Scarlat et al., 2018; Shuokr & Jwan, 2021; Tanigawa, 2017; Trinomics, 2021; Umesh et al., 2021; Venegas et al., 2021; Vázquez-Fernández et al., 2022; Water Europe, 2021a; Water Europe, 2021b; Woo et al., 2022; World Health Organization, 2017; Xu & Lancaster, 2012; Zhang et al., 2017; Zhao et al., 2023a; Norsk Vann., 2012a; Norsk vann., 2016c.

The literature review of local biogas and biochar production as a circular economy strategy in the water and wastewater sector revealed key allowing and limiting factors. These factors have a significant impact on the feasibility and effectiveness of implementing these productions in municipal treatment plants in Norway.

Facilitating factors include:

Renewable Energy Incentives: In order to transition to an environmentally friendly economy, the Norwegian government promotes renewable energy, including biogas.

Policy Support: Biogas and biochar production is supported by policies such as the Climate Agreement and the Circular Economy Action Plan.

Environmental Impact: Biogas and biochar production from sludge can reduce greenhouse gas emissions and provide sustainable alternatives to fossil fuels and chemical fertilizers.

Technological Advancement: Enhanced anaerobic digestion, pyrolysis, CHP units, and other technologies have increased the production efficiency of biogas and biochar.

Knowledge Sharing: Knowledge networks, research institutions, and industry collaborations promote the exchange of knowledge and innovation.

Challenging factors include:

Elevated Production Costs: Biogas and biochar production from sludge necessitates significant financial expenditures (CapEX) and operational costs (OpEX), as well as advanced technology and infrastructure.

Limited Market Demand: Regions with low demand for renewable energy may not sustain a robust market for biogas and biochar.

Funding Constraints: Municipal treatment plants frequently struggle to obtain funding for essential infrastructure and equipment.

Regulatory Obstacles: Complex requirements and permits can impede operations.

Technical Challenges: Municipal plants frequently lack the specialized knowledge and equipment necessary for efficient and high-quality production, compromising efficiency and quality.

Public Perception: Concerns regarding odor, pollution, safety, and product quality may hinder public acceptance.

Storage and Transportation Costs: Costs increase for storage and transport if plants are located far from potential purchasers.

Land Use Constraints: In regions with limited space or competing uses, the need for additional land for storage, processing, and distribution may present difficulties.

These findings highlight the need to overcome these challenges and capitalize on facilitating factors to improve the production feasibility of biogas and biochar. Researchers, policymakers, and industry stakeholders should collaborate to develop supportive policies, secure funding, improve technology, and raise public awareness.

In addition, the literature reveals that although circular economy approaches generate interest in the water and wastewater sector, a number of obstacles exist. A significant obstacle is the absence of a supportive regulatory framework. According to a number of studies, regulatory frameworks frequently favor traditional linear approaches, preventing the adoption of circular strategies. Infrastructure and technology also require significant investment to facilitate wastewater resource recovery and reuse. Research frequently emphasizes the absence of supportive policy and regulatory frameworks, and many studies argue that municipalities lack financial incentives to invest in circular economy practices. Market barriers, such as low resource value and the absence of demand, can make circular strategies economically undesirable. Some studies emphasize the need for a comprehensive approach involving multiple stakeholders with the goal to implement circular economies. Despite these obstacles, circular economy practices in the water and wastewater sector may result in reduced pollution, increased resource efficiency, and new economic opportunities.

3.9 Important supporting theories

The following supporting theories are essential because they provide a structured and scholarly-recognized perspective through which data or observations can be interpreted. They enhance research by providing conceptual frameworks that facilitate the comprehension, explanation, and prediction of phenomena. In addition, they contribute to academic rigor by grounding the current paper in scientific discourse, demonstrating that the problem statement is based on established knowledge, and demonstrating how the work extends or challenges these theories.

3.9.1 Sensemaking perspective

The sensemaking perspective is a cognitive framework that aims to comprehend how individuals collectively attribute significance to their experiences (Weick, 1979; Weich, 1988). According to Seidel et al. (2013), the process entails the continuous interpretation and reinterpretation of occurrences and behaviours within the framework of prior encounters, individual identities, and anticipations. This viewpoint hearts on the process by which individuals and organizations interpret ambiguous circumstances to establish mutual understandings, which ultimately lead to the development of synchronized behaviours. The methodology emphasizes the procedure as opposed to the end-result, prioritizing the way comprehension is achieved over the actual comprehension itself (Laroche & Steyer, 2012; Weick, 1979).

The adoption of the sensemaking perspective has the potential to make a constructive impact on the green shift aimed at augmenting the generation and commercialization of biogas and biochar derived from sludge generated by WTPs and WWTPs. The green transformations can be comprehended and fostered by stakeholders through the establishment of shared meanings regarding their significance. For example, it can aid in clarifying the ecological, societal, and financial advantages of the production of biogas and biochar. Taking advantage of the sensemaking perspective has the potential to influence behaviours, decisions, and actions that are conducive to the advancement of sustainable practices (Seidel et al., 2018). The process of sensemaking has the potential to enhance comprehension of the operational capabilities of information systems and technologies in the context of environmentally sustainable changes, encompassing those employed in the processing and production of biogas and biochar (Seidel et al., 2013).

Nevertheless, it is worth noting that the sensemaking perspective may have adverse effects on the aforementioned environmental changes. According to Kadibu (2021), sensemaking is a socially constructed process that can be influenced by past experiences, which may result in the reinforcement of traditional practices and resistance to change. Consequently, unfavourable past encounters or beliefs regarding the production of biogas and biochar may impede the assimilation of these environmentally friendly methodologies. Furthermore, the process of sensemaking may give rise to diverse interpretations and comprehensions among various stakeholders, which can potentially cause conflicts and impede the execution of environmentally sustainable changes (Laroche & Steyer, 2012).

The effective application of a sensemaking perspective has the potential to enhance the generation of revenue and financial gains for both WTP and WWTP. This can be achieved through the facilitation of the development of collective interpretations and synchronized efforts among diverse parties involved. As exemplified by Reynolds and Holt (2021), the aforementioned process has the potential to enable the harmonization of objectives, tactics, and endeavours across diverse stakeholders engaged in the manufacturing and distribution of biogas and biochar. In addition, the process of sensemaking has the potential to facilitate the identification and pursuit of novel prospects within the market, ultimately bolstering the economic viability and enduringness of these endeavours (Schembera et al., 2022).

The adoption of a sensemaking perspective can prove to be advantageous in the identification and management of potential hazards and obstacles that may arise during the production and commercialization of biogas and biochar. According to Medlin and Törnroos (2014), sensemaking can assist stakeholders in developing suitable strategies and responses to surmount these challenges by offering a structure for comprehending and interpreting them. Hence, the process of sensemaking not only facilitates the advancement of sustainable practices but also amplifies the fortitude and flexibility of institutions and frameworks when confronted with the intricacies and uncertainties linked with eco-friendly conversions.

3.9.2 Path dependency theory

The philosophy of path dependency is a widely employed concept in various fields, including economics, technology, and social sciences. It posits that present choices are frequently constrained by past events, even when previous circumstances have become obsolete. The principle is notably evident within the realm of technology, as demonstrated by the phenomenon of “technological lock-in”. This refers to a scenario in which a dominant technology maintains its market position despite the availability of superior alternatives, due to factors such as initial advantages, increasing returns, and transition costs (Morrey et al., 2010; Hannon & Bolton, 2013).

The development, administration, and incentives of biogas and biochar production and marketing, which are made from the sludge of wastewater treatment plants (WWTP) and water treatment plants (WTP), can be significantly influenced by path dependency:

The concept of **Economies of scale** is applicable in the context of processing larger quantities of sludge to obtain biogas and biochar, as it leads to a reduction in per-unit production costs. The provision of incentives can serve as a motivator for sustained production, which may lead to the establishment of an industry lock-in effect subsequent to initial investments (Hannon & Bolton, 2021; Johnstone & Haščič, 2013; Midttun, 1997; Wiesmeth, 2020).

The emergence of **Learning effects** is observed as industrial experience is gained in the manufacturing of biogas and biochar from sludge. The acquisition of knowledge has the potential to facilitate improvements in processes and enhance the usefulness of products, thereby stimulating greater acceptance and usage. Facilitating a knowledge transfer mechanism between wastewater treatment operators and end-users of biogas and biochar has the potential to enhance the efficiency of the entire process (Johnstone & Haščič, 2013).

Adaptive expectations are also a factor to consider. The widespread production and usage of biogas and biochar serve to mitigate technological ambiguities. The potential integration of the biogas and biochar industry with other sectors could lead to a reduction in the attractiveness of alternative technologies. This may occur due to the interdependence and mutual development of these industries (Hannon & Bolton, 2021; Johnstone & Haščič, 2013; Midttun, 1997; Wiesmeth, 2020).

The process is notably impacted by **Network economies**. The adoption of sludge-to-biogas/biochar technology by multiple facilities can yield advantages such as collective problem-solving and rapid innovation diffusion. The proliferation of biogas and biochar consumers and manufacturers enhances prospects for productive cooperation, leading to a more robust marketplace for these commodities (Hannon & Bolton, 2021; Johnstone & Haščič, 2013; Midttun, 1997; Wiesmeth, 2020).

It important to note that path dependency may present certain difficulties. If the initial techniques employed to produce biogas and biochar from sludge are found to be ineffective or pose environmental risks, their adoption may still be widespread due to the advantages of being the first to introduce such methods. However, transitioning to more sustainable and efficient technologies at a later stage may prove to be a challenging task. The aforementioned situations highlight the significance of conducting a comprehensive analysis of the enduring consequences of initial technological decisions, given that a shift would necessitate significant expenses and coordination, which may result in technological entrenchment (Hannon & Bolton, 2021).

The phenomenon of path dependency can have significant ramifications for the advancement and management of biogas and biochar technologies that originate from sludge obtained from wastewater treatment plants (WWTP) and water treatment plants (WTP). The phenomenon of technological path dependency may manifest in situations where the current waste management infrastructure primarily prioritizes conventional techniques such as incineration or landfilling, which may discourage the uptake of alternative technologies such as biogas or biochar production. The phenomenon arises because of significant capital investments in current infrastructure, leading to a path-dependent system that may impede the transition towards more contemporary and environmentally friendly technologies (Hannon & Bolton, 2021).

The phenomenon of **Societal path dependency** may also be observed in the context of waste management, wherein societal attitudes towards this issue may impact the uptake of biogas and biochar production. The perception of waste as a mere burden to be disposed of, rather than a valuable resource to be utilized, could potentially hinder the adoption of sludge for the purposes of biogas and biochar production. The presence of a deeply ingrained perspective may impede the progression towards a circular economic model (Hannon & Bolton, 2021; Johnstone & Haščič, 2013; Midttun, 1997; Morrey et al., 2010; Wiesmeth, 2020).

In addition, there may be economic and policy path dependencies that could potentially provide an advantage to current waste management techniques while discouraging the creation and distribution of biogas and biochar. Should current policies and market mechanisms remain in place, landfilling or waste exporting may persist as the more economically viable options. On the other hand, the lack of sufficient policy backing or monetary encouragements to produce biogas and biochar may impede the progress and implementation of these technologies (Morrey et al., 2010).

To facilitate the establishment of a circular economy, it is imperative to comprehend and tackle the path dependencies involved, which may be accomplished through adjustments in policy, economic incentives, or societal education regarding the benefits of waste utilization (Wiesmeth, 2020). Acknowledging and addressing these past interdependencies can aid in formulating efficacious tactics to enable the shift towards more sustainable trajectories, such as the generation of biogas and biochar via the utilization of WTP and WWTP sludge. The concept of path dependency emphasizes the significance of comprehending how prior decisions, procedures, and customs can influence and restrict present and future trajectories. This highlights the fact that our current choices are not independent determinations made anew each time, but rather an extension of our historical decisions.

3.9.3 Consumer Theory

The fundamental concept of consumer theory in economics is centred on the notion that consumers strive to optimize their utility, or level of satisfaction while adhering to their financial limitations (Shukla, 2023). This theory analyses the decision-making process of consumers in allocating their available resources toward the acquisition of goods and services. Consumer theory can have both positive and negative impacts on sustainable consumption, the green shift, and the production and sale of biogas and biochar from sludge generated by WTPs and WWTPs.

Consumer theory has the potential to facilitate a transition towards environmentally sustainable practices by influencing the demand for products and services in the market, in a positive manner. In the event that consumers exhibit a preference for eco-friendly products, their purchasing behaviour will likely align with this inclination. According to Lanzini et al. (2016), the market demand for biogas and biochar can be increased through consumer education and awareness of their environmental benefits, resulting in higher production levels. The theory of consumption values suggests that consumers are incentivized by a range of values, such as functional value, social value, and emotional value. Functional value pertains to the utility derived from a product's performance, while social value refers to the utility derived from a product's ability to enhance social relationships. Emotional value, on the other hand, pertains to the utility derived from feelings or affective states. These values can potentially impact consumers' inclination to pay for ecological products (Zailani et al., 2019; Groening et al., 2018).

Likewise, the examination of consumer behaviour regarding organic food can provide valuable insights. Food safety incidents tend to capture the attention of consumers, indicating a state of heightened vigilance. The replication or direction of such conduct toward environmental consciousness has the potential to stimulate the market for eco-friendly commodities such as biogas and biochar (Liu & Zheng, 2019; Bangsa & Schlegelmilch, 2020).

Consumer-level theory in green marketing highlights the significance of the perception of environmental consciousness in influencing consumer behaviour. According to Groening et al. (2018), if a company or product is perceived by consumers as being environmentally friendly, there is a higher probability of receiving support from them. The aforementioned theories have the potential to provide valuable insights into the development of effective strategies aimed at boosting consumer demand for biogas and biochar. This, in turn, can facilitate the growth of production and revenue for WTP and WWTP.

Nonetheless, the application of consumer theory may have adverse effects on the transition toward sustainability. Consumer theory has been subject to criticism on the basis that consumer agency is constrained. Consumer behaviour can be significantly impacted by various factors, including structural constraints, social conventions, and cultural traditions, which may impede the acceptance of eco-friendly practices (Davies, 2022; Welch & Warde, 2015). The incorporation of cultural factors into the theory of planned behaviour emphasizes the influence of cultural norms and beliefs on environmentally conscious consumer behaviour (Ghali-Zinoubi. 2022).

Furthermore, the manner in which consumers perceive sustainable consumption can be intertwined with various roles and perspectives. According to Xu et al. (2018), in certain countries, sustainable consumption practices are primarily attributed to government policies rather than individual decisions, as perceived by consumers. Jacobsen et al. (2022) suggest that consumers may face obstacles in their efforts to avoid and recycle plastic packaging waste (Cf. Wishcycling), such as insufficient information, perceived product performance, and limited convenient options. These challenges may also extend to other sustainable products or practices.

The application of consumer theory can offer a significant perspective in comprehending the factors that motivate or hinder the acceptance of sustainable behaviours, such as the amplification of biogas and biochar production and utilization (Arranz & Arroyabe, 2023). This can aid in the development of efficacious approaches for promotion, education, policy formulation, and other related endeavours. Simultaneously, the constraints of consumer theory emphasize the necessity of a comprehensive strategy that encompasses not only consumer education and marketing but also structural and policy modifications.

3.9.4 CSR and ESG

Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) are closely related and have a significant impact on promoting sustainable and ethical business practices. Although CSR and ESG share similar objectives and principles, there are notable distinctions between them.

Corporate Social Responsibility (CSR) is the incorporation of social and environmental considerations into a company's business activities and interactions with its stakeholders through voluntary actions that exceed legal requirements. CSR encompasses a wide range of activities, including but not limited to charitable contributions, involvement in local communities, emphasis on employee welfare, adherence to ethical procurement practices, and dedication to environmental sustainability (Liu et al., 2022; Theodoulidis et al., 2017). CSR refers to the moral and ethical obligations of businesses to contribute positively to society and the environment by addressing social and environmental concerns (Khalid et al., 2023). According to Sarfraz et al. (2023), harmonizing economic success with social and environmental responsibilities is commonly viewed as a sign of a company's commitment.

Environmental, Social, and Governance (ESG) is a comprehensive evaluation framework that analyses a company's environmental, social, and governance practices to determine its sustainability and performance (Apiday, 2022). According to the Organisation for Economic Co-operation and Development - OECD (2021a; 2021b), investors, stakeholders, and rating agencies use ESG factors to evaluate a company's ability to generate long-term value and susceptibility to risk. The environmental pillar of the ESG focuses on a company's impact on the environment, which includes its efforts to mitigate climate change, preserve natural resources, and reduce pollution (Boffo et al., 2020b). The social aspect of a corporation refers to its relationships with its employees, customers, suppliers, and communities. This dimension includes issues such as human rights, labor regulations, inclusiveness, diversity, and community development (Boffo et al., 2020b). Governance is the evaluation of a company's leadership, board structure, executive compensation, transparency, and accountability (Apiday, 2022).

The interdependence between CSR and ESG is evident in their shared mission to promote sustainable and ethical business conduct. The incorporation of ESG factors into CSR strategies can result in enhanced company performance and reputation, as well as effective risk management and the creation of long-term value (Rehman et al., 2022). The potential benefits of CSR and ESG practices in promoting the transition to a more sustainable economy can be examined from multiple perspectives, particularly in the context of producing and marketing biogas and biochar derived from sludge generated by water treatment plants and wastewater treatment plants.

