TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

CO-DIGESTION OF SEWAGE SLUDGE AND BIOWASTE FOR BIOGAS PRODUCTION, GHG AVOIDED EMISSIONS AND PROFITABLE CARBON CREDIT DEVELOPMENT

REOVEESETTE JA BIOJÄÄTMETE KOOSKÄÄRITAMINE BIOGAASI TOOTMISEKS, KASVUHOONEGAASIDE HEITKOGUSTE VÄHENDAMISEKS NING TULUSAMA SÜSINIKUKREDIIDI ARENDAMISEKS

MASTER THESIS

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Tallinn 2023

(*On the reverse side of title page*)

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Department of Civil Engineering and Architecture

THESIS TASK

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main speciality: Environmental Engineering and Management
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Thesis topic:
(in English) *Co-digestion of sewage sludge and biowaste for biogas production, GHG avoided emissions and profitable carbon credit development*
(in Estonian) reoveesette ja biojäätmete kooskääritamine biogaasi tootmiseks, kasvuhoonegaaside heitkoguste vähendamiseks ning tulusama süsinikukrediidi arendamiseks

Thesis main objectives:

1. To calculate the environmental footprint for co-digestion of sewage sludge and biowaste with biogas production for Narva city
2. To calculate the substitution of GHG emissions from the background system for electricity production with the emissions produced from the use of biogas as an energy source.
3. To develop carbon credits as a profitable source

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Problem formulation and thesis objective setting	31.01.2023
2.	Literature review and methodology development	31.03.2023
3.	Result analysis and drawing conclusion	20.05.2023

Language: English **Deadline for submission of thesis:** 29.05.2023

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PREFACE

The thesis topic was initiated by the supervisor by consulting with the student and seeking her consent to work on this thesis for 6 months. The major thesis work was done in Tallinn, Estonia. The supervisor and co-supervisor assisted the author in collecting data, searching relevant literature, and formulating the thesis work. I wish to express my gratitude to my supervisor and co-supervisor for being patient, supportive, and understanding during the thesis work.

The present study was focused on evaluating the possibility to use the combination of sewage sludge and biowaste as feedstock in the anaerobic digestion process and analyse the environmental impacts caused by the digestion process. The most important output of the co-digestion process is biogas which is a renewable source of energy and can cogenerate heat and electricity. The generated electricity can replace the use of fossil fuel-based electricity consumption thus generating opportunities for GHG emission reduction. This emission reduction can lead to generating carbon offset projects and profitable carbon credits. The study further focused on generating carbon credits from the avoided emission resulting from the use of electricity from biogas.

Keywords: co-digestion, sewage sludge, biowaste, carbon credit, master thesis

List of abbreviations and symbols

AcoD	Anaerobic co-digestion
AD	Anaerobic Digestion
CDM	Clean Development Mechanism
CH_4	Methane
CO_2	Carbon dioxide
COD	Chemical Oxygen Demand
EU	European Union
GHG	Greenhouse Gas
VCM	Voluntary Carbon Market
VCO	Voluntary Carbon Offset
VS	Volatile Solids

1. INTRODUCTION

Over the past few years, there has been a growing focus on renewable energy resources, and biogas technology has emerged as a promising solution for energy needs while also addressing environmental concerns [1]. Anaerobic digestion (AD) is the favored method for transforming organic-rich substances into environmentally friendly and sustainable products, i.e., biogas. Biogas generation can be achieved using agricultural residues, municipal/industrial biowastes, and sustainable biomass, with a particular emphasis on utilizing locally accessible materials. [2]

In Estonia, biowaste constituted a quarter (122,000 tonnes) of municipal waste generated in 2019. Less than half of the total biowaste generated (51,000 tonnes) was collected through source-separated collections, while the remaining fraction was collected as mixed municipal waste. It was estimated that nearly one-third of the mixed municipal waste collections consisted of food waste. However, only a fraction of separately collected biowaste, representing less than a third (13,858 tonnes) of the separate collections, underwent recycling into certified compost or biogas. Unfortunately, the utilization of biowaste for biogas production remains minimal in Estonia. Currently, Estonia has at least five operational anaerobic digestion (AD) facilities, with four of them exclusively accepting agricultural waste such as slurry, manure, and silage residues. An estimation suggests that by substituting 10% of the input to these five AD plants with the food waste fraction obtained from municipal waste (similar to practices in Nordic countries), the capacity required for treating the separately collected biowaste fraction could be met. This approach not only has the potential to significantly increase biogas production but also generate additional income through energy revenues. Moreover, the increased production of biogas contributes to the reduction of greenhouse gas emissions by replacing certain fossil fuels. [3]

Biowaste is an attractive feedstock for anaerobic digestion since it contains carbohydrates, proteins, and lipids that can be easily converted into biogas under anaerobic conditions [4]. However, the process may be hindered by nutrient imbalances, accumulation of volatile fatty acids (VFAs), and inhibition by high levels of ammonia or salt content when only biowaste is used as feedstock [5]. Co-digesting biowaste with sewage sludge (SS) has been found to have a synergistic effect, resulting in increased organic loading rate (OLR), biogas production, and system stability. This is because the combination of the two substrates overcomes nutrient imbalances, utilizes the diverse bacterial population in each substrate, and dilutes potential inhibitory compounds. [6-11] Overall, anaerobic digestion technology offers a promising pathway for sustainable energy generation from organic waste. To achieve cost-effectiveness and maximize greenhouse gas (GHG) savings, the process heavily relies on utilizing waste and by-products [2]. One crucial aspect in this field is the augmentation of the flow of unconsumed food and food residues, which can be effectively recycled through anaerobic digestion (AD). AD not only facilitates methane production but also allows for the return of nutrients to the soil through the digestate. [12] This nutrient recycling, especially nitrogen, and phosphorus, holds significant advantages for organic farming practices by reducing the reliance on inorganic fertilizers [2]. Furthermore, AD has the potential to minimize odors [13] and mitigate potential risks associated with pathogens [14].

Given this context, the author of this study intended to calculate the environmental footprint for the co-digestion of sewage sludge and biowaste from a holistic view with the life cycle assessment (LCA) tool. On one hand, the result of this study could provide information on whether the co-digestion process will bring about environmental benefits, i.e., increase in methane production, reduction in GHG emissions, eutrophication and freshwater toxicity potential, availability of nitrogen and phosphorous for organic farming to reduce the use inorganic fertilizers, etc. On the other hand, it will help to reduce the carbon footprint of the process by calculating the substitution of the electricity produced from the background system for electricity produced from the biogas that is generated from the anaerobic co-digestion process. This finding will further help the author to develop a profitable carbon credit for the avoided emission.

The author of the paper has set the following objectives:

1. To calculate the environmental footprint for co-digestion of sewage sludge and biowaste with biogas production for Narva city
2. To calculate the substitution of GHG emissions from the background system for electricity production with the emissions produced from the use of biogas as an energy source.
3. To develop carbon credits as a profitable source

2. THEORETICAL BACKGROUND

2.1 Anaerobic digestion

Organic material found in solid waste can be converted into bioenergy and bioproducts using one of two different techniques. One category of techniques is physicochemical, which also includes pyrolysis, gasification, and hydrothermal carbonization. The second category is biological, which includes anaerobic digestion, composting, fermentation, and transesterification. [15,16]

The process of anaerobic digestion (AD) is a well-established method of converting biowaste, where microorganisms are employed to transform organic matter into biogas and bioproducts. When compared to alternative conversion techniques, anaerobic digestion is an economical approach [17]. The process of anaerobic digestion (AD) involves the natural breakdown of waste into simpler substances by strong and mixed microbiomes in the absence of oxygen. Synergistic interaction among a group of microorganisms allows them to break down resistant lignocellulosic biomass into their core structures. When lignocellulosic biowaste is processed using this method, organic matter, and fuel biogas are typically produced. [18]

Anaerobic digestion waste treatment offers numerous benefits beyond waste management. One such advantage is the ability to introduce alternative energy sources, which helps promote environmental sustainability by reducing the need for fossil fuels and instead using biogas for energy generation [19,20]. Further advantages of anaerobic digestion for the environment include decreased greenhouse gas emissions, better air quality, better disease prevention, less sludge generation, and reduced odors [21]. Despite these advantages, anaerobic digestion encounters several problems, such as inadequate biogas production, digester foaming, low/high organic loading rates, digestate stability, and a lack of understanding of the reaction mechanisms [22-25].

Anaerobic digestion includes benefits like methane production, a decrease in organic matter, and the ability to use leftover sludge as a soil conditioner, but it also has significant downsides. High capital expenditures, the potential build-up of metals and pollutants in the sludge, and the requirement for professional staff for design, building, operation, and maintenance are a few of these. Maintaining ideal reaction conditions can also be difficult and complex. [26-27]

2.1.1 Phases of anaerobic digestion

The anaerobic digestion process relies on microorganisms to break down organic matter into simpler compounds such as amino acids, fatty acids, sugars, and glycerol, without oxygen. The process occurs in four stages, namely hydrolysis, acidogenesis, acetogenesis, and methanogenesis, and requires a comprehensive understanding of the biological and chemical processes involved to optimize its effectiveness. Microorganisms present in each stage work together to facilitate the degradation of raw materials, leading to the formation of a gas mixture with methane as the primary component and a decomposed material called digestate. [27]

In the hydrolysis stage of anaerobic digestion, insoluble organic compounds (e.g. cellulose – ($C_6H_{10}O_5$)n) are transformed into soluble ones (e.g., glucose - $C_6H_{12}O_6$), which are then utilized by bacterial cells. This process is considered to be slow and can impede the digestion process, especially when solid waste is employed as the source material. During this stage, substances like cellulose, proteins, and fats are disintegrated into smaller, water-soluble fragments by the exoenzymes of certain bacteria, which accomplish this by breaking down the covalent bonds using water. [26]

In the acidogenic phase of anaerobic digestion, the monomers produced during the hydrolysis stage are utilized by various facultative and obligatorily anaerobic bacteria, which break them down further into short-chain organic acids, alcohols, hydrogen, and carbon dioxide [28, 29].

Bacteria in the acetogenic phase use the products produced in the acidogenic phase as their substrate. Acetogenic reactions require energy input and are only possible with low levels of hydrogen. These bacteria produce hydrogen as a byproduct. The production of acetate from the oxidation of long-chain fatty acids is only possible under low hydrogen pressure. The acetogenic phase slows down the degradation rate in the final stage. The activity of the acetogenic bacteria can be determined by analysing the quantity and composition of the biogas produced. [28, 29]

The final stage of anaerobic digestion is the methanogenic phase where methane formation occurs in strictly anaerobic conditions by the microorganism methanogenic archaea. In this stage, hydrogen and acetic acid formed by acid producers are converted into methane and carbon dioxide, which are the main components of biogas. This reaction is exergonic. However, not all methanogenic species can degrade all substrates as described in their microorganisms. [28, 29]

Methane-producing archaea are critical for anaerobic digestion, as they have a slow growth rate and are highly sensitive to environmental changes. These microorganisms can only consume and digest the simplest of substrates. Methane-producing archaea fall into two categories: acetotrophic and hydrogenotrophic. The former uses decarboxylation of acetate to generate CH_4, which accounts for roughly 70% of CH_4 production, while the latter utilizes the reduction of H_2/CO_2. Methanogenesis has six main metabolic pathways, with each pathway transforming a unique substrate into CH_4. The key substrates utilized in this step include acetic acid (CH_3COOH), methanoic acid ($HCOOH$), carbon dioxide (CO_2), dimethyl sulfate ($(CH_3)_2SO_4$), methanol (CH_3OH), and methylamine (CH_3NH_2). [27]

2.1.2 Factors affecting biogas yield from anaerobic digestion

The illustration in Figure 1 depicts the various factors that are associated with biogas yield. These factors play a crucial role in determining the efficacy of biogas yield from the anaerobic digester process [30].

