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COMPARATIVE ANALYSIS OF BIOGAS AND COMPOST PLANTS FOR SOURCE-SEPARATED BIOWASTE TREATMENT

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ABSTRACT

This study presents a comparative analysis of biogas and compost plants for treating 9,400 tonnes of annually source-separated biowaste. The research evaluates the current semi-closed composting system and explores the feasibility of incorporating an anaerobic digestion (AD) facility with a post-composting process. Through a life cycle assessment (LCA), the environmental impacts of these treatment methods are assessed across several categories, including global warming potential, acidification, eutrophication, and resource use. The results reveal that the existing composting system contributes 19.15 kg CO2-equivalent emissions per tonne of waste, whereas the proposed AD system shows a net reduction of -25.87 kg CO2-equivalent per tonne, indicating a significant reduction in greenhouse gas emissions. However, the AD system also exhibits higher acidification potential (0.34 kg SO2-equivalent) and eutrophication potential (0.06 kg PO4-equivalent) compared to composting. In addition, biogas plants require a substantial initial investment for construction and equipment, and market fluctuations, particularly in energy prices and demand, can affect profitability. Compost plants, on the other hand, are characterized by their lower initial investment and simpler technology, making them easier to operate and maintain.

1. INTRODUCTION

In Germany, the separate collection of biowaste began in 1985. The mandatory separate collection of biowaste was enacted in 2012. Germany employs a dual system for collecting biowaste, utilizing both bio-bins and garden waste collection points to effectively manage organic waste. In 2020, this system resulted in the collection of approximately 5.3 million tonnes of biowaste through bio-bins, equating to 64 kilograms per capita (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023). Additionally, around 5.33 million tonnes of garden and park waste were collected separately, also averaging 64 kilograms per capita (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023; German Environment Agency, 2019).

There are currently 1,102 biological treatment facilities in Germany. This includes 218 biowaste composting plants, 599 green waste composting plants, 227 anaerobic digestion plants, and 58 facilities that integrate both composting and anaerobic digestion processes (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023). These facilities ensure that 97 percent of received biodegradable waste undergoes material recovery. Specifically, the composting process produced approximately 4.8 million tonnes of compost, used as nutrient-rich fertilizers and soil improvers in agriculture, forestry, and landscaping. Anaerobic digestion plays a crucial role in this system, processing around 6.24 million tonnes of biowaste to produce digestate and substantial quantities of biogas (Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection., 2023; German Environment Agency, 2019). This biogas is then utilized for electricity and heat generation, contributing significantly to Germany's renewable energy supply. The Renewable Energy Sources Act (EEG) supports the integration of anaerobic digestion into existing composting facilities, enhancing the overall sustainability and efficiency of biowaste treatment.

This study focuses on the treatment of biowaste in a medium-sized city in Germany (Soroush Nakhaei, 2024). Currently, source-separated organic waste is transported to a compost plant where it is processed using a box system. This setup ensures legally compliant treatment of biowaste waste until 2027. However, due to the impending end of the technical service life of the composting facility, a re-evaluation of the treatment processes and location beyond 2027

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is necessary. In response, a proposal over the next two years to shape the future of organic waste treatment and utilization is required. These proposals will analyze volume developments, site considerations, and potential upgrades to system technology to enhance environmental and socioeconomic outcomes. Among the alternative technologies under consideration is the establishment of a biogas plant with a post-composting system for biowaste.

Numerous studies have examined the environmental impact of biological waste treatment methods such as composting and anaerobic digestion (AD) in European cities (Table 1). Several factors must be considered when assessing the environmental benefits of these technologies, including system boundaries, life cycle inventories, and the selected impact categories (Oviedo-Ocaña et al. 2023). When comparing case studies from different countries, variations in energy mix, feedstock composition, and regulatory frameworks significantly influence the final results. In Germany, government subsidies support AD plants. Mayer et al. (2020) found that AD followed by composting was the most cost-effective and environmentally sustainable option. It had a median levelized energy cost of 27 €ct/kWh, lower than AD with incineration or bio-drying with incineration. While biological treatment demonstrates greater environmental benefits in Germany and Switzerland, in the Czech Republic, where the country remains dependent on fossil fuels, incineration has been shown to provide higher benefits in most impact categories (Edelmann and Schleiss 1999; Mayer et al. 2020; Guillaume et al. 2023).