CSR and ESG initiatives have the potential to yield positive results by fostering innovations and enhancing processes in the production of biogas and biochar (Sarfraz et al., 2023). Organizations that implement sustainability-focused approaches are likely to allocate resources to research and development initiatives intended at enhancing operations, streamlining resource consumption, and mitigating ecological footprints. Adopting eco-friendly practices and technologies enables WTPs and WWTPs to optimize the transformation of sludge into biogas and biochar while simultaneously reducing energy consumption and emissions (Rehman et al., 2022).

Furthermore, both CSR and ESG are essential for facilitating stakeholder engagement and cultivating relationships. Achieving support and social acceptability for biogas and biochar production initiatives depends on effective communication and collaboration with stakeholders, such as local communities, regulators, investors, and customers (Shiri & Jafari-Jafari-Sadeghi, 2023). Implementing CSR and ESG principles can encourage transparency and stakeholder engagement. In turn, this may foster the establishment of trust, the resolution of concerns, and the cultivation of support for sustainable initiatives (Liu et al., 2022).

Essential indicators and metrics must be monitored and measured in order to track progress, improve performance, and provide incentives to stakeholders and customers. As suggested by the Organization for Economic Co-operation and Development (OECD, 2022a), metrics such as greenhouse gas emissions, energy efficiency, waste reduction, and social impact indicators can facilitate the evaluation of the environmental and social performance of WTPs and WWTPs. By defining unambiguous objectives and regularly communicating progress on these measures, businesses can demonstrate their commitment to sustainability and encourage stakeholders and customers to support their initiatives (Boffo et al., 2020a).

It is possible to use CSR and ESG strategies in a variety of ways to improve the productivity, profitability, and viability of WTPs and WWTPs. Initially, businesses are able to integrate CSR and ESG principles into their overall business strategy and decision-making processes. By aligning sustainability objectives with primary business objectives, organizations can incorporate environmental and social considerations into their operations and value chain. The implementation of sustainable practices may involve the incorporation of environmentally conscious methodologies into procurement procedures, supply chain management, and product development (Khalid et al., 2023).

Moreover, both WTPs and WWTPs are able to effectively engage relevant stakeholders, such as nearby communities, environmental organizations, and government entities, in order to foster cooperation and obtain support for initiatives concentrated on the production of biogas and biochar. Through consistent communication, the active solicitation of feedback, and stakeholder engagement in the decision-making process, organizations can effectively address concerns, foster agreement, and ensure that project plans are in accordance with the community's expectations and requirements (Shiri & Jafari-Sadeghi, 2023).

Technology and data analytics have the potential to increase the effectiveness of CSR and ESG initiatives. Organizations can use advanced monitoring and reporting mechanisms to track and analyse key performance metrics, allowing them to identify opportunities for improvement, streamline operations, and embrace evidence-based decision-making strategies (OECD, 2022b). In addition, utilizing digital platforms and transparency tools can facilitate the dissemination of ESG-related information to investors, enabling them to make well-informed decisions and allocate resources to companies with strong ESG performance (Bifulco et al., 2023).

The concepts of corporate social responsibility (CSR) and environmental, social, and governance (ESG) are interrelated and mutually reinforcing, thereby facilitating the adoption of sustainable business practices. CSR refers to the initiatives a company takes voluntarily to address social and environmental issues. In contrast, ESG is a comprehensive system that facilitates the evaluation of the environmental, social, and governance performance of a company. Implementing both CSR and ESG practices can facilitate the transition to sustainable production and sale of biogas and biochar derived from WTP and WWTP sludge. This can be accomplished by promoting innovation, involving stakeholders, and monitoring key performance indicators. Through the strategic incorporation of CSR and ESG considerations into their business strategies and operations, WTPs and WWTPs can increase their production, revenues, and sustainability while simultaneously satisfying the needs of their stakeholders and customers.

3.9.5 Resource Allocation (RA) and Integrated Management System (IMS)

The concept of Resource Allocation theory (RA) pertains to the allocation of resources across various settings and contexts, and it holds significant importance in the effective management of an organization's sustainability (Ingenbleek & Krampe, 2023). The theory in question focuses on optimizing the utilization of existing resources in order to attain predetermined objectives in a manner that is both effective and efficient. The resources encompassed in this study comprise financial capital, human capital, time, and material resources (He et al., 2021). The primary objective of resource allocation is to optimize the utilization of resources by assigning them to suitable tasks at the appropriate time to achieve optimal results (Amirteimoori & Tabar, 2010).

The theoretical framework of Resource Allocation incorporates principles from a cost-benefit analysis, which prioritizes the attainment of optimal results through the efficient utilization of available resources (Haveman & Weimer, 2001). The utilization of diverse tactics is observed, including menu auctions, a bidding approach that prioritizes resources based on their significance and usefulness, and other strategic mechanisms for resource allocation that promote sustainable development (Bernheim & Whinston, 1986; Shuqair & Abdel-Aziz, 2015). Kogan et al. (2017) emphasize the significance of allocating resources toward innovation endeavours to facilitate growth and advancement in the realm of technological innovation. The theoretical framework also encompasses the allocation of political resources, regulated agendas, and the maintenance of the existing state of affairs (Romer & Rosenthal, 1978). The theory presented by Rajkumar and Kumar (2004) offers a structured approach to customer selection and resource allocation strategy, with a focus on the long-term value of customers.

The Integrated Management System (IMS) is a management strategy that integrates an organization's systems and processes into a comprehensive framework, allowing the organization to function as a cohesive unit with shared goals (Asif et al., 2011). The purpose of an IMS is to optimize organizational processes, minimize redundancy, and foster a cohesive corporate environment (Gapp et al., 2008). The concept of integrated management systems can be interpreted as a unifying framework that accommodates various management systems, including but not limited to quality management, environmental management, and occupational health and safety management. This integration facilitates their coordinated functioning and synergy (Asif et al., 2013).

The Integrated Management System seeks to unify and streamline diverse systems, procedures, and processes, whereas Resource Allocation centres on the allocation and utilization of resources to attain organizational goals. The interaction between the two concepts (IMS and RA) pertains to the management of resources and processes. However, their primary focuses differ, with IMS emphasizing integration and synergy, while RA prioritizes allocation and efficiency.

The application of Resource Allocation theory can potentially have a positive impact on the transition towards sustainability by facilitating the allocation of resources towards the production and commercialization of biogas and biochar derived from sludge generated by WTPs and WWTPs. The optimization of resource allocation has the potential to enhance productivity and profitability, thereby fostering the commercial feasibility and durability of environmentally friendly technologies (Ingenbleek & Krampe, 2023; Su et al., 2023). Nevertheless, the difficulty lies in the prioritization of distributing resources towards environmentally sustainable initiatives, particularly in the presence of other conflicting demands (Shuqair & Abdel-Aziz, 2015). Pearce (1998) argues that an excessive focus on cost-benefit analyses may result in the undervaluation of environmental and social benefits, thereby impeding the advancement of environmentally friendly initiatives.

The Integrated Management System has the potential to facilitate the transition towards sustainability by advocating for a comprehensive strategy towards environmental stewardship. The objective is to streamline all operational systems and procedures toward the common aim of producing and selling biogas and biochar derived from WTP and WWTP sludge. This approach aims to foster collaboration and eliminate the redundancy of activities (Jørgensen et al., 2006; Zeng et al.,2007). The implementation of an IMS can pose significant complexity and challenges, particularly in the context of large organizations that operate multiple, disparate systems (Wilkinson & Dale, 1999). According to Salomone (2008), there is a possibility of encountering opposition from employees as a result of alterations in work practices and procedures.

Strategic application of Resource Allocation theory and Integrated Management System can enhance the productivity, profitability, and ecological viability of WTP and WWTP. The Resource Allocation tools have the potential to optimize resource allocation towards the production of biogas and biochar, while considering cost-benefit analyses and return on investments (Rajkumar & Kumar, 2004; Trigeorgis, 1996). Conversely, the implementation of an Integrated Management System has the potential to optimize and standardize manufacturing procedures, enhance productivity, minimize resource depletion, and cultivate an ethos of ecological responsibility (Gapp et al., 2008; Asif et al., 2011). The implementation of this strategy is expected to not only enhance operational efficiency but also foster organizational dedication to environmental sustainability, thereby augmenting the reputation of both WTP and WWTP

3.9.6 Industrial Symbiosis (IS)

The concept of Industrial Symbiosis (IS) entails the utilization of waste or by-products from one industry as inputs for another, thereby emulating a natural ecosystem where the waste of a single type serves as a resource for another. This notion constitutes a pivotal facet of the circular economy, which advocates for the optimization of resource utilization and the mitigation of ecological footprints (Chertow, 2000). The Industrial Symbiosis approach strives to maximize the allocation of resources by effectively converting waste into value-added products and services (IWA, 2022; Linköpings universitet, n.d.) .

The concepts of Industrial Symbiosis (IS), Resource Allocation (RA), and Integrated Management System (IMS) are interrelated, yet each refers to distinct aspects of environmental sustainability. As mentioned above, the concept of RA is applied to the distribution and utilization of resources within a given system, with the objective of achieving maximum efficiency. While an IMS combines all the systems and processes of an organization into a single framework and enables the organization to function as a cohesive entity with synchronized objectives. Integrated Management System might efficiently coordinate the allocation of resources through the practical approach or model of industrial symbiosis (Agudo et al.,2023).

The implementation of Industrial Symbiosis has the potential to make an important contribution to the green transition by augmenting the production and distribution of biogas and biochar derived from WTP and WWTP sludge. The utilization of waste generated by these facilities as a valuable resource for other industries has the potential to foster resource efficiency, reduce expenses, and encourage environmentally friendly innovation (Hu et al., 2020). The sale of biogas and biochar could potentially generate revenue that can be utilized to support additional sustainability operations within these facilities (Symbiosis Center Denmark, 2019a, 2019b).

However, there may exist potential adverse consequences as well. The adoption of an IS approach may necessitate substantial initial expenditures and modifications in operational protocols. The handling and transfer of waste materials may entail regulatory obstacles and potential hazards. Therefore, it is imperative for organizations to conduct a thorough analysis of potential risks and benefits prior to adopting an IS approach (Symbiosis Center Denmark, 2020).

From a strategic point of view, taking advantage of IS can be applied to enhance the production, revenues, and sustainability of WTP and WWTP. Organizations must have the ability to identify potential symbiotic partnerships and recognize beneficial collaborations with industries that can repurpose their waste as a valuable resource. Collaboration with municipalities to establish favourable policies and incentives for the implementation of IS is also a viable option (Symbiosis Center Denmark, 2021). Furthermore, carrying out an environmental impact assessment of the industrial symbiosis strategy can help organizations in mitigating potential risks and enhance sustainability (Symbiosis Center Denmark, 2017a, 2017b).

3.9.7 Lean and Agile methodology

The Lean and Agile methodologies are two distinct approaches that are commonly employed within businesses to improve productivity and enhance customer satisfaction. The Lean methodology has its roots in the Toyota Production System (TPS) and mainly focuses on the reduction of waste (inefficiency) and the enhancement of customer value. Lean places a significant emphasis on continuous improvement and efficiency through the reduction of waste in the form of unnecessary steps, materials, or processes (Modig and Åhlström, 2016; Dennis, 2015).

On the other hand, Agile methodology, primarily used in the software development industry, emphasizes adaptability, continuous improvement, and customer involvement. Agile teams operate within brief development cycles, commonly referred to as "sprints," during which the product or service is subject to ongoing testing and refinement, informed by customer feedback (Alqudah & Razali, 2017; Hall, 2018).

Although Lean and Agile methodologies possess distinct characteristics, they share similarities such as prioritizing the delivery of customer value, promoting continuous improvement, and fostering active stakeholder participation. However, their strategic implementation may vary. The lean approach is characterized by a greater emphasis on prescribing specific processes to address inefficiencies, while the Agile approach prioritizes flexibility and adaptability, with a focus on favouring interactions and collaborating with customers (Di Pietro et al., 2013; Brosseau et al., 2019).

The application of Lean and Agile techniques within the context of the green shift with the goal of boosting the production and sale of biogas and biochar derived from WTP and WWTP sludge can yield several positive outcomes. Lean has the potential to detect and eradicate inefficiencies in the production process, including but not limited to overproduction, defects, and unnecessary transport. This could potentially lead to cost savings and enhanced production. Additionally, Lean promotes sustainable practices as reducing waste aligns with environmental objectives (Cabral et al., 2012).

The application of agile techniques can prove to be advantageous in promptly accommodating dynamic environmental regulations, market conditions, or technological advancements. The iterative nature of the Agile system enables businesses to periodically reassess and modify their strategies and practices in response to feedback, thereby facilitating the creation of more sustainable and innovative solutions (Silva et al., 2022; Clark & Eisenberg, 2008). Poor implementation of these methodologies may result in negative interactions with green shift initiatives. The Agile methodology's principle of maintaining a sustainable pace could potentially clash with the demands of rapidly scaling green production initiatives.

The integration of Lean and Agile practices into the operational and strategic planning of WTP and WWTP has the potential to enhance their production efficiency, revenue generation, and sustainability. The implementation of Lean practices has the potential to optimize operational efficiency, minimize expenses, and augment production yield by means of waste elimination. The implementation of Agile practices can potentially cultivate a corporate culture that values flexibility, innovation, and continuous learning. This, in turn, can facilitate the advancement of novel and enhanced techniques for producing biogas and biochar. Additionally, an Agile strategy can enable a prompt reaction to alterations in market trends and environmental policies (Plonka, 1997; Schuh et al., 2018).

The effective implementation of Lean and Agile strategies necessitates a thorough evaluation of the organization's contextual factors, goals, and available resources. If the principal objective is to enhance operational efficiency and reduce costs, then the approach of Lean may be more pertinent. In the event that the company functions within a context characterized by frequent technological advancements and dynamism, the Agile approach may prove to be more suitable.

A hybrid approach that combines Lean and Agile approaches can prove advantageous to companies as it enables them to strike a balance between efficiency and adaptability (Modig and Åhlström, 2016; Alqudah & Razali, 2017).

3.9.8 Ambidexterity innovation theory

The capacity to use both hands equally effectively is referred to as ambidexterity. Ambidexterity in an organizational context refers to an organization's capacity to efficiently use its current skills while simultaneously seeking innovative prospects (Simeoni et al., 2020). Exploitation refers to the use of pre-existing resources and capabilities to improve efficiency and production. Exploration, on the other hand, entails venturing into new domains, inventions, and the development of novel knowledge. Ambidexterity fundamentally finds a balance between two organizational tasks that are usually in conflict with each other. Effective management requires the ability to handle activities that are present-oriented and align with the organization's current operations, as well as duties that are future-oriented and have the potential to change the organization's strategic direction (Grant et al., 2019).

Agile approach, on the other hand, places a strong premium on flexibility, collaboration, and customer-centricity. The technique in issue is applicable to project management and product development, and it encourages cross-functional teams to engage in iterative and incremental work processes. This method encourages constant development and allows for rapid response to change. Ambidexterity refers to the balance between exploration and exploitation, whereas Agile is focused on quick responsiveness to change and gradual delivery of valuable products.

Ambidexterity may play an important role in facilitating the transition to more sustainable practices, particularly in terms of boosting the production and commercialization of biogas and biochar derived from WTP and WWTP sludge. Ambidexterity allows firms to capitalize on their existing waste management capabilities (exploitation) while simultaneously exploring innovative approaches to turn sludge into biogas, biofuel, and biochar (exploration). The simultaneous emphasis on productivity and sustainability can improve the operational outcomes of both WTPs and WWTPs. This strategy has been proven to increase income and overall efficiency (Cancela et al., 2022; Medlin & Törnroos, 2015). Through ambidexterity, the incorporation of sustainable practices into essential business operations can enhance company sustainability (Sulphey & Alkahthani, 2017).

However, if the balance between exploitation and exploration is not successfully managed, negative repercussions may result. An overemphasis on exploration may result in uncontrolled innovation efforts with no measurable effects, whereas an overemphasis on exploitation may impede an organization's capacity to innovate and adapt to the rapidly shifting green economy. As a result, it is critical to strike a careful balance to guarantee that the exploration process is not compromising the efficiency of current operations and that the exploitation process doesn't hinder creativity, innovation, and growth (Peters & Buijs, 2021).

Ambidexterity implementation requires an organizational architecture that encourages both explorative and exploitative actions. Ambidexterity may be encouraged inside companies in a variety of ways, including structural separation, contextual ambidexterity, and sequential ambidexterity. The idea of structural separation refers to the formation of different entities for the purposes of exploration and exploitation. Contextual ambidexterity refers to the development of a supportive environment or culture that promotes individuals' autonomy in allocating their time between activities of exploration and exploitation. Sequential ambidexterity refers to the ability to switch between phases of exploration and exploitation (Maine et al., 2021).

Ambidexterity in organizations demands strong leadership capable of understanding and managing the underlying conflict between exploration and exploitation. Fostering a culture that promotes learning, collaboration, transparency, and experimentation while maintaining a focus on operational excellence and efficiency is part of effective leadership (Grant et al., 2019; Nicolopoulou et al., 2016).

3.9.9 Full cost pricing principle (Selvkostprinsippet)

Full cost pricing principle, also known as "selvkostprinsippet" in Norwegian, is a strategy that guarantees that the prices of goods or services reflect the whole costs of resources used in their production, including direct costs, indirect costs, and capital costs (UN, 2023). Its goal is to provide pricing transparency and to prevent cross-subsidization between services or sectors (Kommunal- og moderniseringsdepartementett, 2014). Other pricing approaches, such as marginal-cost pricing, ignore fixed and sunk costs and focus solely on the cost of manufacturing the next unit (Duignan, 2023). In other words, the full-cost pricing principle is a fundamental principle in the water and wastewater sector, requiring customers to pay the actual costs of the provided services. Municipalities are prohibited from making a profit on the sale of water and wastewater services under this principle (Lovdata, 2004). This principle aims to ensure that service pricing is transparent and equitable.