Temperature

The temperature maintained inside the digester primarily determines the fermentation time of the process. This temperature has three different conditions: thermophilic, mesophilic, and psychrophilic. The preferable conditions for anaerobic bacteria are thermophilic and mesophilic. The optimal temperature regulates the activity of the microbial intracellular enzyme, which impacts the fermentation and metabolic activity of the process. Microbial consortia play a crucial role in breaking down complex biopolymers found in the organic fraction of feedstock during anaerobic digestion, producing methane and other fermentation products. Each class of microbial interaction is vital in shaping a degradative consortium, with mutualistic interactions being the foundation for all four stages of anaerobic digestion. These interactions are required to achieve complete degradation of the substrate into gaseous and soluble end products, influencing the anaerobic digestion process. [31, 32]

Chemical Oxygen Demand (COD) represents the total amount of oxygen required to oxidize all organic compounds in a digester, whether they are soluble or insoluble. Seasonal variations can cause a decrease in temperature, leading to lower solute chemical oxygen demand and less accumulation of fatty acids. Introducing bacteria or microorganisms that break down organic compounds is a fundamental technique used to handle lower saluted chemical oxygen demand. Another way to address this issue is by adding coagulants and flocculants, although this can result in high recurring costs. The thermophilic condition (55°C) is advantageous as it leads to better and faster biogas yield. However, the downside is that this condition requires a higher amount of energy to heat the digesters. [33-34]

pH

The pH level is a crucial factor that can impact microbial growth during fermentation. To ensure optimal conditions for anaerobic digestion, the pH range of the digester should be maintained between 6.8 and 7.2. The pH level of the digester can be affected by the presence of carbon dioxide and volatile fatty acids, which is why the concentration of acetic acid and volatile fatty acid should be kept below 2000 mg/L for proper anaerobic fermentation. [35] The biogas production efficiency is highest when the pH of the digester is around 7 [36]. However, if the pH level is too high, it can lead to an imbalance in the ammonia-ammonium ratio and affect methanation. An increase in the concentration of cations can also have a negative impact on anaerobic digestion due to osmotic pressure [37]. The production and concentration of acid inside the digester can reduce the biogas yield [38]. It has been observed that when ammonium or ammonia is used as a buffer, the pH level of the digester can rise to around 10 [39].

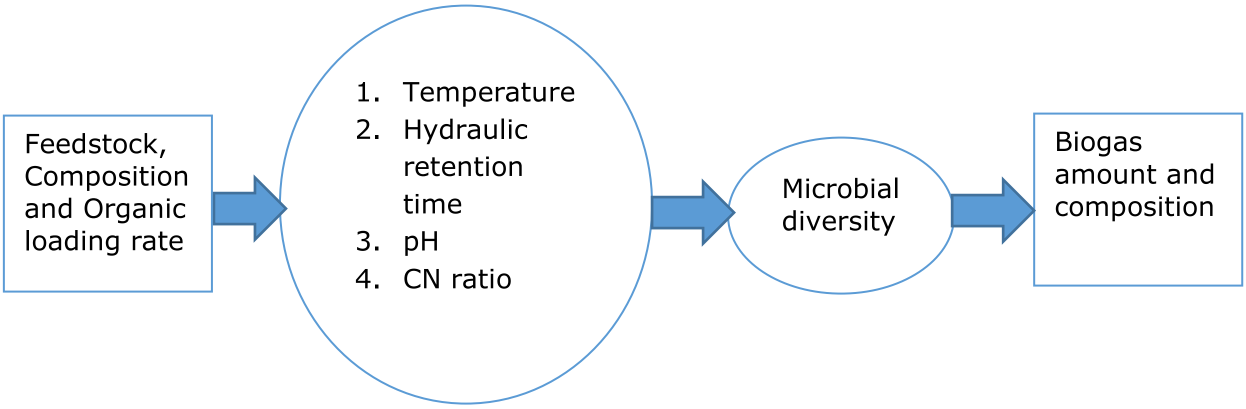

Figure 1 Various factors that are associated with biogas yield [30]

Organic loading rate

The efficiency of biogas production depends on the organic loading rate, which is determined by the chemical properties of the feedstock [40]. The biogas yield will be higher when the loading rate is lower, but the rate is decided by the size of the plant. Bio waste is composed of carbohydrates, proteins, lipids, and inorganic compounds, and its composition varies by type [40]. Liquid, hazardous, restricted, and general solid wastes are classifications of bio waste, and most have high moisture content, low pH, and high solubility. Increasing the loading rate will improve efficiency, but it will also affect methanogenesis bacteria [41]. Methane-forming bacteria will be adversely affected by an OLR of above 1.5 kg/m^3 of fresh feedstock. Increasing the substrate concentration with proper OLR will lead to higher microbial activity. The hydraulic retention time of the biogas plant depends on the type of feedstock [42].

CN ratio

The carbon-nitrogen ratio and choice of feedstock are the main factors that influence the yield of a biogas plant. The pH level of the slurry is also impacted by the carbon-nitrogen ratio, with a higher carbon content resulting in lower pH and increased carbon dioxide formation, while higher nitrogen content leads to the production of ammonia gas and a higher pH. This, in turn, affects the microorganisms involved in the process. [43] The CN ratio is crucial for anaerobic digestion, and finding the ideal sludge recirculation requires testing various feedstock mixtures to balance the C/N ratio and maximize methane production. While studies suggest that the optimal C/N ratios for methane fermentation range from 25 to 30, operational conditions such as temperature can affect carbon and nitrogen depletion and cause inhibitory effects. For example, increasing temperature from mesophilic to thermophilic conditions may result in ammonia inhibition. However, increasing the C/N ratio of mixed feedstock to an appropriate level can help reduce or avoid this type of inhibition. [44]

Particle size

The size of the feedstock particles plays a significant role in biogas production, with larger amounts of feedstock causing digester clogging. Smaller particle sizes lead to increased microbial activity, which in turn enhances biogas production. Studies show that methane yield is highest when the feedstock is ground to a size of 0.088 mm, while a particle size of 25 μm results in a higher methane yield due to the larger surface area of exposed microbes [45][46]. To fractionate the particle size, a vibratory sieve shaker with multiple sieves of different sizes and an amplitude of 30% for 10 minutes can be used [47].

2.1.3 Anaerobic digestion of sewage sludge and biogas production

Sludge stabilization is commonly achieved through anaerobic digestion (AD), which offers a sustainable waste management solution by producing renewable energy, recycling nutrients, and reducing volatile solids (VS) [48]. Technologies that can enhance biogas production from sludge include co-digestion with other organic wastes, such as municipal, industrial, and agricultural wastes [49]; co-digestion with food and fruit-vegetable waste [50]; and digestion with a serial configuration [48]. However, upgrading biogas remains a significant challenge in this field.

Sludge digesters produce biogas, which is a gaseous combination of methane (55-65%) and carbon dioxide (35-45%), with minor quantities of hydrogen sulfide and ammonia. There may also be traces of hydrogen, nitrogen, carbon monoxide, halogenated or saturated hydrocarbons, and oxygen present in the biogas. The gas mixture is typically saturated with water vapor and can contain particulate material as well as organic compounds that have silicon (siloxanes). [51]

Anaerobic conversion can be applied to the sludge of municipal wastewater treatment plants and can convert a specific load of chemical oxygen demand (COD) ranging from 13-16 kg COD per inhabitant per year. COD can be directly transformed into methane, which has a conversion rate of 0.35 Nm^3 CH_4/kg COD, and then into thermal energy which has a conversion rate of 10 kW h/m^3 CH_4. With the assumption of an electrical efficiency of 35% and a total efficiency of 90% for the combined heat and power (CHP) equipment, it is estimated that 25-31 kW h of thermal energy and 16-20 kW h of electrical energy can be produced annually per capita from sludge. [52] The energy capacity of biogas, or its calorific value, is dependent on the concentration of methane present. Biogas with 60% methane concentration can generate a total of 5-7.5 kW h or 1.5-3 kW h of electrical energy per cubic meter, which is equivalent to an average of 6 kW h/m^3 or 21.6 MJ/m^3. However, the actual values may be lower, ranging from 1.3 to 2.3. [53]

With some conditioning, biogas's methane component can replace natural gas [54]. Biogas must be enriched with methane and have its carbon dioxide, sediment, water, and foam content removed before it can be compressed and injected into the electric energy grid as a heat and energy source at the same quality as natural gas [54]. The enriched biogas, with increased methane concentration, is referred to as biomethane or "green gas" [55]. Many countries and businesses are currently utilizing this approach.

Biogas can also be upgraded into compressed natural gas (CNG) or liquefied natural gas (LNG) to be utilized as fuels for vehicles [56].

2.2 Biowaste management

Biowaste is composed of biomass and its byproducts, including various organic compounds. These byproducts comprise carbohydrates, lipids, and other useful compounds that can be transformed into bioproducts and bioenergy. The classification of biowaste and its conversion processes are determined by the origin and properties of the valuable compounds. Proper management of biowaste is critical for reducing environmental pollution and maintaining ecological standards. Biowaste is categorized into different types based on its origin, and the impact of biowaste on the ecosystem is illustrated in Figure 2. [57]

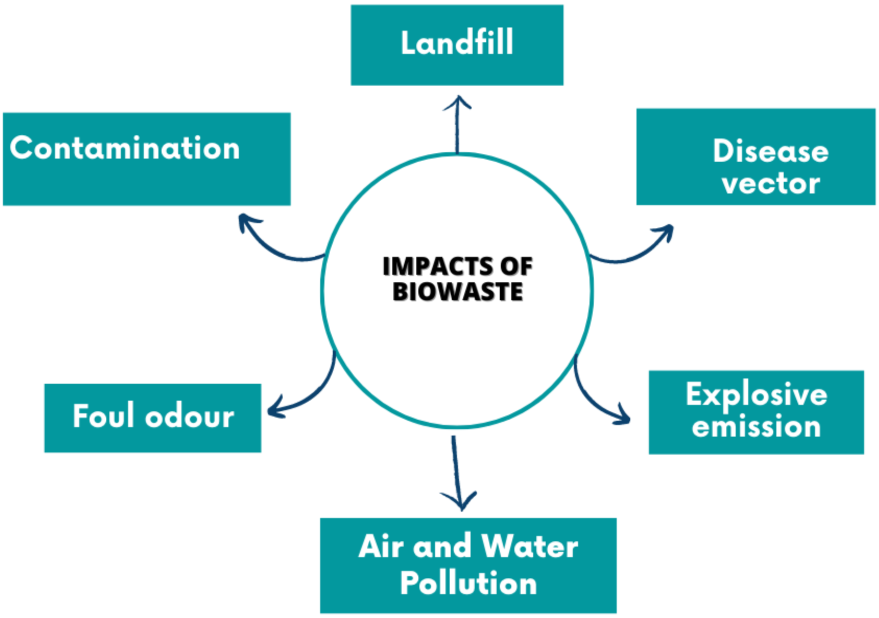

Figure 2 Impacts of biowaste [57]

The potential of bio-waste as a resource for energy production and valuable product recycling is promising, but it is not without challenges and limitations. Challenges such as accessibility, economic sustainability, and large-scale conversion processes hinder its potential. Factors like biowaste collection and transportation, land fill fees, and operation methods can negatively affect profitability and expansion. Additionally, the complexity and variety of bio-waste may require non-economic separation and purification techniques, and introducing new technology can be costly. To ensure high-quality biodegradable waste recycling, proper source-based separation of biowaste is necessary, but this step can be complicated prior to the conversion process. [57]

The issue of cluttered biowaste distribution can be addressed by sourcing the feedstock for conversion close to its generation. This could help manage solid garbage by reducing the amount of waste that ends up in landfills or illegal dumps while creating value-added products from biowaste [58, 59]. However, the product recovery process from biomass has its own set of challenges and drawbacks. The compost produced during anaerobic digestion of biowaste can contain hazardous elements like heavy metals, pathogens, organic pollutants, and impurities, which can negatively affect plant metabolism, human health, and soil contamination. Therefore, it's crucial to ensure the reliability of anaerobic digestate to prevent adverse effects. Frequent application of anaerobic digestate can lead to the accumulation of heavy metals, antibiotic residues, and persistent organic pollutants (POPs) in soil, which raises concerns about its assimilation into the food chain and environment. [60]

2.2.1 Types of biowaste

The classification of biowaste depends on its nature, with three types being solid, liquid, and microbiological. Solid biowaste includes discarded plant matter such as food, husks, and municipal solid waste. Further classification of solid biowaste can be done based on its source, which can be domestic, commercial, or industrial. Bioprocessing industries generate liquid biowaste that contains organic compounds that can be converted into biochemical or bioenergy. Lastly, microbiological waste comprises disposable microbe cultures, like residual algal biomass, that have high levels of organic matter and can be used as substrates for biohydrogen production. [61, 62]

For anaerobic digestion, food waste is a useful and promising feedstock as it produces more methane than other types of waste [63]. It is crucial to separate food waste at the source, such as in restaurants and canteens, as it may contain plastics, cardboard, and paper cups. The initial screening phase is crucial to ensure proper anaerobic digestion. The composition of food waste is variable and must be regularly analysed as it can include vegetables, uneaten food, spoiled food, and uneaten meat. The characteristics of food waste can differ greatly depending on the source. The nutrient content of the food waste is critical in determining the required nutrients for successful anaerobic digestion. [64]

2.2.2 Sources of biowaste

Valuable resources, such as lignocellulose, carbohydrates, and lipids, can be obtained from biowaste derived from biomass, which includes forest biowastes, residual algal biomass, and food industry waste. Forest-based biowaste is created during plantation thinning, road clearing, and wood processing. A significant portion of the waste produced during the manufacture of wood furniture, about 45%, can be transformed into a bioenergy resource. [65] For the production of cellulose and biofuel, feedstock with a reduced lignin concentration is preferred [66, 67]. Meat processing, breweries, confectioneries, and oil manufacturing are some of the food industry sectors that generate both liquid and solid residues. Valuable resources, such as sugar, organic matter, and starch, are present in the liquid wastage produced during food processing [68]. Waste oil disposal leads to environmental pollution during oil processing. Biorefinery-based concepts can convert food biowaste into useful products, such as biochemical and biofuels. Carotenoids, pectins, biohydrogen, biodiesel, polyhydroxyalkanoates, biogas, and polyphenols are some of the bioproducts that can be produced from food waste [69].