Regarding the combined effects of feedstock composition and energy mix, (Lewerenz et al., 2023) showed that, among various German case studies, composting with a semipermeable membrane resulted in the lowest emissions when treating waste composed of 40% lignocellulosic material and 60% food waste across all treatment options. However, in a case study conducted in Italy, where household waste constituted 75% of the feedstock and green waste made up the remaining 25%, upgrading an existing composting facility to an integrated AD and composting system handling 40,000 tonnes per year led to an overall reduction in environmental impacts across all categories analyzed (Neri et al. 2018). Notably, GHG emissions fell by more than 20%, fossil resource use decreased by 40%, and human toxicity impacts dropped by 70% (Neri et al. 2018).

Emission management at composting plants and transportation distance are other decisive factors in the overall environmental impact (Söllinger, 2018). Well-managed processes help minimize emissions, improve the efficiency of composting plants, and make them a more favorable option (Essonanawe Edjabou and Scheutz, 2023; Bong et al. 2017). When large amounts of organic waste are available locally, AD becomes more viable, and biomethanization is an effective solution for improving efficiency (Lombardi and Francini 2020). It enhances the global warming potential and non-renewable energy impact categories more effectively than combined heat and power (CHP) systems (Ardolino et al., 2018).

While the literature highlights the relationship between financial and environmental sustainability, it lacks an in-depth analysis of how to choose waste treatment technology for a city/town concerning decisive technological factors and national policies. This article aims to bridge this gap by contextualizing organic waste treatment strategies within real-world urban settings, providing a more practical and policy-relevant perspective. The goal of this research is to analyze and compare the sustainability of different organic waste treatment methods, specifically focusing on composting and AD. The central research question addressed is: " Which organic waste treatment method, composting or AD, is appropriate for treating source-separated biowaste in the context of a medium-sized town?" The analysis will quantify the potential environmental impacts, including CO2-equivalent emissions per tonne of biowaste, and discuss the pros and cons of developing each technology. The results of this study are intended to provide data-driven insights into the environmental sustainability of biowaste management systems. These findings will inform waste management authorities and stakeholders about the most sustainable and environmentally beneficial practices for treating separately collected organic municipal waste.

2. METHOD

2.1 Biowaste generation and collection

The study area is a city with approximately 200,000 inhabitants located in Germany. In 2022, the city generated about 9,374 tonnes of biowaste, accounting for around 19% of the city's total waste generation (Figure 1). Biowaste is collected using brown bins with capacities of 120 liters and 240 liters, depending on the generation rate. These bins are emptied weekly in the summer and biweekly in the winter, ensuring efficient management of organic waste throughout the year. The collected biowaste contains about 6% contaminants, primarily plastic, glass, metal, and other materials. The city has an ongoing public awareness campaign to reduce impurities, especially plastic, in the collected biowaste.

2.2 Scenario analysis

In the existing biowaste treatment system (S0), biowaste treatment is conducted using a semi-closed, automated composting system (Figure 2). The process begins with shredding and screening the waste to remove contaminants, followed by homogenization (Amuah et al., 2022). The prepared waste undergoes intensive composting in enclosed composting boxes, where the environment is tightly controlled to optimize efficiency and minimize odor emissions and environmental impact. This is followed by a secondary composting phase, using turned windrows. The final stage involves refining the compost to meet quality standards for soil improvement. This semi-closed, automated system ensures a controlled environment and reduced risk of groundwater contamination.

In the future scenario (S1), a biogas facility is evaluated. The treatment process starts with the acceptance and screening of biowaste waste, using a magnetic separator to remove metals and other contaminants (González et al., 2022). This is followed by a 2 to 4-day homogenization phase. The materials are then fed into a dry fermenter for

TABLE 1: Literature analysis on biological waste treatment methods.