The **Generation Principle** (Generasjonsprinsippet in Norwegian) asserts that costs should be divided equally among the present and future generations that benefit from an investment (VA-finansiering, 2023b). This concept, coupled with the full-cost price principle, serves as the foundation for project financing for Norway's water and wastewater treatment plants (WTP and WWTP), creating a framework for cost allocation (VA-finansiering, 2023b).

Bank interest rates, inflation, currency depreciation, exchange rates, and crises can all have an impact on full-cost pricing. These factors have an impact on the costs of producing products and services, and hence the price that must be set to recuperate those costs. An increase in interest rates, for example, might increase the cost of financing projects, forcing a price increase to pay these expenses (Norsk Vann, 2015b). Currency depreciation and fluctuating exchange rates can also have an impact on the cost of importing goods or technology, which is reflected in the full cost price. Closing of borders like during the COVID-19 pandemic or conflicts (war), such as the ongoing one in Ukraine, can interfere with supply chains and escalate costs, influencing the full cost price (Norsk Vann, 2017b).

The Full cost pricing principle can both positively and negatively affect the shift towards green practices, such as the production and sale of biogas and biochar derived from WTP and WWTP sludge. On the positive side, full-cost pricing might make green alternatives such as biogas and biochar more competitive by guaranteeing that all environmental costs are included in the price of traditional energy sources (Olewiler, 2012). However, if the costs of implementing these green practices are significant, full-cost pricing may result in higher prices for consumers, thus slowing adoption (Goldstein, 1986).

To effectively apply the full-cost pricing principle to clients, it is critical to properly describe its benefits. Producers should explain how this approach fosters equitable cost allocation, avoids cross-subsidization, and encourages sustainable practices (Kommunal- og moderniseringsdepartementett, 2014). It should be noted that the principle promotes long-term sustainability and equity among generations (VA-finansiering, 2023b).

The full-cost pricing approach requires identifying all costs associated with the production of a service or product, which can be a challenging task. Direct costs (e.g., labor, materials), indirect costs (e.g., overheads), and capital expenses (e.g., depreciation, interest) are all factors to consider (Choné & Linnemer, 2021). The formula for full-cost pricing is:

Total Price = **Direct Costs** + **Indirect Costs** + **Capital Costs**

In Norway, municipalities use a **Full-cost fund** (Selvkostfond in Norwegian) to administer the revenues and expenses associated with providing water and wastewater services. Municipalities are required to balance their revenues and expenses over a five-year period in accordance with the full-cost regulation. This is intended to mitigate any significant fluctuations in annual service fees caused by large investments or unexpected costs. However, this can be problematic when the timing of investments or costs is uncertain or beyond the municipality's control (Kommunal- og moderniseringsdepartementett, 2014; VA-finansiering, 2023c).

In contrast, **Investment fund** (Investeringsfond in Norwegian) is a financial mechanism used to accumulate reserves for future investments. Current regulations prohibit municipalities from establishing investment funds by setting aside a portion of service fees for future investments. This can hinder the ability of municipalities to plan for long-term investments and manage financial risks (Norsk Vann, 2023c; VA-finansiering, 2023c).

To mitigate the economic disparities in the cost drivers for full-cost pricing, it is necessary to implement measures to ensure that the costs are distributed equitably among the residents in the municipality. These measures may include inter-municipal cooperation, state subsidies, tax increment financing (TIF), and fee structure modifications. In addition, efforts should be made to improve the efficacy of the water and wastewater services and reduce total costs (E&Y, 2007; VA-finansiering, 2023c).

Building and managing a full-cost fund to mitigate fee growth, save for future investments, and establish prudent investment funds demands a proactive and strategic approach to financial management. This could involve a review of the current full cost regulations to allow for greater flexibility in managing the fund, enhanced forecasting and budgeting processes, and a long-term financial plan that correlates with the strategic goals of the water and wastewater services (VA-finansiering, 2023c; Evavold & Lykken, 2009).

Strategically using accumulated full-cost funds in the investment accounts can strengthen long-term projects in the water and wastewater sector, and treatment plant management. For instance, these funds can provide a stable source of financing for capital-intensive projects, reduce the need for loans, and strengthen the municipalities' financial resilience. It can also stimulate innovation by financing research and development and the adoption of new technologies. In turn, this can contribute to the sustainability of water and wastewater services by reducing their environmental footprint and increasing their climate change resilience (Norsk Vann, 2023c; VA-finansiering, 2023c).

Full cost pricing must be utilized strategically to ensure the financial sustainability of WTP and WWTP, ensuring that all costs are covered, and facilities are adequately maintained. This strategy promotes revenue stability, transparency, and long-term planning, all of which are important parts of sustainability (Massarutto, 2007; 2015). The principle also emphasizes the "user pays" approach, which reflects the cost causation principle and potentially drives more efficient water use (Norsk Vann, 2015b).

3.9.10 Organizational structures of municipally owned enterprises

Municipal enterprise or municipally owned corporation (In Norwegian: Kommunale foretak, or KF), Intermunicipal company (In Norwegian: Interkommunale selskap, or IKS), municipally owned Joint-stock company (In Norwegian: Kommunalt eide Aksjeselskap, or AS), Cooperative company (In Norwegian: Samvirkeselskap/andelslag, or SA), are the four most popular organizational structures for municipally owned enterprises in Norway. Each entity has its own set of norms for organization, management, advantages, and disadvantages, and interactions among them can be complex.

Other forms of organization for municipally owned enterprises in Norway include Foundation (In Norwegian: Stiftelse), Association (In Norwegian: Foreninger), and Host municipality cooperation (In Norwegian: Vertskommunesamarbeid).

The selection of a particular organizational form can have an important influence on the strategic direction, operational efficiency, and financial performance of these entities.

Municipal Enterprise (KF) is a legal entity established by a municipality to provide products or services to the general public). It is governed by a board of directors appointed by and reporting to the municipal council. The board has decision-making autonomy and authority over operational matters, while the municipal council is responsible for strategic decisions and approval of the annual budget (Brattås et al., 2009; Lovdata, 2018).

The primary advantage of a KF is its operational flexibility and ability to leverage the financial strength of the municipality to gain access to capital. In other words, KF supports operational flexibility and privileges the delivery of public services over profit maximization. Nevertheless, it is subject to public procurement regulations, and its financial performance may be affected by political considerations. This indicates that it is susceptible to political influence, which can lead to changes in a direction following municipal elections (Braaten, 2018; Brattås et al., 2009).

Intermunicipal Company (IKS) is a cooperative arrangement between two or more municipalities for the delivery of common services. Similar to a KF, but with the added complexity of representation from multiple municipalities, an IKS has a similar governing structure. The board is responsible for operational management, while the municipal council makes strategic decisions (Vaskinn & Nibe, 2017; Lovdata, 1999).

The primary advantage of an IKS is its ability to achieve economies of scale and improve service quality by joining together resources and expertise to provide or manage resources more effectively. The main drawback is the complexity of decision-making due to the involvement of multiple municipalities, which can delay the decision-making process (KS, n.d.; Brattås et al., 2009).

A municipally owned **Joint Stock Company** (AS) is a joint-stock corporation in which the majority of shares are owned by one or more municipalities. The company is administered by a board of directors, which is elected by the shareholders at the annual meeting. The board has management autonomy, subject to the shareholders' authorized strategy and budget (Regjeringen, 2016; Lier kommune, 2014).

The main advantage of an AS is its ability to operate independently from municipalities, which can boost operational efficiency and financial performance. Nonetheless, it is subject to corporate tax and its activities may be limited by the need to generate a return on investment (KS, 2020).

Cooperative Company or (In Norwegian: Samvirkeselskap/Andelslag, or SA) is a cooperative organization whereby members use its services or purchase its products. I.e., a group of enterprises united to meet their shared economic, social, or cultural needs and aspirations through a structure that is jointly owned and democratically governed. Each member has one vote, regardless of their capital contribution, and the board is elected by and accountable to the members.

The key advantage of a SA is its democratic governance and members' active participation in decision-making. The biggest drawback is the complexity and expense of administering the democratic process, particularly when the membership is large and diverse. The limited profit distribution makes it less attractive to investors (Vaskinn & Nibe, 2017).

Foundation (Stiftelse) is a legal entity established for a specific purpose and without proprietors. A board of trustees oversees the foundation and ensures that its assets are used to execute its mission. This could result in less democratic control and less transparency, despite its stability and independence from proprietors or members (Regjeringen, 1995).

Association (Foreninger) is a membership organization with a specific purpose. Typically, its management structure consists of an assembly, a board, and a chairman. Despite being democratic in nature and simple to establish, associations frequently rely on membership fees and may struggle to fund large projects (Regjeringen, 1995).

Host Municipality Cooperation (Vertskommunesamarbeid) is where a municipality (the host municipality) provides services to one or more other municipalities. The host municipality is accountable for the execution and finances of the service. This form of cooperation can result in professional and efficient service delivery, but it may also contribute to a loss of local control over the service in the cooperating municipalities.

In the context of industrial symbiosis for the production and sale of biogas and biochar from municipal wastewater treatment plants, the optimal organizational structure would be determined by a number of factors, including the scale and complexity of the operations, the financial and operational capabilities of the municipalities, and the strategic objectives of the project. Depending on their objectives and responsibilities, these organizational forms can interact in a variety of ways. E.g. a KF and an IKS may establish a partnership to jointly provide a service, while an IKS and an AS may work together on a commercial project (KS, 2020; KS, n.d.).

For instance, if the project is managed by a single municipality and seeks to improve the sustainability of local wastewater treatment services, a KF may be an appropriate choice. If the project involves multiple municipalities and seeks to attain economies of scale, an IKS may be preferable. If the initiative aims to generate a financial return and can profit from a more business-like approach to operations, an AS may be the best option. If the project involves a large and diverse group of stakeholders, and if the democratic participation of these stakeholders is deemed essential, SA may be a viable option. If the undertaking requires stability and independence from outside influences, a foundation may be the optimal solution. If the initiative is small and entails a tight-knit group of stakeholders, an association could be a suitable option. If the initiative involves numerous municipalities and seeks economies of scale, host municipality cooperation may be a viable option (KS, 2020; Lier kommune, 2014).

The organization and management of the selected entity should strive to increase the efficacy of operations, minimize waste in the management system, and maximize production and sales. This may entail employing best practices in project management, implementing performance-based contracts, and creating a solid business plan. The entity should also engage actively with stakeholders, including municipalities, customers, and the general public, to ensure their requirements and expectations are met and to improve the sustainability of its operations (Sommerset, 2021).

3.10 Case study - Lier Municipality's new main WWTP

The municipality of Lier is taking innovative strides in centralizing its wastewater treatment system. The plan is to construct a cutting-edge treatment plant that will not only replace existing municipal facilities in Linnes, Sjåstad, Sylling, and Tonstad, but also accommodate the processing of wastewater from the Lahell treatment plant in Asker municipality.

By 2050, it is estimated that the plant will serve approximately 60,000 residents and manage additional load equivalent to biochemical oxygen demand (BOF) of around 100,000 during peak weeks. The aim of the solution is to enhance Lier's sanitation system and simultaneously transform waste into valuable byproducts like biogas and biochar. This conversion presents significant environmental and economic benefits.

Project Data

Data Description	Symbol/Unit	2026 Value	2050 Value
Calculation Interest Rate	-	4%	4%
Depreciation	Years	20	20
Total Investment Cost	NOK (million)	1019.1	-
Biogas Plant Investment	NOK (million)	47	-
Service Building Investment	NOK (million)	11.5	-
Infrastructure & Outdoor Works Investment	NOK (million)	101.6	-
Land Acquisition and Developer Costs	NOK (million)	153.9	-
Uncertainty Reserve	NOK (million)	144.2	-
Dimensioning Person Equivalent (PE)	-	60000	60000
Maximum Design Wastewater Flow (Qmax)	m^3/hour	1932	-
Design Flow Rate (Qmax_dim)	m^3/hour	1400	-
Sludge Production	kg TS/day	3244	4681
Energy Consumption for Heat and Electricity	GWh/year	1.6	1.7

It is very important to note that the calculations below are based on basic assumptions and average values from literature. Real-world application may require additional considerations. The financial analysis does not account for inflation, energy market changes, potential subsidies, or broader socio-economic benefits like employment generation, greenhouse gas reduction, waste reduction, and improved sanitation.

Assumptions

Assumption	Symbol/Unit	Value
Volatile Solids (VS) Content of Sludge	%	70
Specific Biogas Yield per Unit of VS	m^3/kg VS	0.35
Biogas Energy Content	MJ/m^3	22
Biogas to Hydrogen Conversion Efficiency	-	48%
Biochar Yield	% of dry weight	30
Operational and Maintenance Cost	% of Biogas Plant Investment/year	2
Biogas Plant Lifespan	Years	20
Hydrogen Upgrading Cost	% of Biogas Production Cost	20
Biochar Distribution Costs and Desired Profit Margin	% of Production Cost	20
Biochar Quality Factor	-	0.8

Calculations and Results

Calculation	Formula	2026 Value	2050 Value
Biogas Yield	Sludge volume * VS content * Biogas yield per VS	795 m^3/d	1145 m^3/d
Energy Production	Biogas yield * Biogas energy content/3.6	4861 kWh/d	6997 kWh/d
Hydrogen Energy Production	Energy production * Conversion efficiency	2332 kWh/d	3358 kWh/d
Biochar Production	Sludge solids * Biochar yield	973 kg/d	1404 kg/d
Biogas Cost	(Total costs) / (Total energy produced by biogas facility over	0.159 NOK/kWh	-
Hydrogen Cost	Biogas cost + Biogas cost * Upgrading cost	0.191 NOK/kWh	-
Biochar Cost	(Production cost + Distribution cost + Profit margin)/Biochar quality factor	0.159 NOK/kg	-
Revenue from Biogas Sales	Volume of biogas produced per year * Price of biogas per unit volume	282,944 NOK/year	-
Payback Period	Initial investment / Cash flow per year	166 years	-

This simplistic calculation suggests the payback period is quite long. However, it doesn't consider the potential revenues from waste treatment fees, possible subsidies, or the long-term benefits of reduced greenhouse gas emissions and waste reduction.

Socio-economic analysis

A socio-economic analysis would consider the broader benefits of the project, beyond just financial returns. This could include employment generation, greenhouse gas reductions, waste reduction, soil improvement from biochar application, and potential health benefits from improved sanitation. The analysis might also consider the potential value of the plant as a demonstration project to promote the adoption of circular economy principles in the water and wastewater sector.

However, quantifying these benefits can be complex and would require more detailed data and a range of assumptions. It's important to note that while the payback period for the biogas and biochar production may be long based on the direct revenues, the broader socio-economic benefits could be substantial and justify the investment.

Although the biogas project in Lier municipality doesn't appear to be financially viable based on the initial calculations, there are various strategic approaches that the Treatment Plant Administration and the government can employ to optimize this project's financial viability while also promoting environmental and social benefits:

Subsidies and Incentives: The government can provide financial support in the form of subsidies and incentives to offset the initial costs of biogas plant setup and operation. This can significantly reduce the overall investment and operational costs, making the project more financially feasible.

Cap-and-Trade System: Instituting a cap-and-trade system for carbon emissions can make the project more economically attractive. If the biogas plant can offset a significant amount of carbon emissions, it can generate and sell carbon credits to other industries that exceed their emissions caps.

Increase the selling price of biogas and biochar: Since both biogas and biochar are environmentally friendly alternatives to traditional fuels, they can potentially be sold at premium prices. Marketing strategies emphasizing the environmental benefits of these products can justify higher prices.

Energy Partnerships: Partnering with local industries or residential communities to sell biogas or heat generated from biogas can help increase revenues. This can be particularly feasible if there are industries nearby that require significant energy inputs.

R&D and Technology Improvements: Investing in research and development to improve biogas yield, energy conversion efficiency, and biochar quality can help enhance revenue and reduce costs in the long run.

Waste Management Services: The treatment plant can consider charging for accepting organic waste from other industries. By broadening the waste inputs to include food waste or agricultural waste, the plant can increase the production of biogas and biochar.

Green Certificates and Renewable Energy Credits: The plant can earn green certificates or renewable energy credits for generating renewable energy, which can be sold to utilities to meet their renewable portfolio standards, thereby providing additional revenue.

Public Education and Awareness Campaigns: Increasing public awareness about the environmental benefits of biogas and biochar can increase market demand and, consequently, the selling price.

Social Benefits: The project can have significant social benefits, such as job creation, waste reduction, cleaner energy, and healthier soils (with biochar application). These benefits can be factored into a broader socio-economic analysis to justify the project from a societal perspective, even if the direct financial return isn't high.

Policy and Regulation: The government can implement favourable policies and regulations, such as mandates for renewable energy use or waste-to-energy initiatives, to stimulate demand for biogas and biochar.

By combining these strategies, the Treatment Plant Administration and the government can turn the project into a more beneficial investment, both in terms of financial returns and positive environmental and social impacts.

3.11 Summary of the chapter and research questions

The theoretical framework concludes that circular economy principles can improve sustainability and reduce operation and maintenance costs in the water and wastewater sector. The sludge produced by water and wastewater treatment can be utilized for biogas and biochar production. Both biochar and biogas can enhance soil health, thereby contributing to the reduction of GHG emissions. Thus, the production of biogas and biochar from WTP and WWTP sludge correlates with the circular economy by reducing waste and producing renewable energy and products with added value.