Biowaste is generated by various industries, and the paper and pulp industry is one of the major contributors, producing solid waste during deinking, pulping, and treatment processes. This waste contains a high amount of organic matter and can pose a threat to the environment if not managed properly. However, anaerobic digestion or other processes can convert this waste into energy [70].

Livestock waste, which includes feathers, bones, meat, skin, and animal feed, is another major contributor to biowaste. As it decomposes, it releases methane, a harmful gas that poses a significant threat to the environment. To combat this, animal waste has been converted into biofuel, with around 25% of solid waste and 10-15% of liquid waste being generated from livestock industries. The quality of animal waste depends on various factors such as waste digestibility, animal species, and age. [71, 72]. Indigenous microbes found in animal biowaste can also be used to aid in waste-to-energy conversion processes [73].

Municipal solid waste (MSW) is another major contributor, accounting for about 20% of total solid waste. This waste includes garbage, residential, and commercial waste and usually doubles annually, affecting public health and the environment. Many nations have focused on using effective treatment strategies to manage MSW, which contains a large proportion of organic material. [74, 75, 76]. In addition, many agro-industrial and biowastes are being converted into bioproducts through integrated biorefineries. For example, biowaste from fish processing is being used to produce nutraceuticals, pharmaceuticals, biofuels, and chemicals [77]

2.2.3 Anaerobic digestion of biowaste and biogas production

Biowaste is a term used to refer to a range of waste materials that include Municipal Solid Waste (MSW), household waste, sewage, food, forest, and other agricultural residues. Implementing a circular economy by recovering resources from these wastes is important for meeting environmental and economic needs. [78] Biowaste can be divided into two categories based on its degradability nature: readily biodegradable and recalcitrant degradable. Useful compounds present in biowaste can be converted into useful products. [79, 80] The conversion of recalcitrant biowaste into useful substances such as syngas, pyrogas, biochar, and biofuel requires complex processes like pyrolysis, hydrothermal carbonization, and transesterification [81]. Solid biowaste typically contains a protein content of 3–22% and sugar content ranging from 35–65%. Waste biomass has become an increasingly popular renewable feedstock for producing value-added chemicals and fuels. [82, 83, 84].

Numerous studies have been reported in the literature regarding the use of biowastes for energy production since they contain organic matter that can be effectively converted to energy. Among these studies, Morale-Polo et al. [85] successfully generated energy from fresh produce wastes, while Charis et al. [86] and Ferrase et al. [87] showed that biomass can be transformed into biochar, which can be utilized as a precursor for bioenergy production. Anaerobic digestion (AD) is a technique that has received much attention due to its ability to treat waste, thereby improving environmental quality, and simultaneously producing sustainable energy. This is in contrast to energy-intensive processes like thermochemical conversion [87], hydrothermal gasification [88], and catalytic pyrolysis [89]. AD is a process that involves the methanogenic degradation of organic matter in the absence of oxygen, facilitated by a diverse consortium of anaerobic microbes, resulting in the production of biogas [90]. AD has been successfully implemented in various biowaste effluents, including municipal sludge, animal manure, industrial sludge, and agricultural waste [90]. This approach offers a more environmentally friendly solution to waste disposal than landfills, incineration, or discharge [91].

In their study, Acosta et al. [92] utilized anaerobic digestion to convert cocoa residues into biogas and methane, employing both wet and dry AD processes which vary in their total solid material content. The results showed that the dry AD process outperformed the wet AD process in terms of several factors, including lower wastewater generation and reduced input energy requirements. Due to the stable reactive conditions and higher biogas and methane yields, the dry AD process was found to be the preferable option for energy production from cocoa residues. [92]

In Kenya, research has been conducted to explore the potential of maize, barley, cotton, tea, and sugarcane as biowastes for the production of biogas. The results indicate that these biowastes can produce a maximum of 1313 million cubic meters of methane, which can generate 3916 GWh of electricity and 5887 GWh of thermal energy. The annual power production in Kenya, which is equivalent to 73%, can be achieved by utilizing the combined electrical potential of these biowastes. [93] Livestock manure has been identified as a viable alternative to fossil fuels for biogas generation in Iran, based on the number of cows, manure generation, and volume of biogas produced. Both experimental and theoretical studies have shown that biogas from livestock manure can replace approximately 3% of natural gas consumption in each province of Iran. These findings suggest that utilizing livestock manure for biogas production can be a promising solution to reduce reliance on fossil fuels in the country. [94]

According to a review of the potential of human excreta as biowaste for biogas production in Indonesia, it has been confirmed that this waste has the capacity to generate 106.85 m^3 of biogas per day, which is equivalent to 652.91 kWh/day. Given the large population and unequal deployment of electricity supply in the country, the production of biogas from human excreta is deemed essential. These findings suggest that biogas generation from human excreta has the potential to make a significant contribution to meeting the energy demands of Indonesia. [95]

Studies have shown that among various renewable energy sources, biogas-plant and biomass briquetting technologies are more valuable. These technologies have been proven effective in countries like Bangladesh, where they have generated an outstanding three billion cubic meters of biogas from cattle and poultry populations of 24 million and 75 million, respectively [96, 97]. In addition, anaerobic digestion of supermarket waste in two-stage digesters has been successful in producing a higher methane yield of 40l CH_4/g VS. Rather than disposing of supermarket waste in landfills, it can be utilized as a source of renewable energy for heat and electricity production. This approach can help mitigate greenhouse gas emissions and improve solid waste management. [98]

2.3 Co-digestion of sewage sludge with biowaste and its benefits

The anaerobic co-digestion (AcoD) process is a modification of the AD process where substrates and co-substrates are digested simultaneously, with the primary goal of enhancing biogas production. AcoD has several benefits, such as reducing greenhouse gas emissions and processing costs, improving process stabilization and nutrient balance, and leveraging the synergistic effects of microorganisms. [99] Researchers have conducted a few studies exploring the anaerobic co-digestion of specific organic wastes as co-substrates to optimize biogas production.

In their study, Tallou et al. explored the potential of anaerobic co-digestion (AcoD) using a combination of domestic wastewater, cow dung, and olive mill wastewater as substrates. They found that the AcoD process resulted in a higher biogas yield compared to the single substrate anaerobic digestion process. The maximum biogas yield of 476 mL g^{-1} was achieved using the AcoD process. Additionally, SEM and FTIR analysis of solid digestate revealed that the structures of the co-substrates disintegrated during the digestion process. [100]

In their research, Iweka et al. explored the potential of anaerobic co-digestion (AcoD) of cow dung digestate and corn chaff to maximize biogas production. They utilized Response Surface Methodology (RSM) to optimize the process and found that a retention time of 37 days and a mixing ratio of 0.65 resulted in a biogas yield of 6.19 L, which was very close to the predicted yield of 6.24 L. [101]

A study by Ivanchenko et al. focused on the anaerobic co-digestion of agro-industrial waste, specifically sewage sludge and vegetable waste, with cheese whey to assess the effect on biogas production. The results showed that the co-digestion process led to a 41% increase in biogas production. Moreover, the process of combining agro-industrial waste with cheese whey was simple and inexpensive and produced liquid organic mineral fertilizer that could be used for both root and foliar feeding of plants. [102]

The impact of solid concentration on the generation of biogas from rapeseed oil cake via anaerobic digestion was investigated by Deepanraj et al. [103]. According to their findings, the highest production of biogas was approximately 4000 mL when the solid concentration was increased to 20% [103]. According to Mudzanani et al.'s study on anaerobic co-digestion, sewage sludge has considerable potential for methane production during biogas generation, with a quantified value of 28.6 g CH_4/kg feed.

Using thick co-substrates in comparison to mono digestion of sewage sludge increased biomethane yield by 3-6 times. Although high solid content co-substrates generated more methane, they also raised the risk of organic overloading. At a 25% co-digestion ratio, co-substrates such as molasses, food waste, animal manure, and fresh produce waste were successful. [104]

2.4 Regulations and biogas potential in Estonia

The European Union (EU) aims to achieve a target of 20% renewable energy sources in the overall final energy consumption by 2020, as outlined in the Renewable Energy Directive (Directive 2009/28/EC) [105, 106]. It should be noted that each EU member state has its own individual target for 2020 based on factors such as the starting point of renewable energy, the potential for growth, and economic performance [2]. The EU's updated bioeconomy strategy and the goal of achieving climate neutrality by 2050 necessitate the decarbonization of the energy sector, leaving no room for reliance on fossil fuels [107, 108]. In this transition, renewable gases and the establishment of a clean energy system are expected to play a vital role. An important legal act issued by the EU in 2018 is the Directive of the European Parliament and the Council on the promotion of the use of energy from renewable sources [109]. This directive sets a binding EU target for the overall share of renewable energy in gross final energy consumption by 2030, further driving the shift towards a carbon-neutral economy [2].

According to the national action plan of Estonia, this necessitates a renewable energy share of 38.4% for thermal energy, 17.6% for electricity, and 10% for transportation by 2020. In total, the yearly renewable energy usage should reach 8,325 GWh, representing 25% of the ultimate energy consumption by 2020. [110] The Estonian Government has established a new objective of generating 100% of the country's electricity from renewable sources by 2030, as of August 2022. To accomplish this, Estonia is implementing various measures, such as a tender that concluded in mid-2022, which is expected to produce 540 GWh of renewable electricity for the market. The government intends to conduct additional small tenders for 1.65 TWh of renewable electricity over the next three years. European Energy has expressed its support for the government's decision and will continue its renewable energy project development efforts in Estonia. [111]

Manures, sewage sludge, herbal biomass, and organic residues are all viable feedstocks for biogas production in Estonia, according to Luna del Risco's research in 2011 [112]. There are 288,000 hectares of abandoned agricultural land in Estonia that are suitable for cultivating energy crops, as well as 128,000 hectares of semi-natural grasslands [112]. The Estonian Biogas Association (EBA) estimates that economically feasible biogas production could reach 500 million Nm^3 per year, resulting in the generation of 300 million Nm^3 of biomethane containing 98 percent methane annually, as of 2012. In 2010, biogas production reached 13.13 million Nm^3, equating to just 2.6% of the available biogas potential [113]. As of the end of 2015, the production capacity had reached 10.56 MW, and in 2014, 42.84 GWh of electricity was generated from biogas, a figure that increased to 49.79 GWh in 2015 [110].