Source	Country	Biological treatment system	Assessment methods	Main findings
(Lewerenz et al. 2023)	Germany	Composting (open, semi-closed, semipermeable membrane, closed) AD (with open and closed post-rotting) AD+ open composting AD+ closed composting	LCA (open LCA), and uncertainty analysis.	• Composting with a semipermeable membrane had the lowest total impact score. • Highest impact score was associated with the combined anaerobic digestion and closed composting system at 31 EPG/kg. • low-tech, smaller systems with short transportation distances have more ecological benefits for municipalities over high-tech, larger ones requiring extensive transport.
(Edelmann and Schleiss 1999)	Switzerland	Windrow, Enclosed composting, AD, AD + Enclosed composting, AD+ Windrow	LCA using Eco-indicator 95+, Energy Balance, Economic Assessment, Sensitivity Analysis	• AD has the lowest environmental footprint, outperforming both composting and incineration. • AD is the most energy-efficient, producing significant energy from biogas. • AD and EC, are more cost-effective than incineration.
(Ardolino et al. 2018)	Italy	Biomethane production by AD	LCA (Simapro8), and sensitivity analysis.	• AD of organic waste into biomethane for transport reduces global warming potential by 79% compared to biowaste-to-energy. • Non-renewable energy potential is decreased by 36% when producing biomethane instead of energy from biowaste.
(Neri et al. 2018)	Italy	Windrow, AD + Windrow	LCA (Simapro), Impact assessment (ReCiPe), energy and resource analysis, and avoided landfill benefits.	• AD reduces environmental impacts significantly compared to traditional composting. • AD produces enough electricity to run the plant, with 20% of the heat being reused. • AD + Windrow is more cost-effective and sustainable, reducing fossil fuel depletion and climate change impacts.
(Söllinger 2018)	Austria	Windrow, Enclosed, Enclosed Aerated	LCA (OpenLCA), Impact assessment (ReCiPe), energy analysis, and sensitivity analysis.	• Enclosed aerated pile composting has the lowest global warming potential. • Proper management is crucial to minimize CH_4, N_2O, and NH_3 emissions. • Energy demand and emission control are key factors influencing environmental impacts.
(Lombardi and Francini 2020)	Italy	Five biogas-to-biomethane upgrading technologies	LCA (SimaPro V8), LCC	• Amine Scrubbing showed the best environmental performance. • Larger-scale biogas upgrading plants are more cost-effective. • Electricity consumption is crucial in determining the economic and environmental outcomes of biogas upgrading technologies.
(Oviedo-Ocaña et al. 2023)	Global	Various composting technologies including home composting, centralized systems, etc.	Review of 56 LCA studies	• Definitions of system boundaries and selection of impact categories vary widely, affecting comparability. • Data quality is often inconsistent and poor due to varying local conditions and assumptions. • There is a need for standardized methodologies, comprehensive assessments, and better training in LCA methodologies.
(Guillaume et al. 2023)	Czech	Windrow, and AD (semi-dry process)	LCA (GaBi)	• Incineration is the most sustainable option due to Czech's fossil-fuel-based energy mix, producing 183.55 kWh of electricity and 2741.94 kWh of heat per ton of OFMSW. • Composting can supply up to 40% of the region's nitrogen fertilizer needs and reduce ecotoxicity and the use of mineral resources. • AD combined with composting is the best option for meeting EU biowaste separation targets, balancing lower environmental impacts, and enhancing CE benefits.
(Mayer et al. 2020)	Germany	AD + post-composting, and incineration	LCA (Open LCA), Impact assessment, and levelized costs of energy (LCOE)	• AD followed by composting had the lowest median LCOE at 27 €ct/kWh. • Incineration showed higher GWP (~500 g CO2-Eq/kWh) and FDP (~0.075 kg oil-Eq/kWh) compared to AD. • The cascaded treatment system (anaerobic digestion + incineration) had the highest economic costs at 89 €ct/kWh.

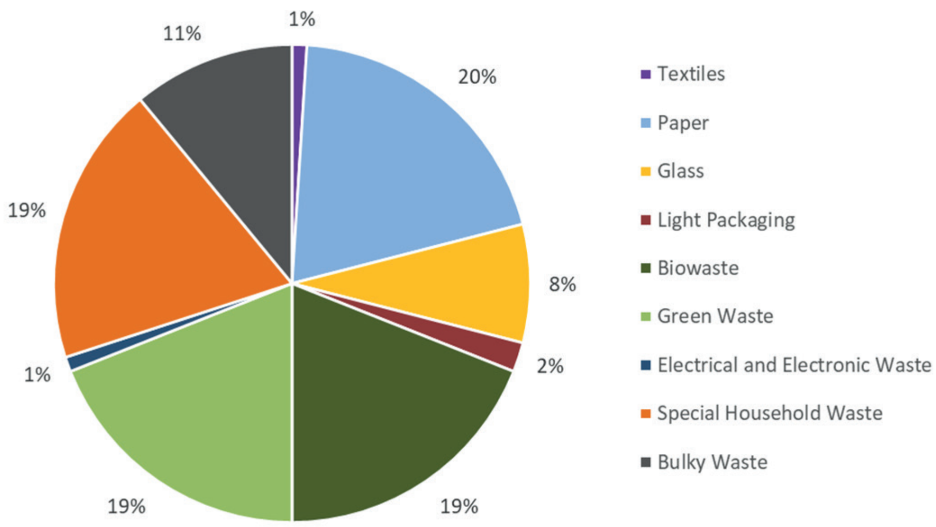


FIGURE 1: Physical composition of solid waste in 2022 (Nakhaei, 2024).