Although previous studies have focused on the technical and economic viability of biogas and biochar production as well as their potential environmental and social benefits, they have neglected their application in the water and wastewater sector and their ability to finance the operation and maintenance of municipal treatment plants. In addition, they neglect the economic viability of local biogas and biochar production, the potential environmental benefits of implementing circular economy practices, and the social and institutional barriers to implementing a circular economy in the water and wastewater sector. This research gap highlights the need for empirical evidence and practical guidelines for implementing the circular economy in this sector.

Despite these gaps, several studies have identified significant environmental and economic benefits of co-digesting wastewater sludge and organic waste and biochar production from sewage sludge. However, these studies also identified several obstacles, including limited availability and quality of food waste in the future, lack of policy incentives, high investment costs, and market and regulatory uncertainty. In addition, the importance of public adoption and awareness of biochar production is emphasized. The majority of studies concur that the implementation of a circular economy necessitates not only technological and economic solutions but also social and institutional changes, as it involves multiple stakeholders.

This thesis intends to address the aforementioned gaps in knowledge. Specifically, it investigates the viability of local biogas and biochar production to finance operation and maintenance costs and improves the sustainability of a particular municipal treatment facility in Norway. The most important research questions concerns are:

(1) ***How can the feasibility factors affecting the implementation of biogas and biochar production from wastewater sludge in a municipal treatment facility in Norway be addressed to enhance sustainability and finance operation and maintenance costs?***

(2) ***What are the costs and benefits of producing and selling biogas and biochar to finance the operation and maintenance of municipal treatment facilities in Norway, and how can local production be used to promote circular economy practices?***

(3) ***How can policies and regulations be improved to strategically encourage the production and use of sludge-derived biogas and biochar in the Norwegian municipalities, and to promote the adoption of circular economy practices?***

This thesis aims to contribute to the circular economy discourse in the water and wastewater sector by addressing these questions, with a particular emphasis on local biogas and biochar production as a financing and sustainability mechanism.

PART 3

METHODOLOGY – ANALYSIS – RESULTS

4 METHODOLOGY

This chapter describes the methodology utilized in this study, including how empirical data influenced the final results, as well as the methodological approaches considered throughout the research process.

Initially, I address the selection of theoretical perspectives and the methodology used to identify pertinent literature from prior research in the field. The chapter then explains the methodological decisions made for data collection and analysis. In addition, I explain how I maintain the anonymity of informants and safeguard their integrity.

In the final part, I consider the generalizability and transferability of the study and my attitude toward the informants. I have selected one of the three research methodologies (Creswell, 2003) used to conduct this study.

4.1 Review and adoption of research methods and procedure

Review of research methods

Using field observation, interviews, and a literature review to acquire empirical data, this master’s thesis is based on a mixed-methods approach with a qualitative research emphasis. While quantitative research seeks to quantify the characteristics or features of a phenomenon, qualitative research is motivated by the desire to comprehend its quality or essence (Widerberg, 2001; Thagaard, 2003). Although a small portion of quantitative methods were applicable to the interpretation of statistical data, I favored a qualitative approach over a mixed-methods approach. The qualitative method allowed for a more in-depth comprehension of how refuse (particularly sludge) impacts the environment and how the regulatory system influences and is influenced by the water and wastewater sector.

The hybrid methodology combines quantitative and qualitative approaches. Its framework is still in development; consequently, it is less constrained than the other two methods. Complex research projects requiring the use of statistics to corroborate or disprove the researcher's perceptions appear to benefit from its use. It enables extensive data collection while addressing the difficulties inherent to the qualitative method. However, it is time-consuming due to the vast quantities of data that the researcher must analyze and compare with other methods (Creswell, 2003).

Procedure for the chosen theory (literature)

The significance of any research study derives from its theoretical and practical approach, a duality that is frequently exemplified by the theory-practice dynamic. It is crucial to remember that theories are not mutually exclusive, despite the fact that their independence may give the illusion of objectivity. Each theory, with its particular strengths and weaknesses, has a utility that is dependent on the research query it is intended to answer.

This thesis focuses on circular economy and waste management, with a particular emphasis on sludge. Given the specific problem statement, I felt compelled to investigate these contexts from multiple theoretical perspectives, namely technological and business-oriented lenses that concentrate on the production of biogas and biochar from WTP and WWTP sludge. The selected theoretical perspectives are influenced by the problem statement of the thesis, the empirical data, previous research foci, as well as my professional experience as a municipal divisional engineer, and my academic background in construction engineering and innovative business development.

Initially, I believed that this niche topic might not have extensive research coverage, but I was soon disproved. As a result, I undertook the task of locating relevant literature, reviewing approximately 280 publications by Norwegian and international authors to identify the gaps that this thesis could fill. This amalgamation of sources was deliberate with the objective to identify potential divergences and convergences, with the intention of nuanced and generalizing the thesis as much as possible in order to accommodate both Norwegian and broader European contexts.

To compile a summary of pertinent research in the field, I combed through a variety of sources, including academic journals, official reports, and literature cited in pertinent studies. This comprehensive and exhaustive strategy was intended to ensure quality and credibility. Despite the broad scope of the available literature, the constraints of time, resources, and adequate tools made it difficult to obtain an exhaustive overview.

Government reports, EU research, scholarly reports published in research journals, and academic articles concentrating on the production and sale of biogas and biochar served as the primary sources for this study. Despite the diversity of these sources, the results and recommendations were remarkably congruent, highlighting the significance and prospective relevance of the thesis's findings.

4.2 Recruitment and selection of respondents

Prior to beginning the research for my master's thesis, I talked with many companies to discuss circular economy issues in the water and wastewater sector, concentrating on sewage sludge as a raw material for biogas and biochar production. Through these initial interactions, I contacted the pertinent collaborative partner, Lier Municipality, which helped connect me with additional sources. In addition, my existing network within the university, previous employment connections, and acquaintances helped me recruit additional informants.

For this study, it was essential that the informants were either highly skilled workers in the sector or had extensive experience working with aspects of the problem statement. For the purpose of preserving the veracity of their insights, the interview guide was provided in advance, allowing the informants to familiarize themselves with the topics and questions, thereby reducing the possibility of the interview deviating off-topic, saving time, and reducing potential frustration. This also ensured that no restrictions or guidelines were imposed on the informants during the interview. The snowballing technique was also employed, with current informants assisting in the identification of prospective future informants in an effort to collect rich data.

Despite initial difficulties in scheduling interviews due to summer vacations, a strategy was devised to reduce dropout rates by allowing informants to determine interview timing. As the topic was fascinating to all informants, a letter of information (annex 1) and an interview guide (annex 2) were sent out in advance, which helped streamline the process and keep discussions on track.

The study relied on strategically selected informants, chosen based on their relevance to the problem statement. The selection criteria were as follows: the informant was not primarily interested in promoting their services/products; they had at least five years of experience relevant to the problem statement; or they worked in the water and wastewater sectors, or with the management or production of sludge-based products.

Four experienced workers of the Lier Municipality were interviewed. Each informant had a minimum of 10 years of experience in a variety of positions, such as economic consultant, agricultural executive, operational manager, and technical supervision leader, and a background in the applied or natural sciences. All informants were interested in sustainable solutions and concerned to contribute to the research, despite having diverse professional backgrounds and geographic origins.

Due to the unwillingness of some informants to be identified, I have refrained from providing specific personal information about the informants in order to preserve their anonymity. To facilitate analysis, enable comparisons, and identify differences, their data have been aggregated and generalized, and the term "informant" has been substituted for their personal identities.

Upon initial data analysis, I recognized the need for diverse perspectives, such as those not employed by the municipality and end-users of biogas and biochar derived from sludge. Due to time constraints and pressing deadlines, additional interviews were not possible.

4.3 Tools and implementation of the methodology

The following research tools were essential for the completion of this study:

Literature Search

This study relied heavily on online databases such as www.oa.mg, www.journals.scholarsportal.info, and www.link.springer.com for its literature. They were indispensable in establishing the research basis.

AI Assistance

The use of Artificial Intelligence (AI) tools, specifically variants GPT-4 and GPT-3.5, facilitated the screening and analysis of voluminous literature sources. It was essential, however, to validate the information provided by the AI, particularly GPT-3.5. A pre-verified inventory of over 400 literature sources, along with their respective web addresses, was compiled and used as a reference to ensure the authenticity of the AI outputs. Despite ongoing debates over the use of AI in research, tools such as GPT-4 have proven to be extremely beneficial when used with care.

QuillBot, an artificial intelligence tool, significantly helped in managing language and grammatical transitions between English, Norwegian, and French.

Books and Reports

Books and reports were essential sources that provided a deeper understanding of the problem statement.

Open and Semi-structured Interviews

Using a combination of semi-structured and open interviews, researchers were able to compare informants and uncover new information. This method's inherent adaptability allowed for modification of the line of inquiry, allowing interview data to inform the formulation of new queries.

A critical awareness of the researcher's own assumptions was maintained throughout to prevent the imposition of preconceived notions on the interpretation of the informant's reality. This aided in preventing the normalization of established beliefs.

Interview Guides

Two thematic interview guides, designed as flexible checklists rather than fixed templates, were prepared. The objective was to encourage informants to reflect upon the questions.

Interview Conduct

Digital interviews began with an introduction to the subject and the interviewer, a review of the consent form, and a request to record the conversation. The respondent was then requested to provide information about themselves, followed by their opinions on the research topic. All informants consented to have their interviews recorded, which facilitated active listening and data collection.

The objective was to create an environment of confidence and trust so that the informants felt at ease expressing their opinions. The impartiality and interest of the interviewer encouraged the informants to share more. The interview questions varied based on the professional category and position of the informant. The interview guide was more of a topic checklist than a list of specific questions. At the conclusion of each interview, informants were asked if they had anything else to add, providing them with the opportunity to emphasize points they regarded significant.

4.4 Validity and Reliability

Validity and reliability are two essential pillars for guaranteeing the quality and integrity of research.

The validity, which denotes the accuracy or legitimacy of the findings, is directly related to the extent to which a study measures what it intends to examine. In the water and wastewater industry, the topic of "circular economy" encompasses a wide range of considerations, factors, constraints, and solutions. This complexity is exacerbated by the involvement of various stakeholders, making it difficult to formulate precise solutions. Although some aspects of the theoretical framework employed in this study do not directly relate to the problem statement, they are essential to obtaining a thorough comprehension of the subject's complexity. Therefore, despite it was difficult to identify highly precise solutions, the findings presented here serve as a guide to potential criteria for a sector's successful entry into the circular economy.

Reliability, on the other hand, is the degree of consistency and dependability of the research findings, as well as the measures' equilibrium, robustness, and endurance. This report bases a substantial portion of its theory on previous research and literature, personal experience, field observations, and pertinent solutions from other industries and sectors. This report can be relied upon as a reliable source of research because it has been subjected to a rigorous process of information selection and quality assurance by a couple of professionals. The findings are verifiable, as they are primarily based on primary data collected from trained professionals and fieldwork.

The correlation between independently collected primary and secondary data with coincidentally similar results strengthens the credibility of these findings. However, any ambiguity associated with generalizing requirements when selecting solutions is a result of the inherent variability in waste (sludge) generation and management across various sources and methods, as well as industry actors' divergent visions and objectives regarding the circular economy. Given these circumstances, the research avoids excessively precise conclusions, instead presenting findings that enable stakeholders to select what pertains to their specific context, given that each case's circumstances will be unique.

4.5 Objectivity, Generalizability, and Transferability

Objectivity

Objectivity in academic research denotes neutrality and the recognition that reality exists independently of human perceptions. This research adheres to this principle by emphasizing objectivity through a meticulous literature review and validation of source references to ensure quality. Field interviews, personal observations, and conversations with knowledgeable individuals significantly contribute to addressing the problem statement from multiple angles. This method makes it easier to reach independent conclusions. Primarily, government agencies, internationally competent organizations, leading consulting firms, research journals, scientific publications, and seasoned professionals, such as those from the EU website, which provides credible, impartial sources, are consulted for the literature. Notably, not all informant data were deemed useful due to personal bias, and these were subsequently discarded to ensure the study's objectivity. Environmentally favourable solutions are frequently expensive, and the actors were left to determine the implementation order of solutions based on corporate resources. This aspect was managed independently throughout the duration of the endeavour.

Generalizability

Given the climate variations in Norway and the autonomy of regional and municipal governance systems, it may be difficult to implement some results uniformly across the country, particularly those with technical recommendations. However, it is unlikely that these will pose a substantial barrier to the application of the study's findings.

Transferability

The primary objective of qualitative research is the 'transfer of knowledge' rather than the statistical generalization' of results to a population. This research, which included interviews with four informants, aimed to obtain a better understanding of how participants perceive circular economy opportunities in the water and wastewater sector. The transferability of a participant's descriptions, concepts, interpretations, and explanations refers to their applicability in other contexts, thereby contributing to a broader theoretical understanding. To transfer my research results to other contexts, it is essential to observe that each informant expressed enthusiasm for their work and the subject of the study. They were eager to provide additional empirical data for the investigation. Nevertheless, their statements are context dependent. A case involving professionals who are dissatisfied with their work or uninterested in sustainable research, for instance, may generate different results. Finally, it is essential to emphasize that human knowledge is not absolute and varies over time and space. Consequently, it is always embedded in a context, according to the theory of sensemaking.

4.6 Analysis of the process and constraints

At each stage of this research, analysis was conducted to inform subsequent steps. Initially, a thematic analysis was conducted on the empirical data collected. The materials included more than six hours of recorded interviews and more than twenty pages of transcriptions. The semi-structured and open-ended nature of the interviews resulted in seemingly chaotic data.

To organize this data, it was first grouped and then divided into four main categories: challenges to the water and wastewater sector and the circular economy; waste policy and influence; sludge treatment and management; and implementation challenges and opportunities. In addition, the data were organized according to respondents' activity categories. For each category, data were extracted from each transcribed interview.

During the process of data analysis, the interviews were read multiple times. This allowed for the extraction of essential phrases and quotes, which were then categorized into various subthemes. Thus, the original data were dissected and linked to concepts, resulting in a greater comprehension of the empirical material. This interaction between the researcher's prior knowledge and data trends affected the categorization and interpretation of the data within categories.

The analysis revealed that it was difficult to reduce the material's interesting trends into a few key themes. In addition, the writing process was an integral part of the data analysis, making it impossible to adhere to a predetermined format. The data analysis was not regarded as complete until all text had been written and categorized according to various themes and focus areas. Initiating diverse discussions in each category using key phrases from interviews and theoretical perspectives.

Interviews were not limited to eliciting responses or opinions from interviewees. Instead, they were distinguished by the interaction between the interviewer and informants, which fostered a relaxed atmosphere in which both parties could participate. The interviews were the result of an interpersonal process, with the responses of the informants influenced by personal characteristics, gender, age, and social status.

Regarding ethical considerations, the informants' anonymity and integrity were protected with great care. The informants were relaxed and provided insightful commentary on their own experiences. This transparency enhanced the data and extended our perspective.

In conclusion, this section described the selection of theoretical perspectives, the various methodological approaches for acquiring literature on previous research in the field, and the methodological decisions made regarding data collection and analysis. It also clarified the researcher's function in this interpersonal interviewing process and its implications for the findings of the study. Finally, considerations regarding the transferability of the research were addressed.

5 DATA ANALYSIS and FINDINGS

Traditionally, the structure of a research report consists of an introduction, methodology, results, discussion, and conclusion. This structure enables authors to organize their work presentation. The results section describes the key findings of the study, while the discussion interprets these findings and clarifies their significance; this section should not repeat the results. Guidelines may differ based on the complexity and scope of the findings and report. Researchers may contemplate combining the results and discussion sections, or they may prefer to keep them distinct. Both formats have advantages and disadvantages. The integrated approach discusses results as soon as they are presented, preventing the need for readers to switch between sections. In contrast, with separated sections, there is continuity in the discussion, allowing readers to comprehend and analyze the study as a whole, as opposed to having to switch between results in a combined section. Consequently, the reader must return to the results section to correlate the discussion.

By comparing the results of theoretical research (secondary data) with those of fieldwork interviews (primary data), remarkable parallels emerge, supporting the well-known assertion that the water and wastewater sector is deeply anchored in old practices (path dependence). Considering the scope and interconnection of the primary and secondary data, I've decided to sharpen them in order to analyze the whole and develop more specific theories, asserts, and solutions for the problem's broad areas. Therefore, the majority of data analysis is presented in the discussion section. Concurrently, I have categorized the data according to the research questions in the discussion section, addressing the challenges disclosed in the theoretical knowledge chapter.

5.1 Secondary data analysis (literature review)

The literature review analysis related to the topic of this master's thesis reveals both potential benefits and challenges. The review explored the potential for biogas and biochar production as a means to finance operations and improve the sustainability of Norwegian water and wastewater treatment plants as the primary focus. Concurrently, the factors facilitating or impeding the full implementation of the circular economy in the Norwegian water and wastewater sector were investigated. The study together screened more than 280 national (Norwegian) and international sources.

The Norwegian full-cost pricing principle, which could potentially stimulate the production of biogas and biochar from wastewater treatment plant sludge, was identified as an important facilitating factor in the national literature review. However, a series of barriers may impede the effective implementation of this principle:

High production costs: The relatively high cost of living in Norway may encourage the purchase of new products rather than recycling, repairing, or refurbishing existing ones. Similarly, the costs associated with biogas and biochar production from sludge may exceed the costs associated with the production of non-renewable energy sources. The fact that the full-cost pricing principle does not allow municipal producers to increase profit margins when selling products, makes it difficult for treatment plants to cover production costs.