The technically and economically feasible potential for biogas production in Estonia can be obtained from various sources. These include hay from semi-natural habitats for nature conservation purposes, silage from unused agricultural lands, energy crops grown on 5% of utilised agricultural areas, sewage sludge, manure, and slurry, and sorted biowaste from the food industry, kitchen, and canteens. The respective shares of each substrate are listed below along with their presumable deadlines for utilisation [114]:

1. Hay from semi-natural habitats can contribute to 15% of biogas production by 2020 and 25% by 2050.
2. Silage from unused agricultural lands can contribute to 20% of biogas production by 2020 and 50% by 2050, with a productivity of 15 t/ha and a yield of 155 Nm^3/t.
3. Energy crops grown on 5% of utilised agricultural areas can contribute to biogas production, with 53,917 hectares assumed for cultivation, a productivity of 15 t/ha, and a yield of 155 Nm/t, as recommended by the Estonian Rural Development plan for 2014-2020.
4. 50% of sewage sludge can be utilized for biogas production.
5. It is possible to use 60% of manure and slurry for biogas production.
6. Sorting biowaste from the food industry, kitchens, and canteens can provide 80% of the collected waste for biogas production.

2.5 Carbon offset and its markets

Addressing the challenge of greenhouse gas (GHG) reduction, particularly in relation to carbon dioxide (CO_2) emissions, has emerged as a critical global concern in the pursuit of a sustainable future [115]. Reducing greenhouse gas (GHG) emissions is widely recognized as necessary to alleviate the consequences of global climate change. Consequently, efforts have been concentrated on establishing emission targets and crafting policies to facilitate their attainment. The design and implementation of GHG policies present distinctive and formidable challenges that are well acknowledged.

Among these challenges, addressing the concerns of high compliance costs and equitable distribution is crucial. In response, almost all GHG policies, regardless of their scale (regional, national, or international), incorporate the inclusion of offsets as a means to achieve emission reductions. [116] The notion of offsets originated within the flexible mechanisms of the Kyoto Protocol, which enable developed nations to fulfill their emission reduction targets through the purchase of emission reductions linked to projects in developing countries (the Clean Development Mechanism, CDM) or transitioning economies in eastern Europe (Joint Implementation) [117]. These mechanisms, along with carbon trading, offer an alternative to costly or politically challenging domestic emission reductions and are known as a regulated or compliance carbon market. Additionally, a separate market for voluntary carbon offsets (VCOs) has emerged outside the regulated CDM. Companies and individuals seeking to offset their emissions have the opportunity to directly offset their greenhouse gas emissions through the voluntary offset market. This market has evolved separately from the international Kyoto Protocol, allowing anyone—NGOs, businesses, individuals—to generate and utilize voluntary offsets according to their own preferences. Currently, there are no widely adopted international standards or regulations governing this market. [118]

According to Kollmuss et al. (2008), carbon offsetting is a mechanism that involves one party paying someone else to reduce GHG emissions elsewhere, thereby compensating for their own emissions. Carbon offset projects result in a reduction in GHG emissions or an enhancement of carbon sequestration that would not have occurred otherwise, by altering natural resource management or industrial processes. The carbon offset is the difference between the emissions generated by the verified carbon offset activity and what would have been emitted without it. [119] Standardized procedures are used to verify carbon offsets to make them marketable in voluntary or compliance markets. However, carbon offsetting can provide a supplementary source of revenue for new technologies or practices. [120] Carbon credits are generated through the implementation of carbon offset projects, which involve the reduction of CO_2 emissions and the promotion of CO_2 absorption. Such projects include initiatives related to renewable energy, energy efficiency, and reforestation. While carbon credits themselves do not directly reduce global CO_2 emissions, they serve as significant incentives for GHG reduction projects. Many companies have also adopted the practice of selling products accompanied by carbon credits that offset the GHG emissions resulting from the use or disposal of those products. This utilization of credits helps neutralize the environmental impact of GHG emissions. [121] Carbon credits are generated by the amount of enhanced carbon sequestration or avoided loss. In general, one carbon credit is equivalent to the reduction or removal of one tonne of CO_2. [120] Several products in the market incorporate carbon credits, including automobiles, disposable diapers, and toys. One notable example is Lufthansa, which initiated a program in September 2007, allowing its customers to voluntarily contribute carbon credits to offset the CO2 emissions resulting from the average fuel consumption per passenger. Through this initiative, Lufthansa offers its customers the opportunity to actively participate in mitigating their carbon footprint. [121]

The initial official registration of a Clean Development Mechanism (CDM) project occurred in 2004. However, as early as 1989, a voluntary carbon-offset project took place when a US electricity facility made a voluntary investment in an agro-forestry project located in Guatemala. [122] During its early stages, the voluntary carbon market witnessed significant demand primarily from public institutions, particularly the World Bank [123]. However, it is highly probable that future demand will be predominantly driven by private companies, as an increasing number of them have made ambitious commitments towards achieving net zero or carbon neutrality. Following six consecutive years of decline, the voluntary carbon market experienced a rise in both market value and volume in 2018 and 2019. In 2019 alone, a total of 104 MtCO2e worth of voluntary credits were traded, contributing to an overall market value of US$320 million. [124] By the end of 2022, it is projected that the voluntary carbon market (VCM) will have facilitated investment flows exceeding $1.2 billion, contributing to the mitigation of approximately 161 megatonnes (Mt) of carbon emissions [125]. The potential market size in 2030 varies depending on different price scenarios and their underlying factors. At the lower end of the spectrum, it could range from $5 billion to $30 billion, while at the higher end, it could surpass $50 billion. These ranges assume a demand of 1 to 2 gigatonnes of carbon dioxide ($GtCO_2$). [126]

3. METHODOLOGY

3.1 Research context

The context of the study is focused on finding and suggesting a sustainable solution to deal with the large amounts of sewage sludge and biowaste generated in Narva City in a year. For that, a thorough understanding of the different types of waste, particularly sewage sludge and biowaste, and their collection systems needs to be analysed.

According to the 2021 statistics, Narva, the third largest municipality in Estonia, has a population of 53,955. Waste generation in the region depends on factors like population, economic development, company structure, and product volume. The central waste treatment facility, known as the Narva Waste Management Center, is located at Rahu tn 3B in the western part of the city. It encompasses a collection and processing area for household waste, along with sorting equipment. In 2012, Narva generated a total of over 849,000 tons of waste. Out of this, approximately 13,590 tons consisted of mixed household waste, while around 5,530 tons were biowaste. [127] According to the Tallinn Center of the Stockholm Environmental Institute (SEIT), the composition of mixed household waste, including the proportion of biowaste, remained relatively consistent between 2012 and 2020 [128]. The wastewater treatment process in Narva also yields significant quantities of sewage sludge, which is classified as biodegradable waste. Both manufacturing companies and households contribute to wastewater generation. Managed by AS Narva Vesi, the city's sewage treatment plant produced 1825 tons of domestic water treatment sludge and 625 tons of industrial wastewater biotreatment sludge in 2012. [127] The total amount of sewage sludge generated that year reached 2450 tons, and this proportion has remained steady, according to the 2020 survey [128].

The author of the study intends to propose an environmentally friendly solution for treating the biowaste and sewage sludge to reduce the impacts of dumping the waste at landfill sites. An anaerobic co-digestion process has been proposed by the author for its synergistic effect of augmenting the biogas yield. Therefore, the study aims to evaluate the environmental impact associated with the co-digestion of sewage sludge and biowaste produced in Narva city. To evaluate the environmental burdens, the life cycle assessment tool has been adopted in this study. The most predominant output of the co-digestion process is the production of biogas, which is further treated to produce biomethane. This biomethane can be used for the production of electricity, replacing fossil fuel-based electricity. This replacement corresponds to reduced or avoided GHG emissions, which further paves the way for the author to develop a carbon offset project. The study also intended to quantify the success of the biogas offset project, which is ensured by the revenues earned by the carbon credits corresponding to the avoided emissions.

3.2 Life cycle assessment

When the activity's location is already determined, life cycle assessment stands out as a highly advanced and extensively utilized environmental assessment tool for evaluating and comparing different alternative technologies [129]. It is a methodology used to examine the full environmental impact of a process or product across the course of its life cycle (from raw materials extraction to the disposal phase after the usage stage) and is frequently referred to as cradle-to-grave analysis. A cradle-to-gate approach can be used when the system boundaries are constrained to specific life cycle stages (for example, from raw material extraction to product manufacture, as in this study under investigation). [130] Furthermore, it aids in identifying the critical areas within the system, commonly referred to as 'hot spots', which exhibit the most substantial environmental impact. This allows for a prioritized focus on improving these areas initially, facilitating the identification of environmentally sustainable alternatives. [131] In this study, the environmental impacts of co-digestion of sewage sludge and biowaste were evaluated using the life cycle assessment (LCA) tool. The ISO 14040:2006 standard for LCA was implemented to translate the inputs and outputs of the co-digestion process into corresponding environmental consequences. This LCA is constructed in accordance with ISO standards from several connected elements, including the definition of the goal and scope, data acquisition and inventory analysis, impact assessment, and interpretation of outcome to come to a conclusion and provide recommendations. [132]

3.3 Goal and scope definition

In this phase, the study's objective was clarified, and the specific object of investigation was described and defined. The selection of the functional unit was made, and the boundaries of the system were established [133]. The goal of this study is to quantify the impending environmental impacts of the co-digestion process of sewage sludge and biowaste as a mixture. The reference flow of the study is the sum of the amount of sewage sludge and biowaste produced in Narva city in a year. For this study, data from the Tallinn Center of the Stockholm Environmental Institute (SEIT) survey on the composition and quantities of different types of waste (2020) in Narva city has been considered [128]. A mixture of 2450 tons of sewage sludge and 5530 tons of biowaste that were produced in Narva city in the year 2012 has been considered as the reference flow. The reference flow is the representation of the reference to which all the inputs and outputs of the co-digestion process are adjusted. To ensure the quality and consistency of information in line with the study's goal, the scope of the investigation was meticulously defined following the guidelines of ISO 14040 [132]. It was essential to provide detailed specifications to maintain the accuracy and relevance of the study's aim [133]. The scope of the study included biogas production from a feedstock that is a combination of sewage sludge and biowaste.

As per ISO 14040, the functional unit serves to quantify the identified functions or performance characteristics of a product [132], providing a quantitative description of the service performance and fulfilling the needs of the product system under investigation [134]. Its primary objective is to establish a reference point that enables the association of inputs and outputs [133]. All material and energy flows, whether entering or leaving the system, are linked to this functional unit to ensure the comparability of life cycle assessment (LCA) results. The function of the life cycle assessment is the production of biogas from the co-digestion process. From the assessment, the amount of biogas produced from the co-digestion process is calculated which is the functional unit of the study.

In LCA studies, the system boundary plays a crucial role in delineating the movement of inputs and outputs within the system or process route. Defining the system boundary involves identifying the processes to be encompassed within the product system. [134] Several factors come into play when determining the system boundary, including considerations such as time, cost, and the availability of reliable data. Ideally, the product configuration should be structured in a manner where the inputs and outputs at its periphery are fundamental components. [133] The product system of the study is schematically shown in Figure 3. The life cycle analysis of the study can be considered as cradle to gate for being limited to the biogas production while neglecting any following uses such as the production of heat and electricity from the biogas produced or the use of digestate for soil amendments.