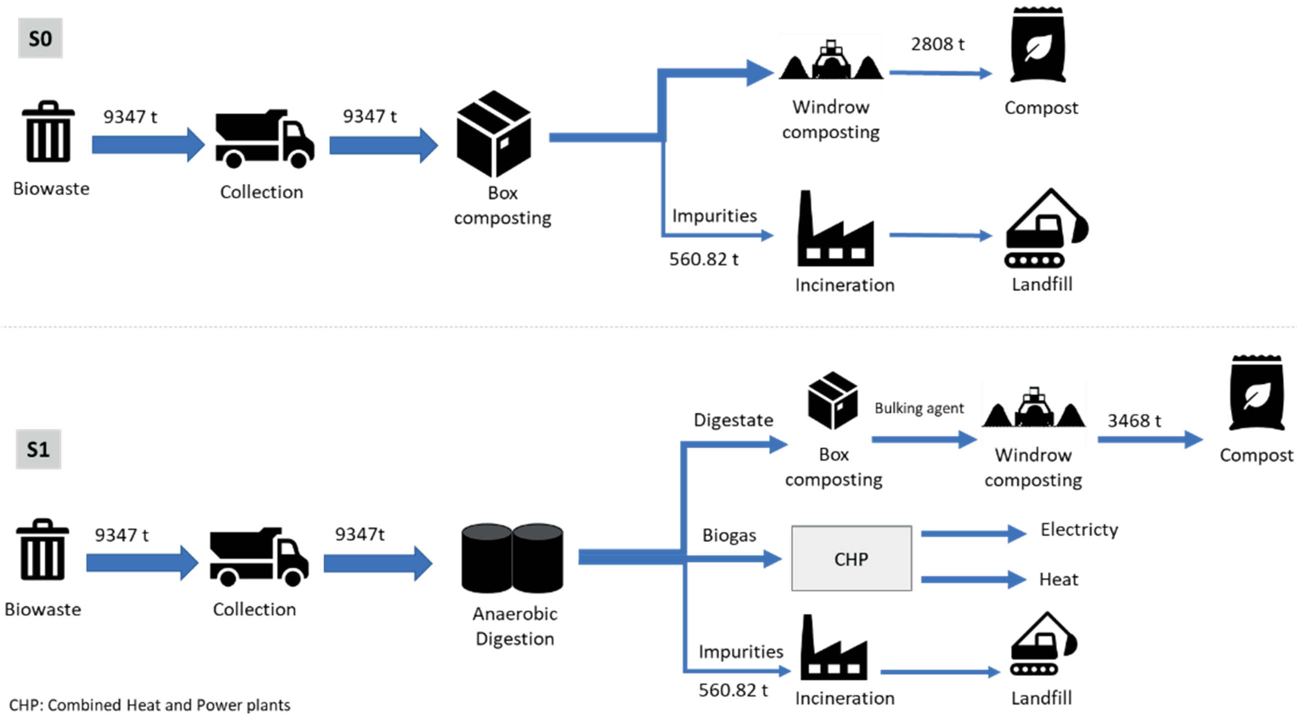


FIGURE 2: Annual biowaste mass flow of the existing system (S0) and future scenario (S1).

anaerobic digestion, which lasts about 21 days. After digestion, the materials are dewatered. The resulting product is mixed with green waste and undergoes a secondary composting phase to produce high-quality compost. The gases generated during the digestion process are utilized in combined heat and power plants to produce heat and electricity (Henriksen et al., 2019).

2.3 Life cycle assessment

2.3.1 Goal and scope definition

Environmental LCA is conducted for both S0 and S1. The system boundary for S0 includes source-separated biowaste storage, collection, transportation, and biological treatment using rotting box composting technology, followed by windrow composting for maturation, and incineration of foreign materials for disposal. For S1, the system boundary involves biological treatment using biogas technology, followed by windrow composting for the maturation of digested biowaste and sending the generated biogas to a CHP plant for the generation of heat and electricity. The functional unit is related to the amount of waste generated in the reference year, 2022. Figure 3 shows the system boundaries for the LCA.