Capital investment and funding constraints: Biogas and biochar production demand a considerable initial investment in infrastructure, technology, and personnel, alongside a big budget. Various treatment facilities may lack the funds necessary to make these investments, especially in regions with limited financial resources or competing priorities.

Infrastructure shortage: For biogas and biochar production, specialized infrastructure such as digesters, pyrolysis units, and Combined Heat and Power (CHP) units are required. Not all treatment facilities have access to these resources, which, paired with financial constraints, further restricts their production capabilities.

Limited market demand and saturation: Many Norwegian municipalities may have limited demand for biogas and biochar, making it difficult for treatment plants to find buyers for their products. Low demand could make it difficult for these facilities to generate revenue, even if they adhere to the full-cost pricing principle. Future market saturation, as more treatment plants produce biogas and biochar, could also have a negative effect on prices and revenues.

Market fluctuations: The markets for biogas and biochar are susceptible to demand and price fluctuations. This makes it difficult for treatment plants to effectively plan their budgets. Changes in government policies, the emergence of new competitors, and the introduction of substitute products can exacerbate these uncertainties.

Technical and operational barriers: Biogas and biochar production can be technically challenging, especially in regions with limited access to advanced equipment, materials, and skilled labor. Many municipal treatment plants in Norway may lack the knowledge to optimize their production processes, resulting in lower yields and higher costs.

Competition from other renewable energy sources: Other renewable energy sources, such as wind and solar, may pose competition. If wind and solar energy are less expensive than biogas and biochar, it may be more difficult for treatment plants to compete on the market.

Regulatory barriers: Norway's regulatory environment may also present obstacles. Restrictions on the use of sludge-derived biochar as a soil amendment may restrict potential markets. Complying with regulatory requirements for the treatment and disposal of sludge and additional waste may also increase production expenses.

Public perception and acceptance: The public may be resistant to the production of biogas and biochar from sludge due to concerns regarding uncertainty in the quality of the product due to the presence of high pollutants in their core material, odor, possible pollution, and other potential negative impacts. Such resistance could hinder the market acceptability of these products.

Storage, transportation, and land use constraints: Storage and transportation of biogas and biochar can be difficult, particularly if the production facility is located far from customers. This can increase production expenses. Additionally, the production of biogas and biochar may necessitate additional land, which may be difficult to acquire in regions with limited space (urban areas) or competing land uses.

Despite the potential for local biogas and biochar production to finance operations and improve the sustainability of water and wastewater treatment facilities in Norway, there are significant obstacles to overcome. These as aforementioned include high production costs, funding constraints, infrastructure shortages, limited market demand, volatile market conditions, competition from other energy sources, and regulatory and public acceptance issues. The findings of this review indicate that these obstacles must be overcome for the Norwegian water and wastewater sector to completely implement the circular economy.

5.2 Primary data analysis (interview)

Upon analyzing and integrating the responses from the four interviews with key informants, several themes regarding the potential and challenges of local biogas and biochar production for enhancing the sustainability of Norwegian wastewater and water treatment plants emerge. These themes include financial considerations, regulatory constraints, the role of innovation, knowledge barriers, the pace of technology adoption, and the societal and political landscape.

Economic considerations: Due to its inflexibility and the limitations imposed by the generation principle and investment fund, the full-cost pricing model (Selvkost) utilized by municipalities was cited as a problem based on economic considerations. This might discourage the application of circular economy measures, such as local biogas and biochar production, to finance the operation and maintenance costs of water and wastewater treatment plants. In addition, the current regulatory framework makes it difficult for municipal treatment plants to produce and sell biogas and biochar derived from sludge. In addition, there appears to be a lack of knowledge regarding the transformation of sludge into products such as biogas and biochar, which could generate additional revenue for treatment facilities. The production of biogas and biochar from municipal wastewater treatment plants could free up expenses from other municipal activities if it is first bought or used locally. The resources the municipality uses, for instance, for fuel and heating, could be subsidized to finance local production of biogas and biochar at the municipal wastewater treatment plant.

Regulatory constraints: Existing regulations (laws, regulations, standards, etc.) are not inclusive or aligned with new innovations. The constant emergence of disruptive innovation creates difficulties for producers, investors, and users to commit to a specific measure over a long period. This factor could slow the introduction and implementation of innovative solutions, like the transformation of sludge into biogas and biochar. The respondents mentioned several regulatory obstacles to the commercialization of biogas and biochar from municipal wastewater treatment facilities. A mentioned from start, existing regulations are not conducive to new innovations, making it difficult for producers, investors, and consumers to make long-term commitments to a particular project. In addition, the municipality's executive and state administrators lack significant incentives to increase the full-cost price due to the possibility of public backlash. Transitioning to new solutions can be time-consuming due to municipal framework agreements and local regulations. This lengthy process, combined with the pace at which technology develops, could hinder the swift implementation of new and sustainable market solutions.

The role of innovation: The continuous emergence of disruptive innovations makes it difficult for existing regulations to adapt rapidly enough, thereby creating a challenging environment for both new and established players. In addition, due to municipal framework agreements and local regulations, the transition to new solutions is time-consuming. For instance, municipalities have recently invested a lot in the dissemination of knowledge and the promotion of other solutions, such as composting. Changing to a new solution, like the production of biogas and biochar, would be time-consuming and expensive for both the municipality and users.

Knowledge and technology adoption barriers: The lack of knowledge regarding the transformation of sludge into other products, such as biogas and biochar, could hinder the implementation of these sustainable solutions. In addition, and as mentioned above, substantial investments have already been made to promote composting as an environmentally responsible solution, making the transition to a new method time-consuming and expensive for both users (agriculture) as well as the community (payer of the full cost pricing).

Societal and political landscape: Despite being acknowledged as essential, the concept of sustainability is not well understood or consistently applied within the community. There is also a perception that politicians only value the water and sanitation sector for their political ambitions and interests. It was also indicated that in the majority of municipal operations, financial and economic considerations take precedence over sustainability.

Opportunities for progress: There are opportunities for advancement despite the difficulties. If purchased or used locally, biogas and biochar produced by municipal treatment plants could potentially reduce expenditures for other municipal activities. A cooperative approach among neighboring municipalities might encourage the development of a biogas and biochar production-promoting business model. In addition, revisions to fertilizer regulations may expand the use of sludge-derived biochar.

Recommendations from informants

- Increase the flexibility and adaptability of self-cost pricing models to address the particular requirements and difficulties of municipal services.

- Improve regulatory frameworks to facilitate the production and sale of biogas and biochar derived from sewage residue by eliminating obstacles and promoting circular economy practices. The regulatory aspect becomes a problem for the commercialization of sludge-produced biogas and biochar from municipal wastewater treatment plants in Norway. However, the current revision of the fertilizer regulation may open more room for the use of sludge-produced biochar.
- Implement policies and incentives, such as subsidies and information campaigns, that promote the use of biochar in agricultural practices. Municipal environmental grants are a good initiative to support the use of biogas and biochar, including among farmers. For example, inland municipalities currently offer 15 NOK per kg of dry matter for the distribution of biochar. However, to further promote the use of biogas and biochar, municipalities should establish or support more projects and fairs to increase knowledge and incentives.
- Promote the carbon capture and storage quota market (Farmers' and landowners' sale of carbon credit or carbon offsets) and offer financial incentives to encourage farmers to employ biochar. If the carbon quota sale were better promoted among farmers and incentives for the use of biochar strategically increased, such as through tax subsidies, many farmers might be motivated to use biochar. For instance, farmers do not see enough profit in using biochar, which is more expensive than existing solutions. In addition, farmers who are already invested in composting may find the shift frustrating and financially burdensome.
- Develop guidelines and regulations that are inclusive, considering innovations, and providing stability for long-term investments in sludge treatment technologies.
- Establish concrete benchmarking systems in the water and wastewater industry to facilitate knowledge sharing and innovation in sludge treatment strategies. The absence of specific competitors or references reduces incentives to implement new innovative solutions, such as the investment in further treatment of sludge to produce biogas and biochar.
- Strengthen communication and public awareness campaigns to emphasize the significance of the water and wastewater sector to sustainability. The water and wastewater sector is currently a neglected service that politicians often value for their political ambitions and interests. However, it is important to communicate the importance of the sector, and the benefits it could bring through the implementation of circular economy measures.
- Integrate sustainable practices into decision-making processes and consider long-term benefits to achieve a balance between financial and sustainability objectives. Finance and

economy are often the first motivations and efforts in most municipal operations. Sustainability often comes last and is often used only as a green façade. This attitude could hinder the investment in new technology, such as the production of biogas and biochar in local treatment plants.

- Encourage municipal collaboration to establish a viable business model for local biogas and biochar production, addressing issues of trust and conflict. It is crucial for a municipality to cooperate with other nearby municipalities to establish a business model that promotes the production of biogas and biochar. This is because Norwegian municipalities are often very small, and a single municipality may not produce enough sludge for the production of biogas and biochar that will meet the demand.
- Support the revision of fertilizer regulations to use product derived from sewage residue as a resource. Nitrogen and Phosphorus are other resources that can be retrieved from sludge. These are resources that are currently misplaced and could contribute to the financing of treatment plants.

In conclusion, while there are major barriers to the local production and sale of biogas and biochar, there are also significant opportunities for growth. The key will be addressing economic and regulatory challenges, improving understanding and adoption of sustainability principles, and establishing a cooperative and supportive political and societal landscape.

5.3 Summary of findings

The analysis of both primary (interviews) and secondary (literature) data regarding the potential for local biogas and biochar production as a circular economy measure in the water and wastewater sector revealed a number of enabling and inhibiting factors. These factors can considerably impact the viability and successful implementation of biogas and biochar production in Norway's municipal treatment plants. The following are scenarios of data convergence, divergence, and gap:

Divergence in the collected data

The interview data and literature review data diverge in a number of ways. The literature review emphasizes high production costs, funding constraints, infrastructure shortages, limited market demand, and volatile market conditions as key barriers. The interviews, on the other hand, place a strong emphasis on regulatory constraints, the role of innovation, knowledge barriers, and the social and political landscape as the primary challenges.

Convergence in the collected data

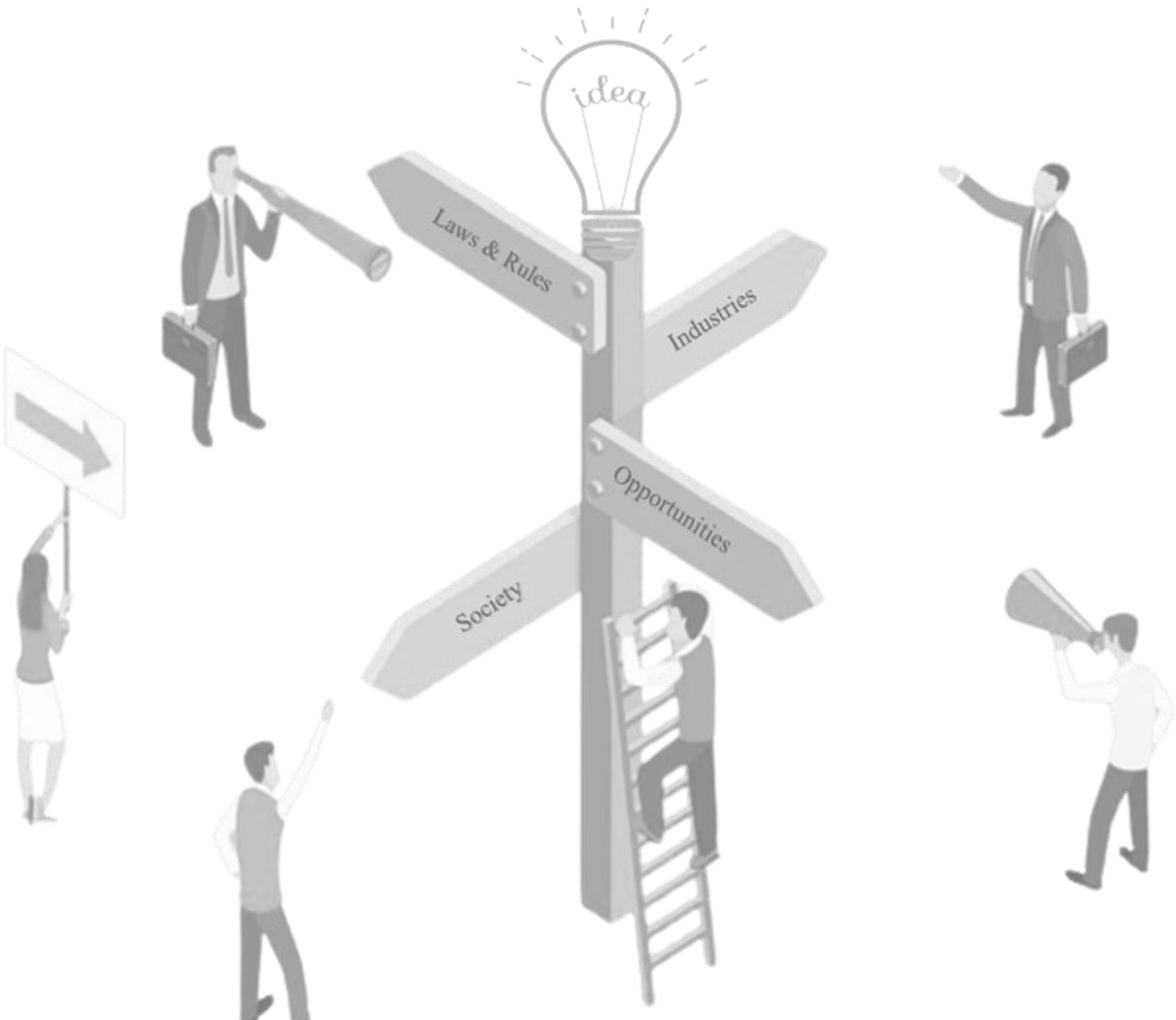
Despite divergence, the two data sets converge on a few points. Both sets of data acknowledge that high production costs and regulatory obstacles are significant barriers. In addition, they concur on the prospective advantages of biogas and biochar production in terms of cutting municipal treatment plant operating and maintenance expenses and enhancing sustainability.

Gap in the collected data

The gap between the literature review and interview data resides predominantly in the discussion of enabling factors and solutions. The literature review indicates that the full-cost pricing principle could potentially facilitate the production of biogas and biochar but does not elaborate on how this principle could be effectively implemented in light of the identified barriers. In contrast, the interview data suggest multiple strategies, such as flexibility in self-cost pricing models, improvement of regulatory frameworks, the establishment of concrete benchmarking systems, improvement of communication, and encouragement of municipal collaboration.

PART 4

DISCUSSION



6 DISCUSSION

This chapter illuminates the problem statement by answering the research questions with regard to findings from both empirical and literature data.

6.1 Addressing research question 1

How can the feasibility factors impacting the implementation of biogas and biochar production from wastewater sludge in a Norwegian municipal treatment plant be addressed to improve sustainability and finance operation and maintenance costs in the water and wastewater sectors?

The feasibility of implementing biogas and biochar production from water or wastewater sludge in a Norwegian municipal treatment plant is influenced by a variety of factors. These range from technical and economic aspects to regulatory, institutional, and societal aspects. Addressing these factors is crucial for improving sustainability and financing operation and maintenance costs in the water and wastewater sectors.

Technical Factors: The technical feasibility of biogas and biochar production largely depends on the availability of suitable technologies and the quality and quantity of sludge available. To address this, continuous research and development are essential to optimize the efficiency and adaptability of technologies. Furthermore, the application of lean and agile methodologies could facilitate the identification of process inefficiencies, the rapid testing of solutions, and the ability to adapt to changing circumstances.

Economic Factors: The high initial investment and operating costs pose major economic barriers. It is therefore crucial to secure adequate funding, potentially through public-private partnerships, and to enhance the economic competitiveness of biogas and biochar by monetizing their environmental and social benefits. For instance, a flexible full-cost pricing principle could be employed to internalize the environmental costs of conventional waste disposal methods, thereby leveling the playing field for sustainable alternatives.

Regulatory Factors: Regulatory factors can either incentivize or discourage the production of biogas and biochar. Currently, there may be regulatory uncertainties or constraints associated with the use of biogas and biochar, such as strict quality standards or limited incentives. Policymakers could address this by establishing clear, supportive regulations and providing financial incentives like tax credits or subsidies for renewable energy and sustainable soil amendments.

Institutional Factors: Institutions can play a crucial role in facilitating the transition to biogas and biochar production. Integrated Management Systems (IMS) could be employed to systematically manage environmental, quality, and safety aspects, thereby enhancing operational efficiency and sustainability. Additionally, the organizational structures of municipally owned enterprises could be adjusted to foster innovation and enable the adoption of sustainable practices.

Societal Factors: Public acceptance is a key factor in the feasibility of biogas and biochar production. Public concerns may arise from perceived risks, such as the potential contamination of soils by biochar or odors from biogas production. To address this, transparent communication is crucial to raise awareness about the benefits of biogas and biochar and address potential concerns. Moreover, active stakeholder engagement could ensure that the interests and needs of different societal actors are taken into account.

Path Dependency and Innovation: The transition to biogas and biochar production could be hindered by path dependency, which refers to the tendency to follow established patterns, such as conventional waste management practices. To overcome this barrier, an ambidexterity innovation approach could be employed, which entails exploiting existing resources while simultaneously exploring new opportunities. This approach could foster incremental improvements in existing systems and radical innovations for sustainable waste management.