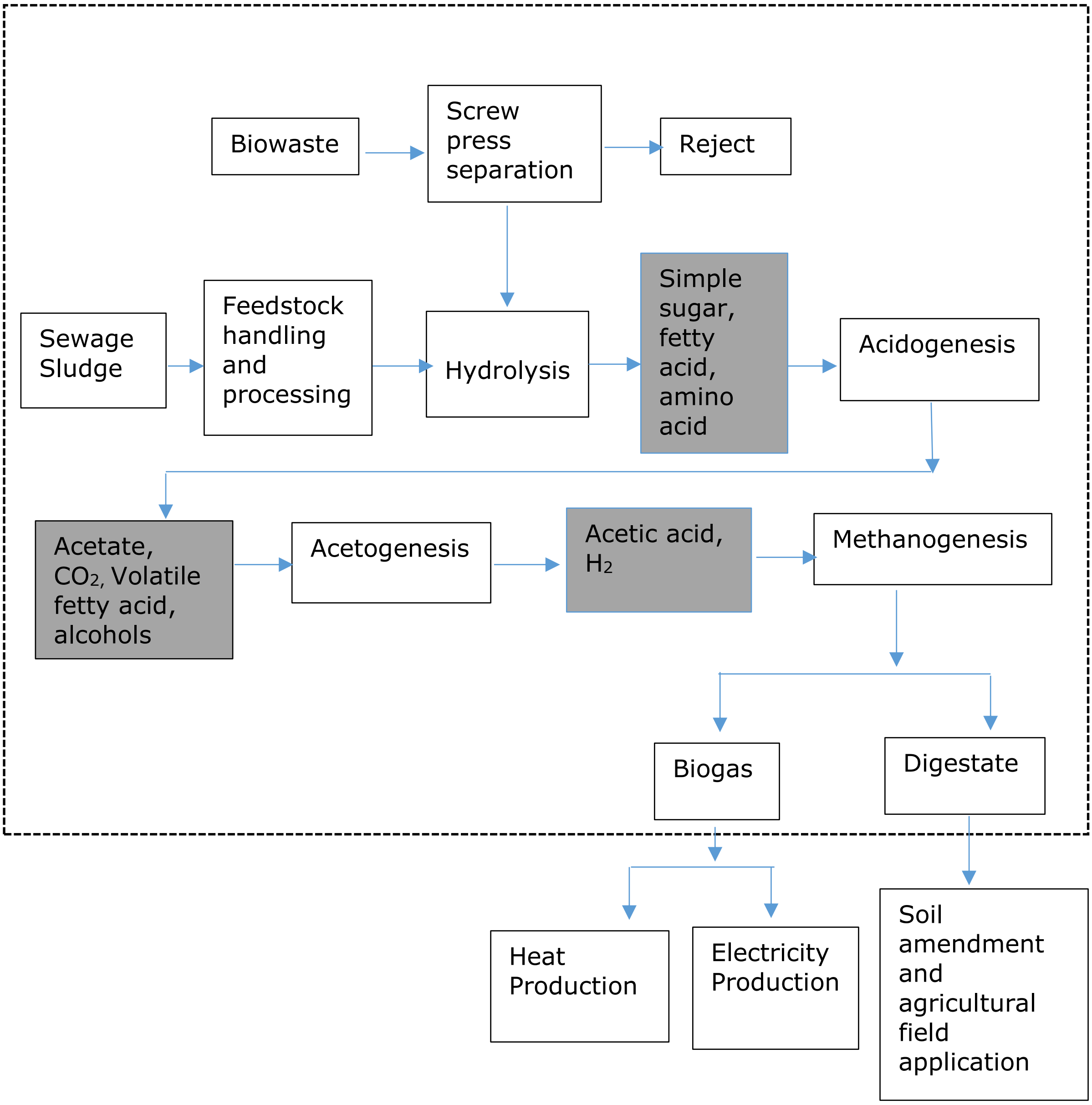

Figure 3 System boundary

3.4 Life cycle inventory and impact assessment

During this phase, the focus was on collecting relevant data and performing calculations to quantify the inputs and outputs associated with a specific product system. A comprehensive inventory is systematically compiled, encompassing all material and energy flows and emissions associated with the product or object under investigation. The outcome of the inventory analysis yields a comprehensive list of emissions, material inputs, and energy inputs for the product being studied. [133] In the context of this study, the life cycle inventory (LCI) phase involved collecting and quantifying the pertinent inputs and outputs related to the co-digestion of sewage sludge and biowaste.

Inventory data for the co-digestion process is shown in Table 1. The co-digestion process is modeled in OpenLCA software with the use of the Ecoinvent 38 database. The database is robust and provided all the information needed to develop the inventory table. All the inputs and outputs have been calculated based on the reference flow of the study. To evaluate and quantify the impacts of the co-digestion process, an impact assessment method is required. For this study, the most reliable and updated impact assessment method Environmental Footprint, version 2.0 (2018) has been used. The Life Cycle Impact Assessment (LCIA) has been carried out in OpenLCA software, version 1.11.0 (2021).

Table 1 Life cycle inventory table

Name of process/material	**Amount of material**	**Unit**	**Source**
Inputs			
anaerobic digestion plant, for biowaste	9.24E-03	item(s)	Ecoinvent
anaerobic digestion plant, for sewage sludge	1.40E-03	item(s)	Ecoinvent
Biowaste	5530000	Kg	SEIT survey on the composition and quantities of waste (2020) [128]
sewage sludge	2311.3208	m^3	SEIT survey on the composition and quantities of waste (2020) [128]
digester sludge	-3428600	Kg	Ecoinvent
electricity, low voltage	19388.544	kWh	Ecoinvent
heat, district or industrial, natural gas	135978.146	MJ	Ecoinvent
heat, central or small scale, other than natural gas	1336048	MJ	Ecoinvent
machine operation, diesel	1935.5	H	Ecoinvent
chemical, inorganic	198.265098	Kg	Ecoinvent
tap water	1244250	Kg	Ecoinvent
Outputs			
carbon dioxide, non-fossil	1165129.096	Kg	Ecoinvent
dinitrogen monoxide	182.49	Kg	Ecoinvent

hydrogen sulfide	495.488	Kg	Ecoinvent
Methane, non-fossil	20401.08037	m^3	Ecoinvent
Nitrate	16.4241	Kg	Ecoinvent
Nitrite	0.513184	Kg	Ecoinvent
nitrogen, organic bound	0.60277	Kg	Ecoinvent
Phosphorus	0.389312	Kg	Ecoinvent
wastewater, average	1216.6	m^3	Ecoinvent

3.5 Assumptions

The main assumptions of the life cycle assessment are the followings:

- A thorough investigation has been conducted to find out the data on the inputs and outputs for each of the processes associated with anaerobic digestion, i.e., hydrolysis, acidogenesis, acetogenesis, and methanogenesis. No previous research was found that provided data on the inputs and outputs in each step of the digestion process as shown in Figure 3. The whole co-digestion process is conducted in one bioreactor. Therefore, data on the energy and other resource inputs are gathered for the whole process instead of each stage of the processes, such as hydrolysis, acidogenesis, acetogenesis, etc. For simplification, in this study, all the inputs and outputs have been calculated for the whole co-digestion process.
- The main output of the co-digestion process is biogas production. The biogas consists of about 60% of methane and 40% of carbon dioxide. In this study, it is assumed and applied that the biogas will be cleaned and upgraded to produce a final product called biomethane which is composed of CH_4 (95–99%) and CO_2 (1–5%). However, before its application, biogas cleaning is often regarded as the initial stage, which is an energy-intensive process.
- The inorganic contaminant was removed from the biowaste using a screw press. As the screw press required no water addition during treatment, it was chosen over wet separation in the co-digestion situation. Comparatively, wet density separation necessitates a water addition of 0.6 m^3 per tonne of entering biowaste, adding stress to the already overtaxed freshwater supply. [135]
- The energy demands of sludge digestion, thickening and dewatering, drying, and general space heating were not considered in this study as it is assumed that all these processes will be completed by the Narva Vesi and the sludge will be ready for the co-digestion process.

3.6 Carbon offset project development

Offsets generate controversy in both compliance and voluntary market contexts. While offsets offer a reduction in GHG emissions, there are individuals who fundamentally oppose the concept of paying others to reduce emissions instead of taking direct action themselves. [116] The credibility of offset markets is undermined by a widespread lack of trust regarding the authenticity of greenhouse gas reductions achieved through offset projects. This lingering skepticism raises doubts about the legitimacy of offsets and their effectiveness in addressing climate change concerns. [136]

The fundamental concept underlying carbon offsets' integrity and credibility is the establishment of "baseline-and-credit" trading systems, where carbon credits are generated to represent the additional emissions reductions beyond the baseline level. These systems direct investments towards emission-reduction projects that would not have occurred otherwise. [137] The key principle here is "additionality," which distinguishes the emissions reductions achieved through offset projects from the projected emissions in a "business-as-usual" scenario without such projects being implemented [138]. Various methods can be employed to establish additionality, including demonstrating that a project would lack profitability or sufficient financing without the revenue generated from the sale of carbon credits. Another approach is to highlight cases where a specific technology would not have been adopted if not for the availability of carbon credits. This evidence helps substantiate the notion of additionality and confirms that the emission reductions achieved through carbon offsets go beyond what would have naturally occurred. [139]

The author of this study is intended to develop a carbon offset project by comparing the GHG emissions from the background system for electricity production for the Estonian mix with the emissions produced from the use of biogas which is mainly methane as an energy source. The author assessed whether the difference in greenhouse gas emission can guarantee a profitable carbon offset project for the biogas produced from the co-digestion of sewage sludge and biowaste. Therefore, to qualify for the additionality criteria, there must be a clearly defined "project" in order to create biogas carbon offsets because calculating carbon offsets necessitates comparing GHG emissions from a 'business-as-usual' scenario with emissions from a project scenario [140]. In other words, simply utilizing biogas produced from the co-digestion process of sewage sludge and biowaste would not qualify to develop carbon credits as in that case the net differential in GHG emission would not be possible to measure. It would be unclear whether the electricity produced from biogas has replaced the use of fossil fuels in electricity production or is just simply used as an additional source for energy production. To solve this issue, a hypothetical project has been developed and the GHG emission differential has been used to calculate the potential number of carbon credits and evaluate if that can be a viable venture for authorities to collaborate for biogas production from the co-digestion of sewage sludge and biowaste.

The hypothetical project has been defined as follows,
The Narva Waste Recycling Center is responsible for the recycling of waste generated by the population and different industrial activities. The recycling center uses electricity for different operations of the recycling process and to operate different types of machinery. The source of the electricity is the electricity produced from the gas and electric turbine. The hypothetical project aims to replace the use of electricity from the conventional source with electricity produced from biogas, i.e., methane from the co-digestion process. In that way, the net differential in GHG emission can be calculated which will lead to carbon credit calculation.

The hypothetical project developed by the author qualifies for additionality since the Narva waste recycling center was not considering using electricity from renewable sources such as biogas produced from the co-digestion of sewage sludge and biowaste. Besides, there will be additional profitability from the sale of carbon credits which will make the biogas production from the co-digestion process more profitable and may obtain financing from different sources. In terms of carbon offsets, the biogas project successfully adheres to the criteria of being cost-effective, verifiable, quantifiable, and possessing long-term benefits in relation to additionality. By fulfilling these standards, the facility is able to provide offsets that are considered legitimate and valuable in mitigating carbon emissions. A number of biogas offset projects are active both in the compliance and voluntary carbon market which also strengthens the credibility of the developed biogas project. For example, in 2020 the Gold standard issued 151 million carbon credits from over 900 projects and among those, 166 biogas carbon offset projects were generating 17.3 million carbon credits [141].

One example of such a biogas carbon offset project is the Lethbridge Biogas facility located in Canada. During the developmental phase, the innovative Lethbridge biogas facility faced challenges due to the absence of a well-defined regulatory framework, despite its ability to satisfy the criteria of true additionality. This facility functions as a biogas cogeneration plant, utilizing agricultural, food, and food processing waste as raw materials to produce biogas, predominantly composed of methane. The biogas is then combusted in two combined heat and power units, generating electricity that is subsequently supplied to the Alberta grid. Moreover, the facility effectively utilizes the captured heat to maintain continuous optimal operating temperatures for the biogas processes. However, the lack of regulatory clarity during development posed difficulties for this ground-breaking project. [142]

4. RESULTS AND DISCUSSIONS

4.1 Environmental impact assessment

The purpose of life cycle impact assessment (LCIA) is to translate the life cycle inventory (LCI) results into the related detrimental impacts on the environment, i.e., effects on natural resources, environment, and human health. The impact assessment results help to prioritize the processes that pose the highest impacts on the environment. Measures can be taken to make the process more environment friendly and sustainable by analysing the contribution of different flows in making the impact category to be in the worst-case scenario.

4.1.1 Impact categories

The impact assessment method, Environmental Footprint, version 2.0 (2018), was used in this study to convert the inputs and outputs, i.e., all materials and energy flows, into quantifiable environmental impacts. The impact assessment generated results for different impact categories in different units and among those the following categories have been chosen to be analysed based on their severity on the environment which is determined by the impact results.