The Lifecycle Analysis was modeled with the “WRATE V4 academic version” software (Castellani et al., 2023).The model contains over 150 standard processes for waste

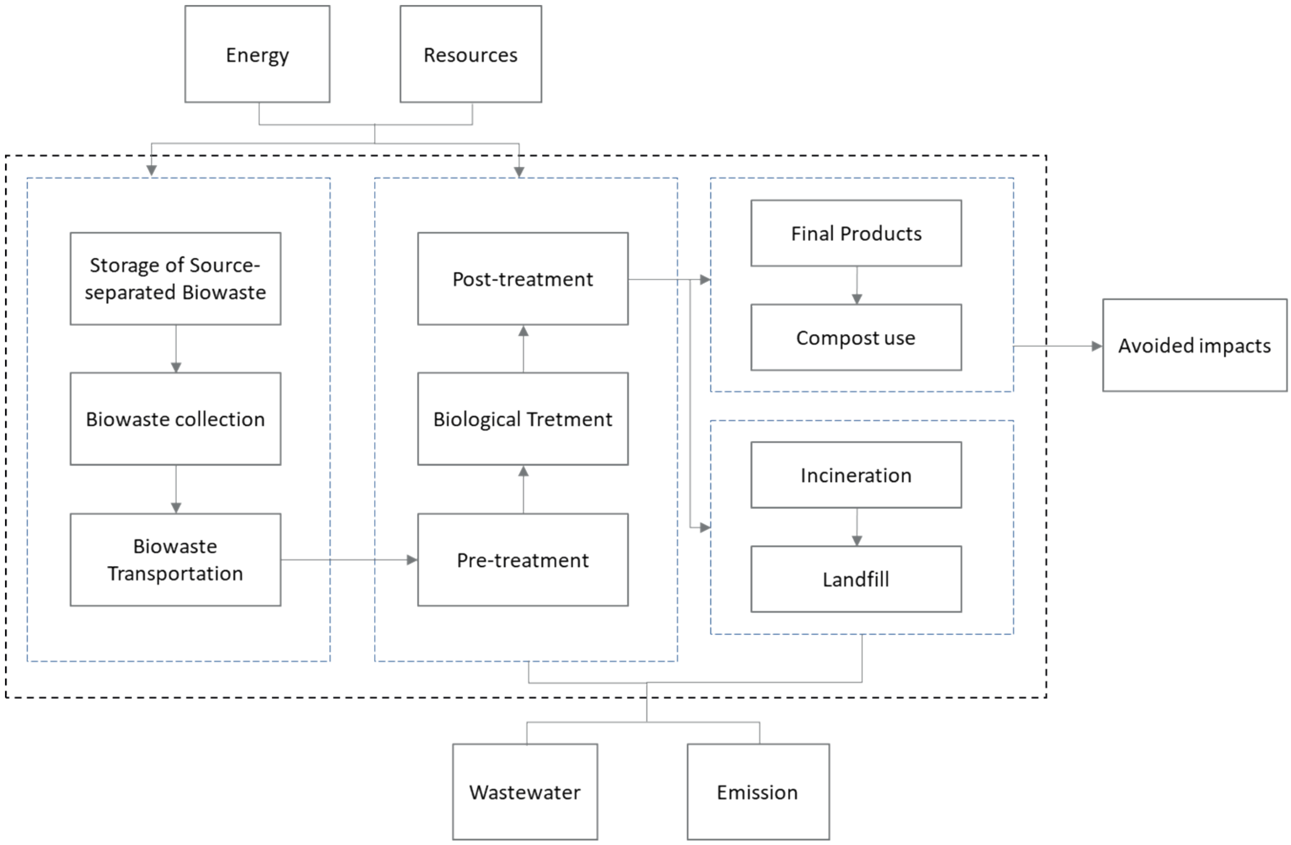


FIGURE 3: LCA system boundary.

management including complex CHP plants, landfills, various vehicles, and numerous recycling. The impact assessment uses the default version provided by the software. However, the software version has limited facilities and vehicles, necessitating the selection of a similar facility and a vehicle with emission class Euro 4.