The feasibility of biogas and biochar production from wastewater sludge in a Norwegian municipal treatment plant depends on a multitude of factors. Addressing these factors requires a comprehensive and coordinated approach, involving technical advancements, economic measures, regulatory reforms, institutional changes, societal engagement, and innovative strategies. By doing so, the water and wastewater sectors can enhance their sustainability, contribute to the circular economy, and generate additional revenues to finance their operation and maintenance costs.

6.2 Addressing research question 2

What are the costs and benefits associated with producing and selling biogas and biochar for financing the operation and maintenance costs of Norwegian municipal treatment plants – how can local production be used to promote circular economy practices?

Understanding the economic and environmental implications of resource recovery and reuse is essential for promoting a circular economy in the water and wastewater sector. Local production of biogas and biochar from WTP and WWTP sludge in Norway provides an opportunity to finance operating and maintenance expenses and improve sustainability. The costs and benefits associated with the production and sale of these byproducts, as well as their function in the circular economy, are of the greatest significance.

Costs of Biogas and Biochar Production: The initial investment cost, which includes the construction of anaerobic digesters and pyrolysis units, is one of the greatest obstacles to the production of biogas and biochar. Operating expenses (OpEX) consist of energy input for the processes, sludge transportation, and routine facility maintenance. In addition, there are costs associated with ensuring that the quality of biogas and biochar meets regulatory requirements, as well as the cost of potential environmental hazards, such as GHG emissions from imperfect combustion and the leaching of contaminants from biochar into soils.

Financial Returns from Biogas and Biochar: Biogas and biochar sales present revenue opportunities. Biogas can be used as a renewable energy source for heat, electricity, or transportation fuel, whereas biochar can be marketed as a soil amendment for agricultural purposes due to its capacity to increase soil fertility and sequester carbon. Moreover, by incorporating the full cost pricing principle which gives room for a long period of building and using investment fund, the environmental benefits of biogas and biochar production (such as emissions reductions) could be monetized, thereby increasing their competitiveness versus fossil-based alternatives.

Reduced Dependence on External Energy Sources: By using biogas as an energy source, treatment facilities can become energy-independent or even net energy producers, thereby reducing their reliance on external energy sources. This results in cost savings and enhanced resistance to energy price volatility.

Diverting Sludge from Landfills and Incineration: Municipalities can reduce their reliance on landfilling and incineration by converting wastewater into biogas and biochar, thereby saving landfill space, avoiding landfill fees, and reducing emissions from waste treatment.

Diverting Sludge from Landfills and Incineration: Biogas and biochar production and use contribute to climate change mitigation by replacing fossil fuels and sequestering carbon, respectively. These advantages could be realized to a greater extent with policies that provide financial incentives for emission reductions.

Promoting Local Economy: The production and sale of biogas and biochar locally can stimulate the local economy by generating jobs in the production, transport, and usage of these products. Additionally, it can foster the growth of local markets for renewable energy and sustainable soil amendments.

Incorporating Industrial Symbiosis: Industrial symbiosis (IS) promotes resource efficiency by encouraging cooperation and resource exchange between industries. The sludge from treatment plants can be regarded as a resource rather than a waste in this context. This perspective facilitates IS by supplying local industries with biogas for heat and power and local agriculture with biochar for soil amendment.

Path Dependency Considerations: Existing infrastructures, regulatory frameworks, and social norms, which tend to favor established waste (sludge) management practices, may pose obstacles to the transition toward biogas and biochar production. However, the concept of path dependence suggests that transitions can be induced through strategic interventions, such as policy incentives and technological advancements.

Despite the fact that the production of biogas and biochar from WTP and WWTP sludge incurs substantial up-front expenses, their benefits extend well beyond monetary returns on sales. These benefits include both environmental and social and economic aspects, such as the promotion of local economies and energy independence. Therefore, policies should seek to reduce impediments to biogas and biochar production and maximize their associated benefits. This will foster circular economy practices in the water and wastewater sector, thereby enhancing its sustainability and providing a potentially significant source of revenue to finance plant operation and maintenance costs.

6.3 Addressing research question 3

How can policies and regulations be improved to support the production and use of biogas and biochar from WTP and WWTP sludge in the Norwegian water and wastewater sector, and encourage the adoption of circular economy practices?

As we navigate through the challenge of transitioning to a sustainable, circular economy in the water and wastewater sector, the role of policy and regulatory mechanisms becomes increasingly crucial. The potential of biogas and biochar production from treatment plant sludge presents a promising path towards a circular economy model. It is therefore important to analyze how policies and regulations can be improved to encourage the adoption of these sustainable practices within the Norwegian context.

A Shift Towards Circular Economy-Focused Regulations: Currently, the regulatory framework for sludge management in Norway, primarily guided by the Pollution Control Act, emphasizes the prevention of environmental harm and the control of pollution. Although important, this perspective lacks a strong focus on the potential for resource recovery. The introduction of regulations that specifically address and encourage the conversion of sludge into beneficial products like biogas and biochar could stimulate the transformation towards a circular economy model.

Enabling Regulatory Environment for Biogas and Biochar Production: The regulatory environment needs to be adjusted to support the production and utilization of biogas and biochar. In particular, there's a need to set standards for the quality of sludge used in biogas production and the resulting gas itself. A clear set of guidelines regarding the treatment, storage, and handling of biogas should be established to ensure safe and sustainable practice. For biochar, the regulation should focus on ensuring its quality and safe use as a soil amendment.

Implementation of Financial Incentives: Consumer theory suggests that financial incentives can drive behavior change. The Norwegian government could provide incentives such as tax credits, grants, or subsidies to stimulate the production of biogas and biochar. These incentives could lower the financial risks for producers, making the investment in biogas and biochar technologies more appealing. Full cost pricing principles could be introduced to account for the environmental costs associated with conventional waste disposal methods, enhancing the competitiveness of biogas and biochar.

Emphasis on Research and Development (R&D): An investment in R&D could facilitate the development of efficient and cost-effective technologies for biogas and biochar production. Funding for pilot projects, technology demonstrations, and innovation hubs could fast-track the development and adoption of these technologies.

Public Awareness and Education: As suggested by the sensemaking perspective, the way individuals interpret their experiences can shape their actions. Therefore, the government and municipalities should prioritize public awareness campaigns to educate the public about the benefits of biogas and biochar. This can lead to an increased demand for these products and stimulate market development.

Promotion of Public-Private Partnerships (PPPs): PPPs can foster collaboration between government entities, private sector organizations, and academic institutions. These partnerships can facilitate the sharing of resources, expertise, and infrastructure necessary for the production of biogas and biochar.

Embracing Industrial Symbiosis (IS): The concept of IS encourages the sharing and recycling of resources among industries. In the context of WWTPs, this could involve an exchange of sludge between plants and biogas/biochar production facilities. This would not only maximize resource use but also promote a circular economy within the sector.

Incorporating Lean and Agile Methodologies: By focusing on waste reduction and adaptability, these methodologies can enhance the efficiency of sludge management and resource recovery processes.

Engagement of Local Stakeholders: Engaging local stakeholders, such as farmers and environmental groups, could create a supportive environment for biogas and biochar projects. These stakeholders could provide unique insights and potential solutions to challenges faced in the production and use of biogas and biochar.

Emphasizing Corporate Social Responsibility (CSR) and Environmental, Social, and Governance (ESG) principles: CSR and ESG principles could be integrated into the operation of treatment plants and biogas/biochar producing entities to promote sustainable practices. These principles could drive these organizations to commit to sustainable resource use, thereby promoting the circular economy.

To conclude, enhancing the policy and regulatory landscape to support the production and use of biogas and biochar from treatment plant' sludge is crucial for promoting a circular economy in the water and wastewater sector. This can be achieved through a holistic approach encompassing circular economy-focused regulations, financial incentives, R&D investments, education, PPPs, IS, lean and agile methodologies, stakeholder engagement, and the integration of CSR and ESG principles. Such measures, informed by relevant theoretical perspectives, will pave the way for a more sustainable, financially viable, and circular Norwegian water and wastewater sector.

6.4 Supplementary comments

The overall feasibility of implementing biogas and biochar production from wastewater sludge in Norwegian municipal treatment plants fundamentally pivots on a cooperative and circular approach. It involves a close-knit partnership between key stakeholders such as the producer, in this case, Lier VVA KF, the Supervision Office (Tilsynskontoret), the Agricultural Office (Landbrukskontoret), and the end users of the products – biochar for the Agricultural Association and biogas for other municipal businesses.

Central to the success of such an initiative is the role of the Agricultural Office, which possesses the ability to foster the use of biochar by deploying a range of strategies. Firstly, through education and capacity building, farmers can gain insights into the benefits of biochar, thereby encouraging its adoption. This may be achieved via educational programs and workshops targeted at the local farming community. In doing so, awareness, understanding, and acceptance of the technology may be fostered, thereby spurring usage.

Furthermore, demonstration projects may be initiated by the Agriculture department, showcasing the advantages of biochar usage. Strategically located on municipal lands or in partnership with local farmers, these demonstrations can tangibly illustrate the benefits of biochar, acting as powerful, evidence-based endorsements.

Fiscal interventions may further incentivize farmers to adopt biochar in their agricultural practices. The municipality's agricultural office, for instance, could provide subsidies to offset the cost of biochar, easing the financial burden on farmers. In addition, partnerships with carbon credit programs may generate revenue streams for biochar produced by the treatment plant. Selling carbon credits can not only encourage more farmers to adopt biochar but also generate additional revenue for the treatment plant, thereby creating a win-win scenario.

Additionally, the Agricultural Office could commit resources to research and development to probe the benefits of biochar in agriculture. By studying its impact on crop yields, soil quality, and greenhouse gas emissions, more comprehensive and data-driven insights could be gleaned. Concurrently, this would facilitate the creation of novel methods for biochar production and application.

Public relations campaigns can be deployed to raise awareness and drum up public support for the use of biochar in agriculture. A well-strategized campaign could pique public interest and foster a sense of community, thereby aiding in the technology's acceptance. To further foster a supportive environment, the Agriculture Office could collaborate with other municipalities, organizations, or research institutions. Such a network could expedite the sharing of knowledge and resources, thereby consolidating support for biochar technology.

To guarantee the sustainable and environmentally friendly production of biochar, certification programs could be enacted to create standards. Networking events, organized by the agriculture department, would offer a platform for farmers and other stakeholders to connect with biochar producers and learn more about the technology. Such events could forge strong relationships and build a community of supporters.

Incentive programs for treatment plants could also be devised by the municipality, encouraging them to produce biochar as a byproduct of their treatment processes. This strategy could incentivize investment in biochar production technology, thereby creating another revenue stream for the municipality. Collectively, these strategies could create a supportive environment for the use of biochar in agriculture, paving the way for improved soil quality, reduced greenhouse gas emissions, and the creation of new economic opportunities for farmers and municipalities.

The Supervision Office also plays a critical role, providing guidance on pollution, processing applications for environmental subsidies, mapping pollution from non-environmentally friendly fertilizers, and conducting sampling at potential pollution sources.

The potential benefits for farmers using biochar produced by the municipality's treatment plants are manifold. Enhanced soil quality, reduced greenhouse gas emissions, and decreased dependency on chemical fertilizers are just a few. Biochar has also been proven to improve plant resilience, reduce soil erosion, and foster increased biodiversity, making it a valuable asset for any farmer. Additionally, it opens up opportunities for diversified revenue streams and reduces waste disposal costs.

The implementation of a collaborative circular economy model can catalyze the production and usage of sludge-produced biogas and biochar. This model operates on the principles of the circular economy, leveraging waste from one process as a valuable resource for another, thereby creating a closed-loop system. In the context of this model, the revenue generated from the sale of biochar and biogas can be reinvested back into the municipality's agricultural and water or wastewater treatment infrastructure. This fosters a sustainable and circular economy, simultaneously promoting local job creation and reducing the municipality's carbon footprint.

To amplify the impact of this model, partnerships with other municipalities, organizations, academic institutions, and research institutions are essential. Sharing best practices, knowledge, and resources, and investing in research on the impacts of biochar and biogas production can yield valuable insights, spur innovation, and improve efficiency.

Moreover, fiscal incentives for local farmers and businesses that adopt biochar and biogas could significantly drive the growth of the circular economy. In offering subsidies or tax credits to farmers using biochar as a fertilizer or businesses purchasing biogas as a renewable energy source, the adoption of these resources can be further bolstered.

However, the successful execution of this circular economy model requires an effective and strategic business model. It necessitates commitment and collaboration from various stakeholders — municipality, local farmers, businesses, and others — to create an innovative and sustainable solution to the challenges faced by the municipality's agriculture and water and wastewater treatment sectors.

A schematic representation of the proposed collaborative circular economy model for local production of biogas and biochar is shown below. This schematic provides a snapshot of the interactions and responsibilities among the key stakeholders: the municipality treatment plant (Lier VVA KF), the agriculture office (Landbrukskontoret), local farmers, and local businesses.

Stakeholder	Responsibilities	Collaboration
Municipality Treatment Plant (Lier VVA KF)	Collection and treatment of wastewater; Production of biogas and biochar	Works closely with the agriculture department to ensure steady production and supply of biogas and biochar
Agriculture Office (Landbrukskontoret)	Promotes knowledge and manages biochar production; Ensures quality control of biochar	Partners with the municipality treatment plant to maintain consistent production and supply of biogas and biochar; Provides biochar to local farmers
Local Farmers	Uses biochar as a fertilizer for crops	Purchases biochar from the agriculture department; Provides feedback on the effectiveness of biochar
Local Businesses	Buys biogas as a renewable energy source	Collaborates with the municipality treatment plant for steady production and supply of biogas

A successful circular economy model is contingent upon active collaboration between these stakeholders. The municipality treatment plant and the agriculture office need to coordinate their efforts to ensure a consistent supply of biogas and biochar. The agriculture department also needs to engage with local farmers to ensure effective usage of biochar and gather feedback on its effectiveness. Additionally, local businesses must work closely with the municipality treatment plant to ensure a steady supply of biogas. This intertwined network of responsibilities and collaborations not only promotes sustainability and reduces waste, but it also enhances the local economy and reduces the overall carbon footprint.

Examining this proposed circular economy model, a prospective business model emerges, which could facilitate collaboration between the Agriculture office and the municipality treatment plant in a Norwegian municipality. This business model, detailed in the following steps, aims to generate revenue from the production and sale of biochar and biogas while simultaneously reducing waste and greenhouse gas emissions:

Biochar Production: The municipality treatment plant produces biochar from wastewater treatment sludge. This biochar is tested and certified to meet established quality and safety standards.

Biochar Distribution: The municipality treatment plant provides the biochar to local farmers at a reasonable cost.

Farmer Education: The Agriculture office organizes educational programs to instruct farmers about the benefits and proper application of biochar as a fertilizer.

Biochar Application: Farmers apply the biochar to their fields, reducing their reliance on synthetic fertilizers and enhancing soil health.

Crop Production: Using the biochar-enriched soil, farmers grow crops that are sold locally or regionally.

Biogas Production: The municipality treatment plant also produces biogas from the water and wastewater treatment sludge, which is used to generate renewable energy.

Revenue Sharing: The revenue from the sales of biochar and biogas can be shared between the municipality treatment plant and the agriculture office, enabling reinvestment in the circular economy model.

The benefits of this model are manifold. It enables the municipality treatment plant to generate revenue from the production and sale of biochar and biogas, thereby providing financial support for its operation and maintenance. The Department of Agriculture benefits from reduced costs associated with synthetic fertilizers and healthier soil. Finally, the local community gains access to sustainably produced food and renewable energy, enhancing local sustainability and self-sufficiency.

The aforementioned business model can be further clarified using a Business Model Canvas (BMC), a strategic tool used to visualize and clarify a business model's key elements. The following table presents the BMC for the proposed business model:

Business Model Canvas	Description
Key Partners	Agriculture office, Local Farmers, Municipal water and wastewater treatment plant, Government regulatory agencies
Key Activities	Biochar Production, Biochar Distribution, Farmer Education, Biochar Application, Crop Production, Biogas Production, Revenue Sharing
Key Resources	Municipal Water and WasteWater Treatment Plant, Sludge from Treatment, Biogas and Biochar Production Technology, Local Farmers, Soil, Government Regulations, Educational Materials
Value Proposition	Sustainable Agriculture, Reduced Waste, Reduced Emissions, Renewable Energy, Increased Access to Locally Produced Food, Revenue Sharing

Customer Relationships	Educational Programs, Quality Control, Feedback Collection
Channels	Municipal Water and Wastewater Treatment Plant, Agriculture and Supervision office, Local Farmers, Local Markets
Customer Segments	Local Farmers, Local Community, Regulatory Agencies
Cost Structure	Biogas and Biochar Production and Distribution, Educational Programs, Revenue Sharing
Revenue Streams	Sale of Biogas and Biochar, Sale of Renewable Energy, Revenue Sharing

This BMC elaborates on the central elements of the proposed business model, shedding light on the key partners and resources required, the activities undertaken, the value proposition, and the targeted customer segments. It also illustrates the model's cost structure and revenue streams, demonstrating the potential for generating revenue for both the municipality treatment plant and the Department of Agriculture.

The proposed business model holds significant promise for promoting a circular economy approach that aligns with the EU's Green Deal by reducing waste, greenhouse gas emissions, and increasing resource efficiency. By generating biogas and biochar from wastewater sludge, the model helps mitigate climate change through the reduction of methane release, a potent greenhouse gas. Additionally, the use of biochar as a fertilizer promotes sustainable agriculture and reduces the need for chemical fertilizers, contributing to soil and water conservation. The reuse of biochar further reduces waste and conserves resources, supporting the EU's circular economy objectives.