Freshwater ecotoxicity: The impact under consideration is specifically associated with the influence on freshwater habitats, including streams, waterways, and reservoirs with a salinity level below 0.05 percent. This impact is primarily caused by factors such as pollution, water contamination, and the presence of radioactive substances in surface concentrations. The impact is expressed in comparative toxic units or CTU. [143]

Climate change: The climate change category provides a direct measure of carbon emissions and their significant connections within the system for a period of 100 years [144]. This measurement is valuable in terms of targeting and addressing emission reduction efforts effectively. It is expressed in Kg CO_2-Eq.

Terrestrial eutrophication: The choice of terrestrial eutrophication was made to encompass and represent the various potential consequences of elevated levels of macronutrients, specifically nitrogen, and phosphorus, on the environment [144]. it is expressed in mol N-Eq unit.

Land use: The environmental effects associated with the utilization, alteration, and administration of land for human activities are encompassed by the impact category known as ′land use′. Land use refers to both the sustained utilization of land over an extended period (such as for agricultural cultivation) and the conversion of land from its natural state to urban or other forms of development. [145] It is measured in points.

Energy resources - non-renewable: The impact category of ′energy resources′ evaluates the consequences associated with the utilization and extraction of energy resources, including non-renewable fossil fuels that are expected to diminish over time. It encompasses the future ramifications arising from the depletion of fossil fuel reserves and the limited choices available to future generations. The measurement unit used for this category is expressed in megajoules (MJ). [146]

4.1.2 Impact analysis

Table 3 lists the environmental impact scores for the selected impact categories associated with the studied scenario. The negative net score means that the scenario brings savings to the environment, while the positive score means that the scenario generates burdens to the environment. From the table, it is evident that none of the impact categories brings benefits to the environment. The co-digestion process performs worse in the energy resources impact category while a better performance in respect to the environmental impacts is demonstrated by the terrestrial eutrophication category. The impact categories are further analysed one by one later in this section.

Table 2 Environmental impact analysis results

Impact Category	Value	Unit
Freshwater Ecotoxicity	8.15E+04	CTU
Climate change: fossil	1.50E+05	kg CO_2-Eq
Climate change: biogenic	7854.22059	kg CO_2-Eq
Climate change	1.58E+05	kg CO_2-Eq
Terrestrial eutrophication	2489.49533	mol N-Eq
Land use - soil quality index	4.98E+05	Points
Energy resources - non-renewable	1.25E+06	MJ

Freshwater ecotoxicity

The total freshwater ecotoxicity potential of the co-digestion process was 8.15E+04 CTU, which is mainly attributed to the anaerobic digestion plant construction and different machine operation with fossil fuel, i.e., diesel. The anaerobic digestion plant construction has a 56.48% contribution to the detrimental impacts on freshwater habitats and the manufacturing process of construction materials such as cement, steel, and others were responsible for these impacts at the upstream stage. Different machine operation with diesel leads to freshwater ecotoxicity as this fuel can cause water contamination due to spillages, leakages, and machine cleaning processes. Figure 4 shows the contribution diagram of different processes to the impending impacts of the freshwater ecotoxicity category.

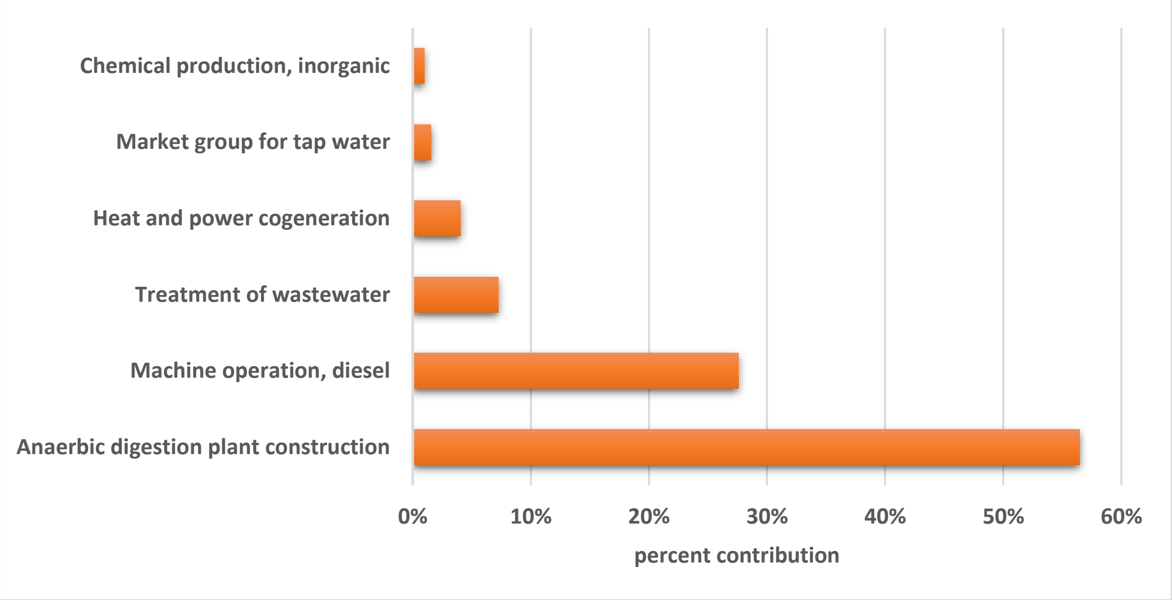

Figure 4 Freshwater ecotoxicity potential for co-digestion process

Terrestrial eutrophication

The total terrestrial eutrophication potential for the co-digestion process was 2489.49533 mol N-Eq causing a harmful impact on the environment which is due to the release of the macronutrients such as nitrogen and phosphorous. As shown in Figure 5, machines operation with diesel has the highest contribution to terrestrial eutrophication potential and can influence human health, flora, and fauna by releasing heavy metals or organics which were biorecalcitrant. Heat and power cogeneration from biogas and natural gas also account for the terrestrial eutrophication potential to a greater extent.

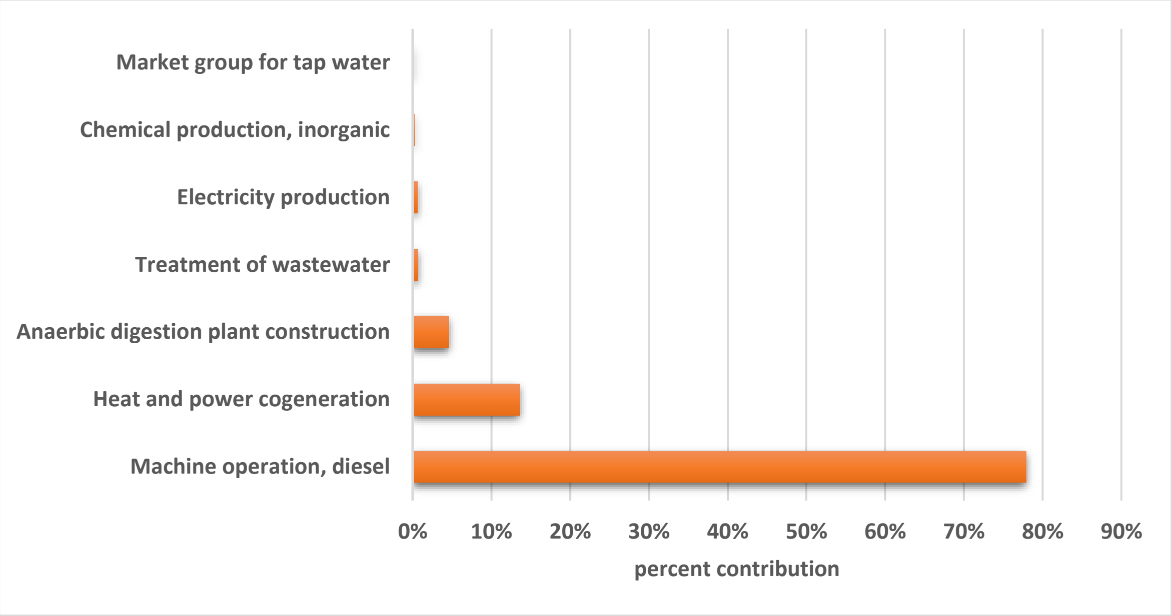

Figure 5 Terrestrial eutrophication potential for the co-digestion process

Land use

With regard to the impact associated with land use, the majority of impacts are derived from the anaerobic digestion plant construction accounting for 52.5%, followed by heat and power cogeneration with a proportion of 28.04%. Land acquisition is required for the construction of the anaerobic digestion plant and power plant that alters the landscape and contribute to the conversion of land from its natural state to urban development. The land use potential is depicted in Figure 6 with all its contributors.

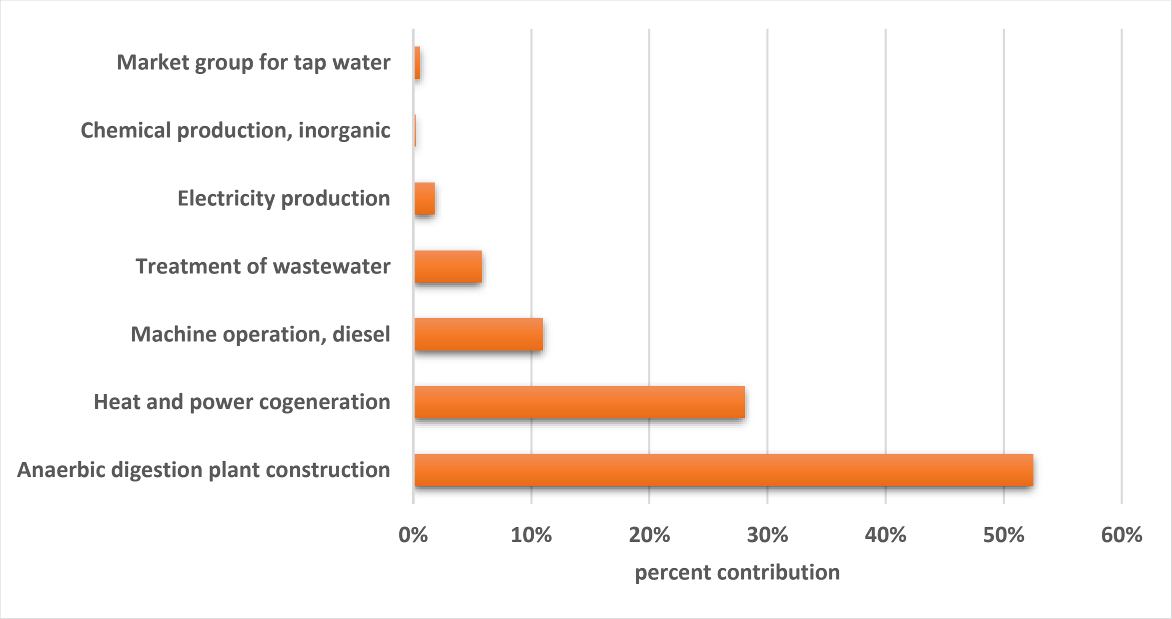

Figure 6 Land use potential for co-digestion process

Energy resource

The impact category energy resource is responsible for the extraction of fossil fuels from nature. Thus, it is obvious that machine operation with diesel and heat and power cogeneration will be the two main contributors in making the energy resource potential the worst impact category for the co-digestion process. The detrimental impact is led by machine operation with diesel with a proportion of 77.91% while heat and power cogeneration process contributed 11.11% proportion. Figure 7 depicts the proportions.