For the environmental assessment, six categories were defined to show the environmental and human impact, including Climate Change (as global warming), Acidification Potential, Eutrophication Potential, Freshwater Aquatic Ecotoxicity, Human Toxicity, and Resources. To make the data comparable various pollutants are assigned to one or more categories based on their impact potential in equivalent quantities of a reference substance. For the impact assessment, all pollutants are multiplied by an equivalence factor according to their significance (Edelmann and Schleiss, 1999). The impact assessment method of the analysis is related to the CML 2001 database.

2.3.2 Life cycle inventory

The required data for the analysis were collected according to the system boundary of the composting and biogas plants. Primary data including storage bins, and km travel to the biological treatment facility per year were collected from the municipality's report. Secondary data including the characteristics of biological treatment plants were retrieved from the literature and WRATE V4 database. First and secondary data were utilized in the life cycle inventory (Table 2). The electricity mix is considered a low carbon emission, as reported in the WRATE v.4 database (5% fossil fuels, 95% renewable), which is comparable to the German city situation.

In the storage of biowaste, the number of containers employed per year was 14,550. For the collection of biowaste, diesel-powered trucks traveled 675 km per year, covering 50% urban roads, 5% rural roads, and 45% motorways. The treatment of biowaste using semi-closed composting technology had a capacity of 20,000 tonnes per year, with a residence time of 84 days and a lifespan of 25 years. In the treatment of biowaste using AD, three reinforced concrete fermenters with a volume of 880 m³ each and a dwell time of about 3 weeks produced around 500 m³/hour of biogas containing 55% methane.

2.3.3 Interpretation

The comparison of environmental indicators was used to analyze the results, utilizing the normalization approach to convert the outcomes into European person equivalents (EP). This allowed for a comprehensive comparison of S0 and S1, considering all environmental indicators to identify potential reductions or enhancements in impacts when transitioning from the current biowaste treatment system (S0) to the proposed future scenario (S1).

2.4 Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis

In addition to the LCA, a SWOT analysis provides insights for decision-makers considering new system de-

TABLE 2: Life cycle inventory of the processes involved in the research.

Process	Description	Variable introduced	Use of materials	Energy demand
Storage of biowaste	Typical plastic bin containers consist of three parts: the bin, the lid, and the wheels, with a capacity of 120 L. The service life of the product depends on how it is handled by residents and waste collection teams.	Number of containers employed per year was 14550 for both scenarios.	Polyethylene	-
Collection of Biowaste	6 × 4 RCV diesel-powered collection trucks (Euro 6) were used.	675 km travelled per year	-	Diesel
Treatment of Biowaste using composting	Incoming biowaste is unloaded onto a concrete slab and moved by a front-end loader to the shredder. The shredded waste is loaded into the rotting box for stabilization, with controlled air circulation. After composting, the material is matured in windrows, and screened. The final compost is stored in the storage building.	50 % urban road, 5% rural road and 45% motorway.	-	Electricity Water
Treatment of Biowaste using AD	A magnetic separator first removes metals. Biowaste is fermented and then the digitated material is dried, mixed with green waste, and undergoes a post-rotting process to produce compost. The biogas generated is used in a cogeneration plant to produce heat and electricity.	Capacity: 20,000 tonnes year−1. Residence time of 84 days. Life span: 25 years.	-	Electricity water
Disposal of impurities	The process for removing foreign material involves shredding the waste to separate and eliminate contaminants.	Three reinforced concrete fermenters, each with a volume of 880 m^3, dwell time of about 3 weeks.	Steel	Electricity

velopments. The analysis highlights the strengths, weaknesses, opportunities, and threats associated with each treatment method, aiding in the selection of the most sustainable and economically viable option for future biowaste management.