The potential for carbon reduction from this business model is significant, depending largely on the scale of operation and the specific technologies and practices employed. The use of biochar as a soil amendment has shown to sequester carbon, with biochar having a long half-life, remaining in the soil for centuries or even millennia. Consequently, this practice removes carbon from the atmosphere and stores it in the soil. Furthermore, the generation of biogas from water or wastewater treatment sludge contributes to carbon reduction by preventing the release of methane into the atmosphere. Thus, the application of biochar and biogas in agriculture could significantly reduce carbon emissions and aid climate change mitigation efforts. The exact carbon reduction figures would depend on the specific circumstances and scale of the business model, but the potential contribution to the EU's carbon reduction goals is significant.

6.5 Response to the problem statement

What is the potential for local biogas and biochar production as a circular economy measure to finance operating and maintenance costs and increase the sustainability of a Norwegian water and wastewater treatment plant? What are the enabling and hindering factors for the full implementation of the circular economy in the Norwegian water and wastewater sector?

Adopting local biogas and biochar production as part of the circular economy in the Norwegian water and wastewater treatment sector offers diverse benefits. Primarily, it could generate additional revenue streams to offset operational and maintenance costs and enhance sustainability via waste recycling. Additionally, this approach could stimulate local economic growth by creating new jobs and businesses. By closing the loop between waste generation, treatment, and product creation, circular economy principles could significantly contribute to reducing greenhouse gas emissions and promoting sustainable agriculture, aligning with the EU's Green Deal objectives.

However, to fully realize these benefits, substantial obstacles need to be overcome. The high costs associated with constructing and operating biogas and biochar production facilities could be prohibitive for many municipalities. Regulatory frameworks might also hinder their widespread adoption, as current rules may not encourage or even accommodate the production and use of biogas and biochar. For instance, regulations related to the safety and quality standards of biochar as a soil amendment or the technical requirements for biogas production and use could present significant challenges.

However, these hurdles are not insurmountable. Potential changes in regulatory and policy frameworks could encourage the production and use of biogas and biochar. Technological innovation could reduce production costs and improve efficiency, and raising public awareness and acceptance of these products could drive demand. A strategic approach addressing economic challenges through financial incentives for biogas and biochar production and infrastructure development could be beneficial.

Adopting such an approach requires a keen understanding of the local context, considering the needs and attitudes of relevant stakeholders, such as farmers. Many Norwegian farmers, for example, have shown little interest in using biochar due to its perceived low profitability and similar pricing to synthetic fertilizers. Therefore, closing this knowledge gap among farmers and authorities is vital.

Cooperative models housing multiple municipalities might help to address this issue. Surplus biochar, after agricultural needs are met, could be sold to other industries, providing additional revenue shared among farmers. Incentives like tax reductions for cooperatives engaged in biochar production, a certification system for biochar-produced food, and continued environmental subsidies could also stimulate interest in biochar.

In conclusion, the potential for local biogas and biochar production within the Norwegian water and wastewater sector is substantial. However, a concerted effort is required to address the existing barriers. Such an effort promises not only financial benefits for treatment plant operations but also significant environmental advantages, aligning with broader sustainability goals. Therefore, the full implementation of the circular economy in this sector is not just beneficial but necessary.

PART 5

CONCLUSION

7 CONCLUSION

This master's thesis contributes to the knowledge and understanding of optimizing sludge treatment in a municipal water and wastewater treatment plant to produce biogas and biochar. The study's findings can inform policy and decision-making regarding water and wastewater treatment and circular economy. In addition, the study can serve as a guide for other municipalities interested in implementing biogas and biochar production in their treatment facilities, and it can contribute to the development of sustainable and circular water and wastewater treatment practices.

7.1 Conclusion

In Norway, the water and wastewater industry find itself in a unique position, representing a monopolistic sector, as consumers are left without alternatives to the services it offers. Water, a fundamental life-giving resource, is supplied by this industry, while the wastewater sector safeguards our water sources and environment. Despite the critical role it plays, the sector is often under-prioritized by state administrators and the community at large, even in the face of substantial efforts made by Norske Vann and other organizations to elevate its standing and establish its worth to state administrators, politicians, the government, and the society. For example, consumers express willingness to spend up to NOK 10 500 per year to procure the latest mobile phone model, even when their current one functions perfectly, yet they complain about any little changes in water and wastewater bills, even though this ensures their life. The self-cost principle, an 'assurance device' implemented by authorities to stabilize water and wastewater prices, ironically, stifles innovation in the sector, necessitating fresh reform.

This master's thesis delves into numerous circular economy barriers, including economic, political, cooperative, social, and technical hurdles, with a particular focus on the exploitation of sludge as a resource for biogas and biochar production. Evidence indicates that, with sludge as a raw material, the water and wastewater sector can contribute significantly to society, primarily in socio-economic terms. However, realizing this potential requires substantial incentives, resources, research, and the empowerment of all stakeholders. As for the contribution of sludge to the finances and economy of treatment plants, the results reveal that the sale of biogas and biochar produced from sludge can generate substantial revenue. Farmers, for example, are likely to be the primary customers for biochar. Unfortunately, they are often inadequately informed about the benefits of this product. Furthermore, farmers have invested heavily in composting in recent years, and the sudden introduction of a new product to the market could lead to frustration. The successful acceptance of biochar necessitates a well-thought-out strategy and support. In addition, municipalities themselves can benefit from biogas produced at treatment plants by implementing strategies for a gradual shift to biogas (biomethane or hydrogen or electricity) for all municipal vehicles. Sludge-derived products should be of significant concern if the municipality can implement a robust system through integrated and collective cooperation and follow the recommendations. The study also shows that the current state of resource utilization from sludge is statistically poor due to lack of funding and rigid legislation.

The implementation of a circular economy in the water and wastewater sector faces many challenges. Key obstacles include uncertainties in almost every aspect of implementing new solutions in the industry's daily operations, the lack or limitation of continuous funding to secure new projects and innovation work, the absence of economies of scale, limited concrete cooperation and transparency among stakeholders, restricted partnerships between municipalities, established companies, start-ups, researchers, and product manufacturers in the water and wastewater sector, and very limited scope for action in legislation. Additionally, outdated regulations do not facilitate the implementation of new and innovative solutions, and there is a lack of quality assurance schemes for products that can result from sludge treatment. There is also limited incentive among politicians and investors to support innovation in the industry, and last but not least, poor communication about water and wastewater work among the community.

From the perspective of politicians, it is expected that new regulations will not be the sole solution to overcome the aforementioned barriers or the only means to accelerate a transition to a circular economy in the water and wastewater sector. An in-depth review of all data (primary and secondary) reveals that the water and wastewater sector require stronger economic incentives to deviate from its existing and often linear business approach. While the circular economy is one of the most prominent concepts for more sustainable development, where business benefits align with resource efficiency, it is considered a complex approach.

Additional minor barriers include a lack of technology, knowledge, and information. A shift to a more circular economy requires strengthening the collaboration (both vertically and horizontally) among all involved in the value chain. Circular economy practices must become a natural and integrated part of the water and wastewater sector. Clear and predictable legislation is crucial for an appropriate response. The findings clearly indicate that among various stakeholders, the state perspective has the maximum positive impact on the implementation of a circular economy in value chains.

The issue of sludge in the water and wastewater sector is highly critical as the volume will continue to increase, and as mentioned above, radical decisions and incentives are needed to manage it sustainably. Based on the statistics, it appears that the sustainability status of the water and wastewater sector is very poor, but according to industry players interviewed, it is on the right upward path. Many new government restrictions and team spirit are required from all players. Among the measures that can be used in sludge management are designing water and wastewater infrastructures for flexibility functions so that they can be easily upgraded, training and empowering stakeholders, responsible and innovative management, implementing a collaborative logistics system between producers of sludge derived products, suppliers, and users, prioritizing the use of industrial symbiosis strategies, host municipality cooperation, inter-municipal company (IKS), and municipally owned joint-stock company (AS) instead of municipal enterprise (KF), rewarding competent actors, and digitizing registration systems for all products derived from refuse to facilitate their traceability.

7.2 Theoretical and practical implications

Theoretical Implications

This research significantly contributes to the theoretical establishment of robust strategic guidelines for the implementation of a circular economy within the water and wastewater industry, as well as within the operations of existing companies in these sectors. It also advances the understanding of how to leverage opportunities from waste sectors, primarily focusing on sludge and its transformation into a profitable venture. This includes investigating how management can configure organizational structures and business models to profit from products derived from sludge as part of a circular economy strategy, whilst maintaining a competitive edge in the market. This research provides all stakeholders with an in-depth understanding of a business from a strategic management readiness perspective, and how they can tailor organizational change through the various supporting theories described in Chapter 3.9 of Part 3.

The findings can be beneficial in providing insights and guidance to various stakeholders. Firstly, municipal wastewater treatment plant management can utilize these findings to efficiently exploit sludge resources, analyze the market for potential product occurrences, consider product development directions, and make informed investment decisions. They may also find it useful when considering potential collaborations with partners and when seeking to enhance their Corporate Social Responsibility (CSR) efforts. Secondly, producers of sludge byproducts, including startups, can use these findings to establish a circular business plan for sludge logistics and its transformation into new products (e.g., biogas and biochar) or secondary materials for other needs (e.g., biogas upgrading).

Thirdly, project managers can involve all stakeholders and actors in the creation of a sludge management plan and in the calculation of the project's environmental emissions. Lastly, these findings can assist state administrators, policymakers, and authorities in designing better framework conditions, policies, legislations, and regulations that provide flexibility and room for development in handling sludge, upgrading byproducts, creating incentives for a circular economy, accelerating sustainable innovations in the sector, and job creation. This can also promote the establishment of numerous startup companies within the industry.

Practical Implications

This research project provides a comprehensive review of the possibilities for optimizing the sludge treatment process in a municipal wastewater treatment plant for the generation of biogas and biochar. The study's findings shed light on the environmental and economic benefits of biogas and biochar production, emphasizing the need of local utilization and collaboration. This study's valuable findings might serve as a road map for towns and wastewater treatment facilities looking to reduce their environmental footprint, earn cash, and promote a circular economy.

The study's findings clearly imply that the water and wastewater industry is deeply embedded in age-old practices (as determined by path dependency) and lacks specific benchmarks, offering a considerable challenge to integrating and implementing new technologies or practices resulting from novel research. This is primarily due to the strict health and environmental safety norms, as well as the necessity for a long observation period to ensure that the proposed solution does not represent a risk to the sector rather than a benefit. However, the findings also reveal that municipalities or entities that deviate from established routines achieve the best project implementation results, despite having to accept a certain degree of risk associated with investing in a technology or solution that might not easily find acceptance among customers (the public), even if it is beneficial, or that may face resistance from the regulatory system or requirements.

The significant differences in management approaches between VEAS (Asker, Baerum, and Oslo Municipality), Lindum (Drammen Municipality), and Linnes treatment plant (Lier Municipality) in the amount of sludge collected and/or processed into different products, as well as their ability to finance their projects, are prime examples. When compared to other players, the actors that are deeply invested in collaboration and innovation as a driving force can quickly deliver novel products or solutions to the market because they are in a strong position to quickly gather investment capital (loans) for their projects. Furthermore, they exhibit higher resilience and adaptability, illustrating how management tactics (strategy) are impacted by the behaviors of others and, as a result, have an impact on the sector's sustainable status. Those actors continuously engaging in innovation quickly ascend to prominence within the sector.

The study's potential impact is great, as optimizing sludge treatment for biogas and biochar production might benefit both the local and global ecosystems. The findings might help to mitigate climate change by lowering GHG emissions and boosting sustainable behaviors. Furthermore, the discovery might have important economic ramifications since biogas and biochar production could generate revenue, lowering the treatment plant's operational and maintenance expenses and dependence on the community contribution (water and wastewater charges). This might also contribute to the development of local businesses and economy, encouraging economic growth and sustainability.

In terms of policy implications, the study could guide the development of regulations and incentives to encourage the adoption of circular economy practices in the water and wastewater treatment sectors. Policies supporting the development and use of renewable energy sources (biogas), as well as the use of biochar for soil improvement, might fall under this category. Finally, the study has significant educational and awareness implications because it emphasizes the importance of sustainable and circular practices in the water and wastewater treatment sector and beyond, helping to raise awareness about the need to reduce environmental impact and promote sustainable practices in all sectors of society. The study has the potential to have substantial environmental, economic, policy, and educational implications, benefiting the promotion of sustainable practices in the water and wastewater treatment sector and beyond.

Limitations of the research

The scope and complexity of the topic area were the most significant constraints in this research. It took an extensive amount of time and effort to narrow down the research and seek out and select appropriate theories that would shed light on the problem statement. To completely confront such broad research or topics, investigators must have a multidisciplinary background and experiential knowledge, as well as pay close attention to the details essential for success. My ability to navigate through these complexities could be attributed to my professional background and expertise within the decentralized wastewater treatment sector, which allowed me to draw upon and synthesize information learned from diverse disciplines and correctly appraise the outcomes obtained.

There were moments of uncertainty, where I had to confront the challenge of deciding between relying on primary or secondary data or trusting my judgment based on my professional experience. In these cases, I needed to be selective, focusing on facts that looked more trustworthy. As mentioned in the methodology section, I attempted to preserve impartiality by ensuring that my own viewpoints and cognitive processes did not bias the process. Instead, I utilized these as a yardstick, comparing the information acquired from primary and secondary sources to my perspective and judgment.

The study does, however, highlight several limitations that should be considered. To begin, the analysis is limited to a single municipal wastewater treatment plant; hence, the findings may be extrapolated to other plants or areas with some uncertainty. Second, because the study is based on data from a particular moment in time, the results may be prone to seasonal or other forms of variations. Finally, the study is limited to the generation of biogas and biochar from sludge, with little consideration given to the possibilities and advantages of producing additional value-added products from sludge, such as nitrogen and phosphorus.

Regardless of these potential constraints and barriers, they may be mitigated through meticulous planning, stakeholder engagement, and in-depth analysis. It is feasible to discover sustainable methods for optimizing sludge treatment using an exhaustive and interdisciplinary approach, which might benefit both the water or wastewater treatment plant and the local community.

There are several other potential limitations to the study that should be carefully considered. To begin, the study appears to be constrained by data availability and quality, notably for technical and economic analyses. The accuracy and reliability of the study's conclusions are dependent on the quality and quantity of data collected. Second, the research may be limited by the local context and the unique conditions of the municipal water or wastewater treatment plant. Because various treatment facilities may have distinctive circumstances, technology, and regulations, the study's conclusions should therefore be generalizable under specific conditions. Third, the study encountered practical and logistical difficulties, particularly with regarding data collecting and stakeholder participation. This might involve concerns with access, safety, and confidentiality. Finally, the study suffered from deadlines as well as financial and resource constraints. Conducting full research that covers technical, economic, and environmental assessments is long-consuming and expensive, necessitating significant budget, effort, time, and expertise.

Despite these constraints, this research provides useful insights into the possibility of optimizing sludge treatment at a municipal water or wastewater treatment plant to produce biogas and biochar, emphasizing the relevance of local consumption and collaboration. Although the study's limits, these can be mitigated through careful design, stakeholder engagement, and resource mobilization. The potential benefits of the study, including environmental, economic, political, and educational implications, make it a worthwhile project with significant potential effects.

Provided Values

The implications of this research can be seen as laying the foundation for a cooperative or business model that can be utilized to approach the impact of a water or wastewater treatment plant on both its internal and external stakeholders.

Here are the key value propositions that were or could be identified in this research:

Product:
This research provides a roadmap for the implementation of the circular economy in the water and wastewater sector, taking advantages of resource recovery from sludge and using principles of eco-design, flexibility, and continuous innovation framework.

Customer Segments:
The target audience for this research includes water or wastewater treatment plants, manufacturers of water and wastewater treatment products, municipal water and wastewater management bodies, municipal environmental departments, farmers and agriculturalists,

environmental consultants, environmental scientists, environmental management bodies, and relevant authorities.

Value Propositions:

1. Value for Customers: This research helps in identifying cost-saving measures related to preventative actions. It allows for the increased efficiency of water and wastewater systems and provides a method to attribute value to waste (particularly sludge), ultimately fostering better collaborations within the sector.
2. Value for the Environment: This research identifies the potential for enhanced recovery and recycling processes, a reduction in the extraction of virgin substances and materials, and a decrease in greenhouse gas emissions.
3. Value for Society: The implications of this study provide opportunities for reducing water and wastwater fees, creating new startups, increasing employment, increasing tax revenue, ensuring safer workplaces and infrastructures, ensuring energy availability, and generating new knowledge.

Value Creation:

The future design and innovation adapted to sustainable technology and processes, coupled with improved business models, are the key areas of value creation.

Value Capture:

Sustainable and responsible management, production, and consumption, coupled with the formation of new networks, constitutes the principal ways of capturing value from the implementation of circular economy principles in the water and wastewater sector as proposed in this study.

7.3 Recommendations and suggestions for further work

Recommendations

Given all the arguments, I will strongly advise that all municipal water and wastewater treatment plant managers and companies in the water and wastewater sector (regardless of size) invest in innovation teams by practicing ambidexterity, allowing them to play dual roles of being observant and innovative simultaneously. This implies that companies can begin to adopt positive or reassuring results while studying other consequences by performing multiple modest pilot research projects (or niche markets) in partnership with other sector operators. The more entities that use this strategy, the better the results, and the industry will progressively move away from its ingrained practices (path dependency). This approach generates and ensures a flow of innovation while gaining a competitive advantage and quick growth.

