ISSN: 2754-4982

Journal of Civil Engineering Research & Technology

SCIENTIFIC Research and Community

Review Article

Open Access

Co-digestion of Sewage Sludge and Biowaste for Biogas Production, GHG Avoided Emissions, and Profitable Carbon Credit Development

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ABSTRACT

In Estonia, where biowaste comprises a significant portion of municipal waste, efficient waste management strategies are essential. Co-digestion presents a promising avenue to enhance biogas yield and reduce greenhouse gas emissions.

This study explores the potential of co-digesting sewage sludge and biowaste for biogas production, emphasizing carbon credit calculation and offset project development. Sewage sludge was effectively utilized as a co-feedstock for the co-digestion process, contributing to increased biogas production. In Narva City, 20,401.08037 m^3/year of biogas was produced in 2012, facilitating the generation of electricity from renewable sources and thus reducing GHG emissions, which facilitates the calculation of carbon credits. We developed a robust carbon offset project based on the biogas volume, meeting additionality criteria and demonstrating long-term benefits. The revenue potential from carbon credits ranged from 118 EUR to 41300 EUR, depending on market prices and project attributes.

Moreover, the offset project and calculated carbon credits offer tangible benefits to sustainable waste management and the implementation of the circular economy. By valorizing sewage sludge and biowaste through anaerobic digestion, the project contributes to waste diversion from landfills, reduces methane emissions, and promotes renewable energy generation. This integrated approach aligns with principles of sustainable waste management and supports the transition towards a circular economy model. Our findings provide valuable insights for policymakers and stakeholders interested in leveraging anaerobic digestion for renewable energy production and carbon mitigation.

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Received: August 18, 2024; **Accepted:** August 23, 2024; **Published:** August 31, 2024

Keywords: Co-digestion, Biogas Production, Carbon Credits, Renewable Energy, Circular Economy

Introduction

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 [1,2].

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 [3]. 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 [4].

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 [5].

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. successfully generated energy from fresh produce wastes, while Charis et al. and Ferrase et al. showed that biomass can be transformed into biochar, which can be utilized as a precursor for bioenergy production [6-8].

In their study, Acosta et al. 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. 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 [9].

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 [10]. 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 [11].

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 [12].

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 [13, 14].

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 [15].

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 [16]. 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 [17]. 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 [18-23].

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 [24]. 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 [25].

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 [26].

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 [27].

The impact of solid concentration on the generation of biogas from rapeseed oil cake via anaerobic digestion was investigated by Deepanraj et al [28]. According to their findings, the highest production of biogas was approximately 4000 mL when the solid concentration was increased to 20% [28]. 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 [29].

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 [30,31]. 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 [32]. 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 [33].

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 [34]. 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 [35]. 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) [36]. 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 [37].

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. Standardized procedures are used to verify carbon offsets to make them marketable in voluntary or compliance markets [38]. However, carbon offsetting can provide a supplementary source of revenue for new technologies or practices. 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 [39]. 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 [40]. 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 [39]. 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 CO_2 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 [40].

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 [41]. During its early stages, the voluntary carbon market witnessed significant demand primarily from public institutions, particularly the World Bank [42]. 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 $MtCO_2e$ worth of voluntary credits were traded, contributing to an overall market value of US$320 million [43]. 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 [44]. 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$) [45].

Within the framework of promoting anaerobic digestion as a sustainable waste management solution and leveraging its potential for greenhouse gas reduction through carbon offset initiatives, this study focuses on evaluating the biogas production potential from the co-digestion of sewage sludge and biowaste in Narva, Estonia, over the course of a year. 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 [46]. 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 [47]. 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 [46]. The total amount of sewage sludge generated that year reached 2450 tons, and this proportion has remained steady, according to the 2020 survey [47].

To mitigate the environmental impact of landfill disposal, this study proposes an anaerobic co-digestion process as an environmentally sustainable solution. The co-digestion of sewage sludge and biowaste is anticipated to enhance biogas production through synergistic interactions between the substrates. The biogas generated from this process will be upgraded to biomethane, which can be utilized for electricity generation, substituting electricity produced from fossil fuels. This substitution is significant as it results in reduced or avoided greenhouse gas (GHG) emissions, thereby facilitating the development of a carbon offset project. The study's objective is to quantify the electricity substitution potential and assess the success of the biogas offset project by evaluating the revenue generated from carbon credits associated with the avoided emissions.

The significance of this research lies in its potential to enhance waste management practices in Estonia by demonstrating the feasibility and efficiency of biogas production through the co-digestion of sewage sludge and biowaste. This study not only aims to optimize biogas yield but also focuses on the broader implications for sustainable energy generation. By replacing electricity derived from fossil fuels with biogas-generated electricity, the research directly contributes to reducing greenhouse gas emissions. Furthermore, the project explores the economic viability of this approach by quantifying the potential revenues from carbon credits, thus integrating environmental sustainability with economic incentives. These findings will offer valuable insights into the development of carbon offset projects and support the adoption of renewable energy technologies in Estonia and beyond.

Materials and Methods

The goal of this study is to quantify the amount of biogas production from 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 [47]. 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 [48]. It was essential to provide detailed specifications to maintain the accuracy and relevance of the study's aim [49]. 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, providing a quantitative description of the service performance and fulfilling the needs of the product system under investigation [48, 50]. Its primary objective is to establish a reference point that enables the association of inputs and outputs [49]. All material and energy flows, whether entering or leaving the system, are linked to this functional unit. The function of the life cycle inventory is the production of biogas from the co-digestion process. From the inventory table, the amount of biogas produced from the co-digestion process is calculated which is the functional unit of the study.

The focus of the life cycle inventory 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 [49]. 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.

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) [47]
sewage sludge	2311.3208	m^3	SEIT survey on the composition and quantities of waste (2020) [47]
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

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. 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 [51].
- 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.

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 [35]. 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 [52].

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 [53]. 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 [54]. 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 [55].

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 [56]. 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 [57].

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 [58].

Results and Discussions

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 [42].

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 [59]. 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 [54].

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 [60]. 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 [61]. 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 [62]. 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 [37].

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 [56]. 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.

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 [63]. 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.

Step 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.

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 [64, 65]. 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 [66]. 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 [35]. 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 [67]. 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.

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:

$$\text{Electricity Replaced (kWh of electricity)} * \text{Differential (kg of } CO_2\text{e/kWh)} * 1 \text{ tonne/1000 kg} = \text{Credits}$$
$$= 92612.375 \text{ kWh} * 0.6369 \text{ kg of } CO_2\text{eq/kWh} * 1 \text{ tonne/1000 kg} = 59 \text{ carbon credits}$$

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:

$$\text{Price} * \text{Credits} = \text{Value}$$

Table 2: 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 2). 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 3 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 [68].

Table 3: Data for Carbon Credits from four Different Studies

Reference	**Feedstock**	**Location**	**Credits generated**
West 2004 [69]	mixed feed	Canada	150
Munster & Juul Kristensen, 2005 [70]	mixed feed	Denmark	118
Row and Neable, 2005 [71]	manure	Canada	104
Ghafoori et al., 2006 [72]	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 [73]. The emergence of co-benefits as a crucial selling point for offset projects is becoming more prominent within voluntary offset markets [74, 75]. The demand for voluntary carbon offsets is driven by the narrative they hold, connecting them to local co-benefits [76]. 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 [77]. 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 [58]. Therefore, the biogas project developed in this study possibly can qualify for higher prices than the average prices per carbon credit.

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 [67]. 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 [39, 78, 79].

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 [80]. 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.

Conclusions

The most robust findings of the study include 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. 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.

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