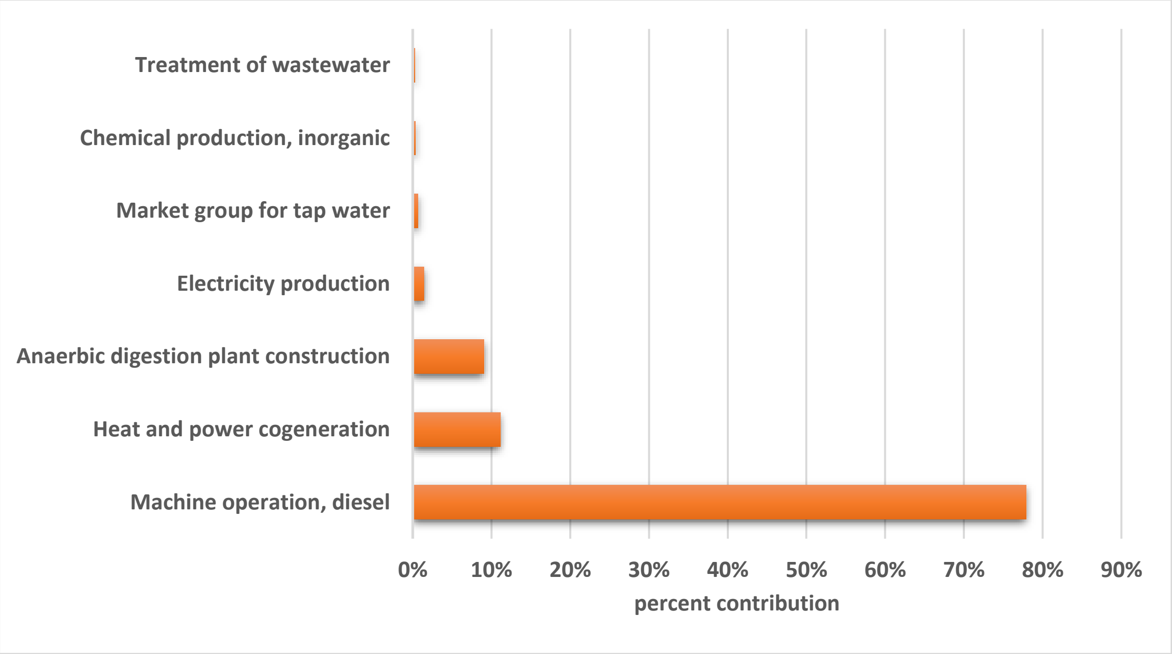

Figure 7 Energy resource potential for co-digestion process

Climate change

The Environmental Footprint impact assessment method subdivided the climate change impact category into - climate change: fossil, climate change: biogenic, and climate change average. The climate change average is the sum of the total impacts caused by fossil fuel and biogenic energy sources. The total impact caused by the climate change impact category is 1.58E+05 Kg CO_2-Eq with a share of 1.50E+05 Kg CO_2-Eq from fossil sources and 7854.22059 Kg CO_2-Eq from biogenic sources, i.e., biogas. The impact is mainly caused by the machine operating with diesel and causing greenhouse gas emissions to the environment. This impact can be reduced by upgrading the biogas produced from the co-digestion process to biofuels which can be used for the machine operation. Thus, the co-digestion process will be more sustainable. Figure 8 shows the overall impacts of the three climate change impact categories.

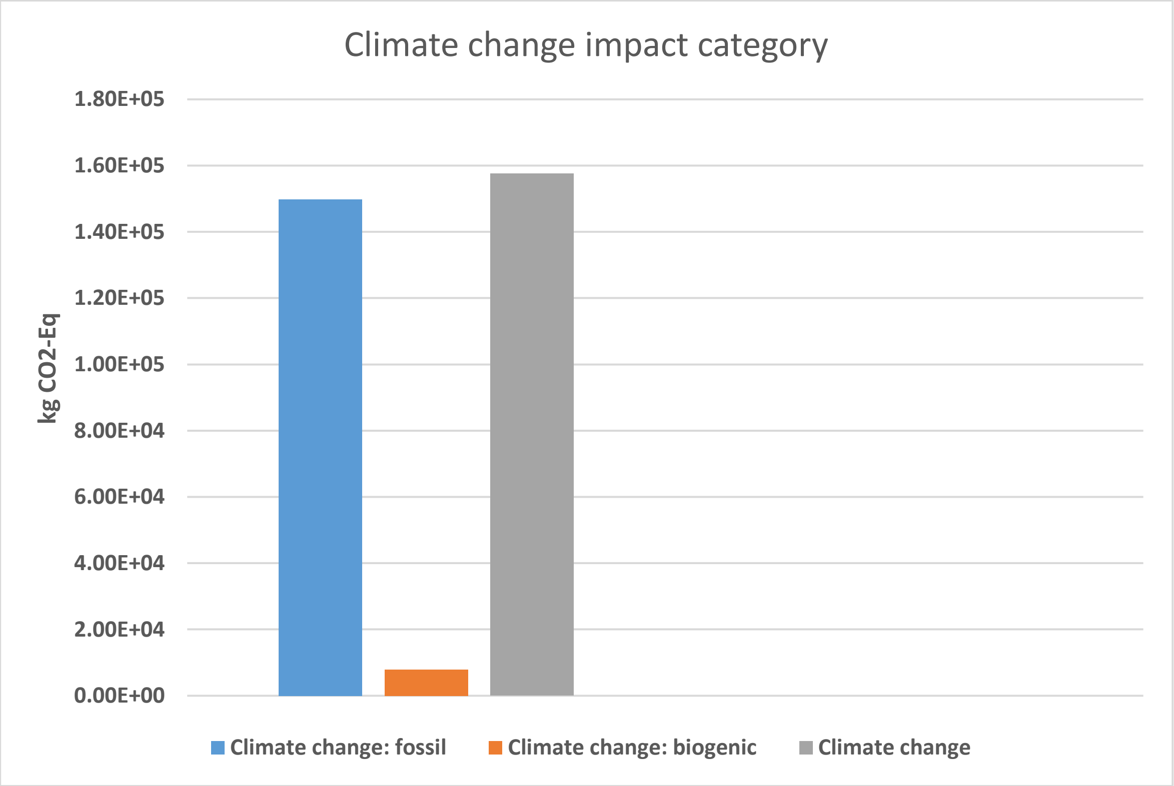

Figure 8 Climate change potential for co-digestion process

Although several studies have been conducted for increasing the yield of biogas from sewage sludge by co-digesting the sludge with different organic substrates such as molasses, food waste, animal manure, and fresh produce waste, etc and implementing different technologies for pre-treatment of the inputs [100-104], very few studies are available on the life cycle assessment of co-digestion of sewage sludge and biowaste or other co-substrates. Tong et al. (2019) conducted a comparative life cycle analysis on mono and co-digestion of food waste and sewage sludge in the context of Singapore. They divided the outcomes into three sub-categories, i.e., neutral, synergistic, and antagonistic when methane production from the mixture was equivalent, higher, or lower than the sum of mono-digestion respectively. The global warming potential for the mono-digestion and the three sub-categories were 7.01E+04, 9.12E+04, 8.40E+04, and 7.53E+04 Kg CO_2-Eq respectively. [147] In the present study, the climate change potential was found 1.58E+05 Kg CO_2-Eq which is higher than the global warming potential of the co-digestion of sewage sludge and food waste. The reason can be the introduction of a pre-treatment process for the sewage sludge implemented by Tong et al. (2019) which increased the yield of biogas and thus reduced the climate change impact. On the other hand, no pre-treatment technologies have been introduced in the present study for sewage sludge.

4.2 Carbon credits calculation

Measuring reductions in carbon dioxide or other relevant greenhouse gases is expressed in tonnes of carbon dioxide equivalent (tCO_2e), with the aim of comparing a baseline scenario to a "project" scenario. This distinction enables the calculation of emissions reductions resulting from the project. Each tonne of reduced emissions corresponds to a carbon credit that can be claimed. This calculation is crucial for offset projects to market the carbon reductions achieved through their activities, selling them as carbon credits. [123]

The methodologies involved in comprehending carbon reductions through baseline calculations are highly intricate. Determining the precise amounts of carbon sequestration in forests is challenging due to factors like weather variations and monitoring issues [148]. Estimating carbon savings in projects involving numerous small actions, such as distributing improved stoves or efficient light bulbs, is also problematic. This is due to variations in the successful adoption of these measures across households and difficulties in monitoring the resulting carbon reductions. [138]

The generation of carbon credits occurs within particular market mechanisms that have defined regulations regarding acceptable methods of credit generation and the calculation of credits [149]. Strict verification is necessary for Clean Development Mechanism (CDM) projects, which entails the submission of ample verification data and measurements as evidence of project legitimacy [150]. For example, to calculate the carbon credits for forest projects CDM has defined protocol and methodology such as ton-year, equivalence-adjusted average carbon storage, temporary crediting, etc [151]. Voluntary offset organizations operate differently from offset organizations operating within the strict regulations established by the CDM. In the case of voluntary offset organizations, they have the flexibility to employ various approaches and governance practices to acquire projects and quantify carbon credits. Referred to as a 'parallel market', voluntary offset projects are generally smaller in scale and place a stronger emphasis on sustainable development, often encompassing social or community-related advantages. Additionally, these projects are typically situated in countries that are not actively participating in the CDM. [118]

The author of this study developed a hypothetical biogas offset project intended to be launched in the voluntary carbon market (VCM). Therefore, it is important to quantify the emission reduction generated by the project. Among the wide range of approaches and governance practices available in the VCM, the author adopted the methodology used in the calculation of carbon credit by Bhandari et al. (2021) where they assessed whether the greenhouse gas (GHG) emission differential might warrant carbon credit creation for cultured protein projects compared to a business-as-usual scenario of traditional milk protein [140]. The calculation includes multiplying the amount of GHG emission reduction in a tonne of CO_2-Eq, that is the carbon credit, by the price for each carbon credit. The following steps can be adopted to calculate the carbon credit number and value for the biogas project under this study.

4.2.1 Step 1: the amount of avoided conventional electricity

From Table 1, it can be seen that one of the major outputs of the co-digestion process of sewage sludge and biowaste in Narva City is biogas production, which is predominantly methane, and it is 20401.08037 m^3/year. According to Suhartini et al. (2019), 1 m^3 of methane produced from the anaerobic digestion of biowaste can yield 10 kWh of electricity [152]. Therefore, the methane produced from the co-digestion process can yield 204010.8037 kWh of electricity per year.

In the year 2022, the hypothetical project facility, Narva Waste Recycling Center, used a total of 92612.375 kWh of electricity for different operations. The data have been obtained by speaking with the representatives from the Narva Waste Recycling Center. According to the hypothetical project, this amount of electricity is replaced by the electricity produced from the biogas of the co-digestion process. From the amounts, it can be seen that 100% of the electricity needed by the Narva Waste Recycling Center can be replaced with the electricity produced from the methane of the co-digestion process and it accounts for 92612.375 kWh of electricity per year. For the study project, the author of this paper has assumed that the Narva Waste Recycling Center might do a pilot project replacing 100% of the total electricity needed with electricity produced from biogas, representing 92612.375 kWh of electricity replacement.

4.2.2 Difference in GHG emission between baseline and project scenario

In this study, the baseline scenario is the use of conventional electricity at the Narva Waste Recycling Center while the project scenario is the electricity produced from methane generated from the co-digestion process. Therefore, the reduction in emission of the biogas project is the difference in the value of greenhouse gas emission between the baseline scenario and the project scenario. According to the Estonian emission factors, the GHG emission for renewable electricity using biomethane as fuel is 0.0001 kg of CO_2eq/kWh, and for conventional electricity, it is 0.637 kg of CO_2eq/kWh. The GHG emission differential is therefore 0.6369 kg of CO_2eq/kWh.

4.2.3 Step 3: carbon credit price

There is a variety of selling prices for carbon credits in the compliance carbon market of Europe, ranging from an average of EUR 32.25 per tonne of CO_2 equivalent in Estonia as reported by OECD and 70-80 EUR per tonne of CO_2 equivalent as reported by European Union Allowances [153, 154]. In contrast, the prices of voluntary offset credits exhibit significant variations influenced by factors such as the standard employed, project types, project locations, offset quality, delivery guarantees, and contract terms [155]. Notably, offset prices are approximately 20% higher when projects are situated in developing or least-developed countries. Additionally, forestry-based offsets tend to be sold at lower prices, with this trend being particularly pronounced in projects located in developing or least-developed nations. [116] According to Hamrick & Gallant (2017), the lowest price for a carbon credit in the voluntary market can be 2 EUR per credit and the highest can be as high as possible depending on the quality of the project [156]. Thus, the author chose to analyze the study scenario for selling prices at 2 EUR, 32 EUR, 80 euros, 500 EUR, and 700 EUR per credit.