Suggestions for Further Work

Continuing research will delve into the potential for augmenting the production of biogas and biochar derived from sludge at a municipal water or sewage treatment facility. More quantitative data will support the findings. Such research should involve optimizing the treatment process to increase the production of biogas and biochar and eavaluate their potential as renewable energy sources and soil enhancers. The study could also assess the feasibility of producing other value-added products from sludge, such as nitrogen, phosphorus, or animal feed.

Additionally, the study could investigate the potential for collaboration between various stakeholders, such as the municipality, local farmers, and producers of biogas and biochar, in the form of an industrial symbiosis pilot project. Such cooperation can provide a market for the products derived from sludge, thereby creating a circular economy where waste generated from one process is utilized as a resource in another.

Several other factors merit consideration for prospective further research. In ongoing research, particular attention should be paid to the following factors.

Technical feasibility: The integration of new sludge treatment technologies or processes may necessitate significant capital expenditures and may not be feasible in all contexts. The technical feasibility of different alternatives should be carefully evaluated, considering factors such as resource availability, existing infrastructure, and local regulations.

Economic viability: The production of biogas and biochar may not always be economically viable, particularly in contexts where energy prices are low or demand for biochar is limited. The economic viability of various scenarios should be meticulously evaluated, considering factors such as market prices, production costs, and revenue potential.

Environmental impacts: While the production of biogas and biochar can have environmental benefits, there is also a possibility that optimizing sludge treatment could have negative environmental impacts if not managed correctly. The environmental consequences of different scenarios should be carefully considered, taking into account factors such as GHG emissions, soil and water pollution, and impacts on local ecosystems and biodiversity. Hence, it is essential to conduct a Life Cycle Assessment (LCA), Life Cycle Costing (LCC), Life Cycle Inventory (LCI), and Life Cycle Impact Assessment (LCIA) for each possible product before transitioning to large-scale production.

Stakeholder engagement: The success of the study will depend on the engagement and collaboration of relevant stakeholders, including operators of water or wastewater treatment plants, local businesses, policymakers, regulators, and the broader community. Stakeholder engagement should be planned and executed meticulously to ensure all perspectives are considered and the findings of the study are communicated effectively.

Data availability: Data related to the operation of water and sewage treatment plants and sludge treatment processes might be limited, particularly in contexts where there is little regulation or monitoring. The study might necessitate the collection of new data, which could be time-consuming and costly.

To alleviate these limitations, careful planning and design of the study are essential to ensure that research questions and methodologies are appropriate for the local context and available data. Also, stakeholder engagement and the building of partnerships could help to overcome practical and logistical challenges and ensure the relevance and applicability of the study's findings. Lastly, securing sufficient funding and resources can help to ensure the quality and rigor of the study.

7.4 Final reflection

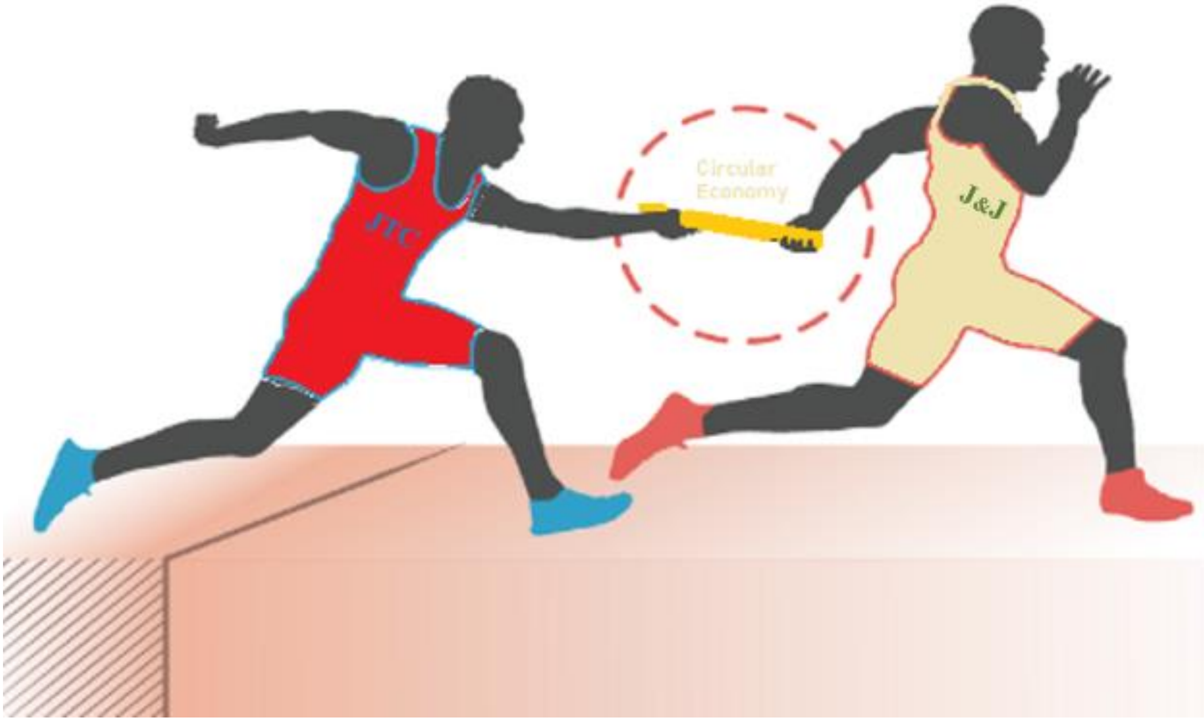


Figure 21: Circular economy research relay. Source: Kadibu, 2021

By using resources that are currently wasted, the circular economy gives us a chance to make the world more sustainable and solve environmental problems. The mission is to cross the threshold of the ecological transition door. The vision is to give everyone green incentives to get to sustainability quickly by thinking circularly. Industry players need to work together and change to take advantage of the future benefits of the circular economy practices. This will promote the 3Rs of the circular economy, which are reducing, reusing, and recycling waste. Once the threshold is crossed, the benefits will far outweigh the effort required to get there. By sustainably using resources, buying sustainably and consequently, using wisely, creating incentives for less waste, and sorting waste correctly at the source, the circular mindset will seep into everyday life and lead to conscious rest. The production and sale of biogas and biochar from wastewater sludge is a circular economy approach to finance operation and maintenance costs in the water and wastewater sectors while enhancing sustainability. By adopting circular practices in water and wastewater treatment, the production and sale of biogas and biochar will reduce waste, provide renewable source of energy, improve soil quality, and reduce water pollution. However, to fully exploit the potential of circular practices in the treatment plants, policies and regulations that support the production and use of biogas and biochar are much needed, and the potential benefits must be effectively communicated to stakeholders.

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APPENDICES

1. Information letter to the informants (in Norwegian)

2. Interview guide (in Norwegian)

Informasjonsskriv til informanter

Mitt navn er Tresor Kadibu,

Jeg er masterstudent i Vann og miljøteknikk, retning Kretsløpsteknikk, på fakultetet for realfag og teknologi ved Norges miljø- og biovitenskapelige universitet (NMBU - campus ÅS), og holder for tiden på med en masteroppgave som handler om: Sirkulær økonomi i vann- og avløpssektoren med fokus på utnyttelse av avløpsslam som kjernemateriale for produksjon av nye bærekraftige produkter til salg for å finansiere ulike prosjekter i sektoren. Jeg ønsker i den forbindelse å intervjue nøkkelpersoner (aktører) i de forskjellige leddene av kretsløpet (aktuelle sektorer), samt miljøforvaltere og eksperter.

Masteroppgavens tittel er:

Sirkulær økonomi i vann- og avløpssektoren: Muligheter for lokal produksjon og salg av biogass og biokull for å finansiere kommunalt renseanleggs drifts- og vedlikeholdskostnader og styrke bærekraften.

Formålet med forskningen er å finne ut hvilken økonomisk og miljømessig gevinst som kan hentes ved å investere i etablering av sirkulærøkonomisk renseanlegg. Den skal også vise hvilke muligheter som finnes for kommunalt renseanlegg/ landbruker/ leverandører/ distributører av bio-baserte produkter (biogass og biokull) for å imøtekomme visjonen til sirkulær økonomi i vannbransjen, samt hvordan aktuelle aktører kan bidra til å oppnå FNs bærekraftsmål. Denne kunnskapen kan også bidra til å forbedre dagens forbruk av fossil energi og jordforbedringsmiddel, redusere renseanlegg miljøkostnad, og øke vannbransjens bærekraftsprofil gjennom endringer i arbeidsprosesser og livssyklusen til avløpsslam.

Intervjuet blir tatt opp hvis informanten godtar og godkjenner dette. All informasjon som kommer frem under intervjuet skal konfidensialiseres, og opptaket vil bli slettet umiddelbart etter at jeg har skrevet den informasjonen jeg trenger. All informasjon vil bli anonymisert innen forskningens slutt 30.09.2023. Hvis ikke godkjent av informanten, vil sistnevnte ikke kunne bli gjenkjent i den ferdige masteroppgaven.

Det er frivillig å delta på dette intervjuet og mulig å isteden svare på spørsmålene via e-post, og dersom man takker ja kan man når som helst trekke seg fra intervjuet, og helt frem til forskningens slutt trekke seg fra undersøkelsen. Prosjektet er innmeldt til Personvernombudet for forskning (NSD) via NMBU.

Dersom du senere har spørsmål i forbindelse med masteroppgaven, kan du kontakte meg på e-post: tresorkadibu@gmail.com eller telefon: +47 48179010. Min veileder for denne masteroppgaven, førsteamanuensis Nazli Pelin Kocatürk Schumacher, kan kontaktes på e-post: pelin.kocaturk.schumacher@nmbu.no dersom det skulle være ønskelig.

Med hilsen

Tresor Kadibu

Samtykkeerklæring

Jeg har mottatt og forstått informasjon om forskningen:
Sirkulær økonomi i vann- og avløpssektoren: Lokal produksjon og salg av biogass og biokull for å finansiere drifts- og vedlikeholdskostnader ved kommunale renseanlegg og styrke bærekraften

Jeg samtykker til:

☐ å delta i intervjuet ☐ å ikke delta på intervjuet, men svare på noen av spørsmålene via e-post

☐ at det gjøres opptak av ☐ intervjuet at det ikke gjøres opptak av intervjuet

☐ at mitt navn ikke blir ☐ anonymisert at mitt navn bli anonymisert

Signert av prosjektdeltaker, dato: ……/……/2023

Intervjuguide (1)

Introduksjon

Jeg vil gjerne takke deg for at du tar deg tid til å delta i dette intervjuet.

Jeg heter …… og arbeider med en masteroppgave på temaet: *Sirkulær økonomi i vann- og avløpssektoren: Muligheter for lokal produksjon og salg av biogass og biokull for å finansiere kommunalt renseanleggs drifts- og vedlikeholdskostnader og styrke bærekraften*.

Formålet med intervjuet er å samle inn informasjon som kan hjelpe meg å belyse min forskningsproblemstilling.

Bakgrunnsinformasjon

Kan du fortelle litt om din bakgrunn (utdanning og erfaring) og din nåværende rolle i Lier VVA KF

Renseanlegg og bærekraft

Hva betyr bærekraft for deg og hvordan ser du på bærekraft i forhold til Lier VVA's drift?

Biogass og biokull produksjon

Hvordan ser du på muligheten for lokal produksjon av biogass og biokull fra avløpslammet?

Har dere vurdert biogass og biokull produksjon som en del av en sirkulær økonomi ved Lier VVA? Hvorfor/hvorfor ikke?

Hvordan tror du lokal produksjon og salg av biogass og biokull kan påvirke drifts- og vedlikeholdskostnadene ved norske kommunale renseanlegg, og hvordan kan lokal produksjon brukes til å fremme praksis for sirkulær økonomi?

Samarbeid med Landbrukskontoret

Hvordan kan kommunale styringssystemer og rammebetingelser påvirke etablering av et internt samarbeid i en forretningsmodell mellom Lier VVA KF og Landbrukskontoret, hvor Lier VVA KF produserer biokull, Landbrukskontoret sørger for å promotere produktet samt skape incentiver for å øke salget, og Tilsynet sørger for tilskudd av spredt avløpsslam som råstoff samt kartlegger spredning av landbruksforurensning?

Har du noe forslag til annen forretningsmodell?

Symbiosemodell i kommunen

Hva synes du om en symbiosemodell i kommunen hvor biogass (oppgradert biomethane eller hydrogen eller energi) produsert av Lier VVA skal prioriteres og kjøpes av alle virksomheter i kommunen, med tanke på bruk til kjøretøy, oppvarming, etc.?

Utfordringer og innovasjon

Hva er din mening om vann- og avløpsgebyrer og selvkostmodellen?

Hvilke utfordringer møter dere i dag for å pådrive innovasjon i deres prosjekter og virksomhet?

Hvordan har dere håndtert disse utfordringene?

Kommunale rammebetingelser

Hva er din mening rundt kommunale rammebetingelser og forvaltning av prosjekter?

Hvordan kan bærekraftpolitikk og forskrifter forbedres for å støtte produksjon og bruk av biogass og biokull fra avløpsslam i den norske vann- og avløpssektoren, og oppmuntre til adopsjon av praksis for sirkulær økonomi?

Ressursutnyttelse

Utover biogass og biokull, hvilke andre ressurser mener du at dere sløser i dag, og som kan utnyttes til å skape mer inntekt i virksomheten deres?

Avslutning

Har du noe annet du vil legge til som du mener er relevant for denne forskningen?

Takk for at du deltok i intervjuet. Din innsikt er veldig verdifull for min forskning.

Intervjuguide (2)

Introduksjon

Jeg vil gjerne takke deg for at du tar deg tid til å delta i dette intervjuet.

Jeg heter …… og arbeider med en masteroppgave på temaet: *Sirkulær økonomi i vann- og avløpssektoren: Muligheter for lokal produksjon og salg av biogass og biokull for å finansiere kommunalt renseanleggs drifts- og vedlikeholdskostnader og styrke bærekraften*.

Formålet med intervjuet er å samle inn informasjon som kan hjelpe meg å belyse min forskningsproblemstilling.

Bakgrunnsinformasjon

Kan du fortelle litt om din bakgrunn (utdanning og erfaring) og rolle innenfor spredtavløp forvaltning i kommune?

Renseanlegg og bærekraft

Hva betyr bærekraft for deg og hvordan ser du på bærekraft i forhold til vertskommuneavtalen?

Hvordan kan vertskommuneavtalen dere har i dag med de seks andre kommunene om spredt avløp utnyttes for å bidra til mer bærekraftige løsninger for spredt avløp og prosjekter i de ulike kommunene?

Biogass og biokull produksjon

Hvordan ser du på muligheten for utnyttelse av ressurser fra avløpslammet?

Hvordan ser du på potensialet for lokal produksjon av biogass og biokull som et sirkulært økonomisk tiltak i et norsk vann- og avløpsrenseanlegg?

Hvordan tror du salg av lokal produsert biogass og biokull kan påvirke drifts- og vedlikeholdskostnadene ved norske kommunale renseanlegg, og hvordan kan lokal produksjon brukes til å fremme praksis for sirkulær økonomi?

Hva er etter din mening de største utfordringene når det gjelder å iverksette biogass- og biokullproduksjon fra avløpsslam i et norsk kommunalt renseanlegg?

Ser du på muligheten for å etablere en foreningsmodell for produksjon av biogass og biokull fra spredt avløpsslam? Hva kan være fordeler og hindringer? Har du forslag til andre forretningsmodeller som kan være aktuelle fra vertskommuneavtalen dere har i dag?

Samarbeid med Landbrukskontoret

Hvordan kan kommunale styringssystemer og rammebetingelser påvirke etablering av et internt samarbeid i en forretningsmodell mellom Lier VVA KF og Landbrukskontoret, hvor Lier VVA KF produserer biokull, Landbrukskontoret sørger for å promotere produktet samt skape incentiver for å øke salget, og Tilsynet sørger for tilskudd av spredt avløpsslam som råstoff samt kartlegger spredning av landbruksforurensning?

Har du noe forslag til annen forretningsmodell?

Symbiosemodell i kommunen

Hva synes du om en symbiosemodell i kommunen hvor biogass (oppgradert biomethane eller hydrogen eller energi) produsert av Lier VVA KF skal prioriteres og kjøpes av alle virksomheter i kommunen, med tanke på bruk til kjøretøy, oppvarming, etc.?

Utfordringer og innovasjon

Hva er din mening om vann- og avløpsgebyrer og selvkostmodellen?

Hvilke utfordringer møter dere i dag for å pådrive innovasjon i deres prosjekter og virksomhet?

Hvordan har dere håndtert disse utfordringene?

Kommunale rammebetingelser

Hva er din mening om kommunale rammebetingelser og styring av prosjekter i Lier kommune?

Hvordan kan bærekraftpolitikk og forskrifter forbedres for å støtte produksjon og bruk av biogass og biokull fra avløpsslam i den norske vann- og avløpssektoren, og oppmuntre til adopsjon av praksis for sirkulær økonomi?

Ressursutnyttelse

Utover biogass og biokull, hvilke andre ressurser mener du at dere sløser i dag, og som kan utnyttes til å skape mer inntekt i virksomheten deres?

Avslutning

Har du noen avsluttende kommentarer eller tanker du ønsker å dele om temaet for forskningen?

Takk for at du deltok i intervjuet. Din innsikt er veldig verdifull for min forskning.

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