4.2.4 Step 4: carbon credit and value calculation

A carbon credit is the reduction of GHG emissions in tonnes of CO_2-Eq. Thus, by multiplying the amount of electricity replaced from step 1 with the GHG emission differential in step 2, the author calculated the total amount of emission reduction in Kg of CO_2-Eq. To convert the Kg of CO_2-Eq into tonnes of CO_2-Eq, the product of the multiplication was divided by 1000 kg since 1 tonne corresponds to 1000 Kg. Therefore, the total carbon credit for the biogas project was calculated. The following equation can be used to calculate the number of credits the project could generate:

$$Electricity\ Replaced\ (kWh\ of\ electricity) * Differential\ (kg\ of\ CO2e/kWh) * 1\ tonne/1000\ kg$$
$$= Credits$$
$$= 92612.375\ kWh * 0.6369\ kg\ of\ CO2eq/kWh * 1\ tonne/1000\ kg$$
$$= 59\ carbon\ credits$$

Using Price values of 2 EUR, 32 EUR, 80 EUR, 500 EUR, and 700 EUR per credit, it is possible to calculate the range of values for those credits:

$$Price * Credits = Value$$

Table 3 Carbon credit value for different prices

	Credit value				
Credits generated	at 2 EUR/Credit	at 32 EUR/Credit	at 80 EUR/Credit	at 500 EUR/Credit	at 700 EUR/Credit
59	118	1888	4720	29500	41300

The hypothetical biogas project generated 59 carbon credits which are valued between 118 EUR to 41300 EUR (Table 3). The results range depending on the credit sale price used. A higher number of credits could be generated if the hypothetical project aimed to use the full amount of electricity produced from the biogas. Table 4 presents data from four different studies, showcasing a diverse range of estimated or reported emission reductions achieved through the utilization of biogas, primarily for electricity generation. The values presented in the table represent the estimated reductions in CO_2 emissions equivalents from biogas power plants. It is important to note that emission credits per tonne of input material are likely to differ depending on the type of feed used. Biogas plants that solely utilize manure as input material tend to produce a significantly smaller amount of biogas per unit input compared to plants that incorporate a mixture of organic wastes along with manure. [157]

Table 4 Data for carbon credits from four different studies

Reference	**Feedstock**	**Location**	**Credits generated**
West 2004 [158]	mixed feed	Canada	150
Munster & Juul Kristensen, 2005 [159]	mixed feed	Denmark	118
Row and Neable, 2005 [160]	manure	Canada	104
Ghafoori et al., 2006 [161]	manure	Canada	55

In the context of the hypothetical project of this study, it appears that the co-digestion of sewage sludge and biowaste project might generate significant and additional revenue for the associated authorities. Sources indicate that buyers have a preference for acquiring credits that demonstrate supplementary advantages beyond the mere reduction of emissions. Moreover, they are occasionally inclined to pay an extra amount if the verification of these co-benefits is possible [162]. The emergence of co-benefits as a crucial selling point for offset projects is becoming more prominent within voluntary offset markets [163, 164]. The demand for voluntary carbon offsets is driven by the narrative they hold, connecting them to local co-benefits [165]. The greater number of local sustainability benefits a voluntary offset project can demonstrate, the more likely it is to command a higher price in the markets [166]. The co-digestion of sewage sludge and biowaste project would likely be able to report on some other positive outcomes - the utilization of biogas for power generation offers significant environmental advantages. By generating electricity from anaerobic digestion (AD) plants, it becomes possible to substitute the conventional grid mix and eliminate the need for consuming fossil fuels. Consequently, the harmful pollution emissions associated with extracting and utilizing these fossil fuels are also avoided. The efficiency of a biogas facility is evident through its ability to generate a high-quality fertilizer, which enhances agricultural productivity while minimizing groundwater contamination. Additionally, biogas facilities demonstrate low emissions intensity, further contributing to their environmental benefits. [142] Therefore, the biogas project developed in this study possibly can qualify for higher prices than the average prices per carbon credit.

4.3 Limitations and future scope for carbon credits

The production of carbon credits does not guarantee the generation of revenue. It is not certain that the credits available on the market will be sold, as evidenced by the fact that in 2016, voluntary carbon offset organizations produced more offsets than they were able to sell [156]. In the analysis of carbon credits, it is crucial to account for uncertainties. Hypothetical projects like the one discussed by the author could potentially experience reduced carbon credit generation due to higher leakage rates or automatic credit reductions associated with uncertain verification schemes. The lack of a specific credit verifier, marketplace, or protocol adds further uncertainty to these potential credit reductions in the voluntary carbon market. The development of a protocol in the compliance or voluntary carbon market for the biogas project from co-digestion of sewage sludge and biowaste is also uncertain, accompanied by significant establishment costs and potential additional transaction costs for project verification. Moreover, the verification process in the compliance market is time-consuming, taking up to 2.5 years for certain credit types. [156, 167, 168]

Being such a novel initiative to develop a carbon offset project for biogas production from the co-digestion of sewage sludge and biowaste, it was tough to get the required data, for example, assumptions needed to be made based on literature for how much electricity can be produced from the biogas. Another shortcoming is finding enough GHG emissions differential to potentially pursue a carbon offset project. The GHG emission differential for the study was quite low which led to lower carbon credit calculations.

Enhanced clarity and comprehension of the co-digestion process will reduce uncertainties and assumptions, thereby instilling greater confidence in the outcomes.

The establishment of carbon credits for the biogas project generated from the co-digestion of sewage sludge and biowaste requires significant further steps. A standard and clear verification method would be needed to estimate and validate the carbon credits for the hypothetical project. The project can be aligned with the ISO 14064-2 standard which is focused on GHG projects or project-based activities specifically designed to reduce GHG emissions and/or enhance GHG removals. It provides the basis for GHG projects to be validated and verified. [169] It would also be interesting to look into the establishment of additional credits based on the application of the digestate from the co-digestion process in soil amendments works which replaces the use of inorganic fertilizers. It can be said that the preliminary results of this study indicate that future efforts to pursue carbon credits based on biogas from the co-digestion of sewage sludge and biowaste project may be a worthwhile endeavor because of the associated co-benefits and scope for additional carbon credits.

5. CONCLUSIONS

The most robust findings of the study include the severity of the environmental impacts from the co-digestion of sewage sludge and biowaste in Narva city, the success of the development of a biogas carbon offset project, and calculation of the carbon credit that can be generated from the offset project. From the result analysis of the environmental impacts, it can be seen that the co-digestion process of sewage sludge and biowaste has considerable detrimental impacts on the environment and the GHG emission from the process is quite high compared to similar studies. These environmental impacts bar the possibility of the co-digestion process from being sustainable. The environmental burdens of the co-digestion process can be minimized by utilizing the produced biogas for the cogeneration of heat and power which can be again used in the processes associated with the co-digestion process. Additional profitability can be added to the co-digestion process to attract financing by developing a biogas carbon offset project.

The amount of biogas produced from the co-digestion process is 20401.08037 m^3/year by digesting a mixture of 2450 tons of sewage sludge and 5530 tons of biowaste that were produced in Narva city in the year 2012. The author of this study developed a carbon offset project for this amount of biogas, which is cost-effective, verifiable, quantifiable, and possesses long-term benefits in relation to additionality, the fundamental criteria defining the credibility of the carbon offset project. But it is quite unsure if the project will be able to overcome the lack of regulatory clarity during development which may pose difficulties for this ground-breaking project. However, the demand for such kinds of projects in both the compliance and voluntary carbon market is high. Moreover, the project needs to be quantified to evaluate how much emission reduction it can generate.

The findings of the study show that the biogas offset project can generate a considerable amount of carbon credits. The revenue generated by the carbon credits depends on the price of carbon credits. The price for carbon credit varies depending on the project location, project type, alignment with the standards, offset quality, and delivery guarantees. The revenue generated by the developed offset project was calculated based on the European market and it was found that it can range from 118 EUR to 41300 EUR depending on the different prices offered in both compliance and voluntary markets. There can be additional credit value generated by the offset project based on the co-benefits associated with the project. The offset projects with higher co-benefits tend to generate more revenue as buyers have an affinity to buy those credits. Some of the co-benefits include a reduction in fossil fuel extraction and associated pollution, the generation of high-quality fertilizer, and minimizing groundwater pollution. However, the generated carbon credit is also susceptible to uncertainties due to the higher leakage rates or automatic credit reductions associated with uncertain verification schemes. The lack of a specific credit verifier, marketplace, or protocol adds further uncertainty to these potential credit reductions in the voluntary carbon market. Therefore, the carbon offset project and the carbon credit generated by the author of the study require further research to combat complications of the regulatory framework and to deal with the uncertainties. As a novel approach, the study shows that co-digestion of sewage sludge and biowaste can bring a lot of opportunities for Narva city and can help the city to produce electricity from renewable sources and avail additional benefits by selling the carbon credits.

However, the study was a preliminary approach limited by data availability and an incomplete understanding of the co-digestion process inside the bioreactor. There are significant environmental impacts associated with the co-digestion process and the biogas yield was considerable which opens the scope for further research into carbon credits development. Based on rough calculations and a very conservative approach, it is found that the hypothetical project can generate income between 118 EUR to 41300 EUR from carbon credit sales. This income can be further augmented by creating additional credit value from the co-benefits of the biogas carbon offset project.

SUMMARY

In Estonia, biowaste constituted a quarter (122,000 tonnes) of municipal waste generated in 2019. Less than half of the total biowaste generated (51,000 tonnes) was collected through source-separated collections, while the remaining fraction was collected as mixed municipal waste. Although biowaste is one of the best feedstocks for anaerobic digestion, the utilization of biowaste for biogas production remains minimal in Estonia. Co-digesting biowaste with sewage sludge (SS) has been found to have a synergistic effect, resulting in increased biogas production. Thus, the present study was focused on evaluating the possibility to use the combination of sewage sludge and biowaste as a feedstock in the anaerobic digestion process and analyze the environmental impacts caused by the process. The most important output of the co-digestion process is biogas which is a renewable source of energy and can cogenerate heat and electricity. The generated electricity can replace the use of fossil fuel-based electricity consumption thus generating opportunities for GHG emission reduction. This emission reduction can lead to generating carbon offset projects and profitable carbon credits. The study further focused on generating carbon credits from the avoided emission resulting from the use of electricity produced from biogas.

A life cycle impact assessment has been conducted to evaluate the environmental impact of the co-digestion process. The analysis of the environmental impacts reveals that the co-digestion process of sewage sludge and biowaste has significant negative effects on the environment, with higher greenhouse gas emissions compared to similar studies. These environmental impacts hinder the sustainability of the co-digestion process. However, the environmental burdens can be minimized by utilizing the biogas produced for heat and power cogeneration within the process. To attract financing, the co-digestion process can be made more profitable by developing a biogas carbon offset project.

In this study, a total of 20,401.08037 m^3/year of biogas was produced from the co-digestion process, utilizing 2,450 tons of sewage sludge and 5,530 tons of biowaste generated in Narva city in 2012. The production of biogas in the co-digestion process is crucial for calculating carbon credits. This study emphasizes the importance of maximizing biogas yield to enhance the profitability of carbon offset projects. To achieve this, efforts should be made to improve the sorting method for removing impurities from biowaste and implement various pre-treatment methods for treating sewage sludge and biowaste. The author of the study developed a cost-effective and verifiable carbon offset project based on this biogas volume, meeting the criteria of additionality and possessing long-term benefits. However, challenges may arise due to regulatory uncertainties during project development. Despite the uncertainties, there is a high demand for such projects in both compliance and voluntary carbon markets. The revenue generated by the carbon credits depends on various factors such as project location, type, compliance with standards, offset quality, and delivery guarantees. Based on European market prices, the revenue from the offset project ranged from 118 EUR to 41300 EUR, considering different prices in both compliance and voluntary markets. The additional credit value can be generated based on the co-benefits associated with the project, such as reduced fossil fuel extraction, high-quality fertilizer production, and groundwater pollution reduction. However, uncertainties related to verification schemes and leakage rates can affect the generated carbon credits. The lack of specific credit verifiers, marketplaces, or protocols adds further uncertainty to the voluntary carbon market.

Further research is required to address regulatory complexities and uncertainties associated with the carbon offset project and the generated carbon credits. Despite the challenges, the study demonstrates that the co-digestion of sewage sludge and biowaste presents opportunities for Narva City to produce electricity from renewable sources and benefit from selling carbon credits. The study conducted was a preliminary approach that had limitations due to data availability and an incomplete understanding of the co-digestion process within the bioreactor. Despite these limitations, the study identified significant environmental impacts associated with the co-digestion process, and the biogas yield was found to be substantial, indicating the potential for further research in the development of carbon credits.

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