3. RESULTS AND DISCUSSION

3.1 Comparative Environmental Assessment of Biowaste Treatment Approaches

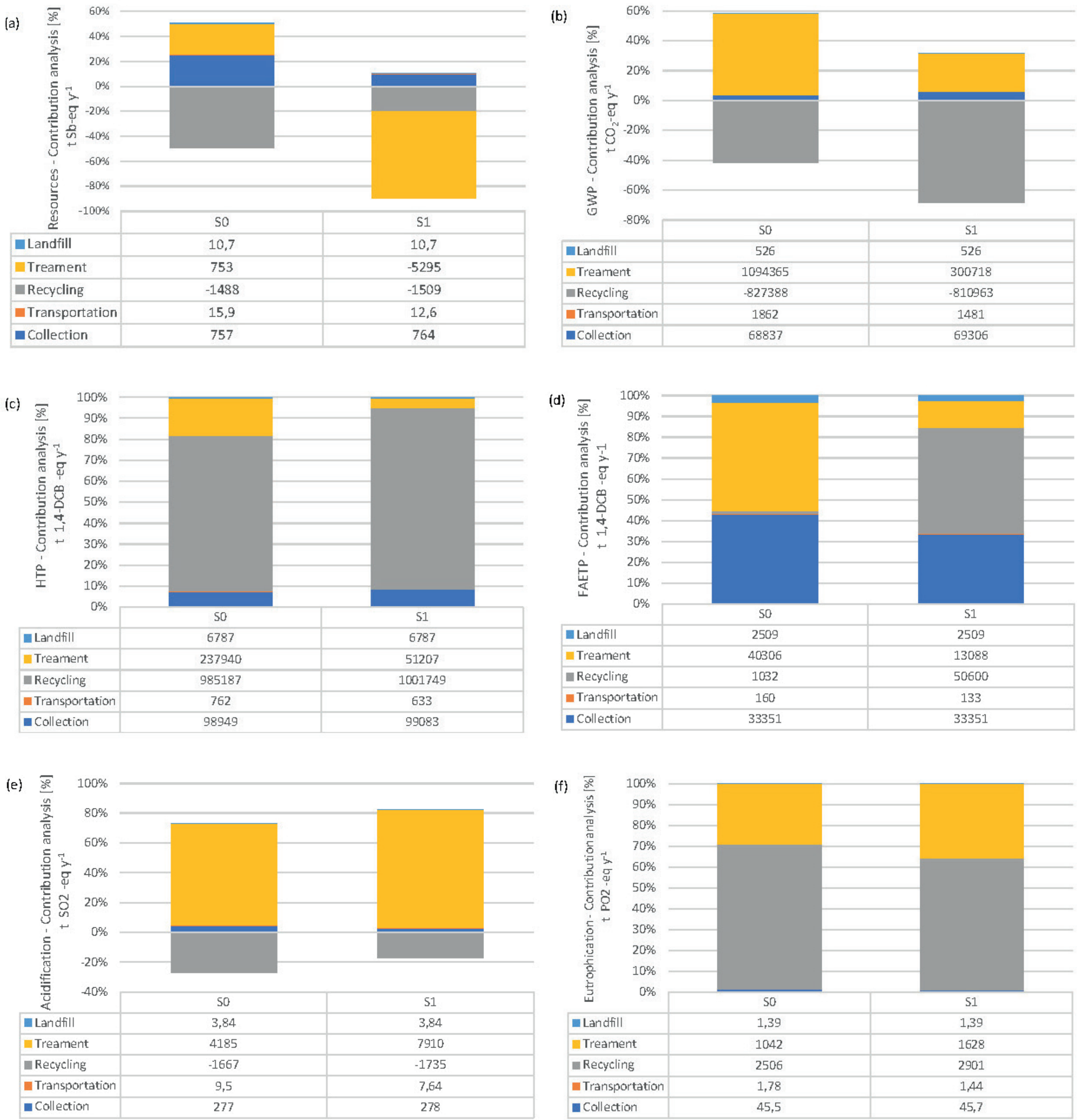
This study provides a detailed analysis of the environmental impacts of two biowaste treatment methods: box composting and AD (Figure 4). The results are based on a life cycle inventory and consider specific hypotheses formulated in the goal and scope definition of the life cycle assessment.

The results reveal variable trends in environmental impacts. Scenario 1 shows generally better performance in terms of resource use and climate change impacts compared to Scenario 0. Scenario 1 exhibits significant negative emissions, particularly in the treatment phase, while Scenario 0 has the most significant overall climate impacts. The primary source of GHG emissions is the direct release during the composting process, particularly from the decomposition of organic matter (Bong et al. 2017). The main contributor is methane, with higher emissions recorded in facilities that process the organic fraction of household waste (Essonanawe Edjabou and Scheutz, 2023). HTP is significant in both scenarios, with Scenario 1 having a greater influence during recycling, especially when the product is used in landscaping. Both scenarios demonstrate harmful FATEP, especially when organic waste is disposed of in bins. Scenario 1's recycling impacts in both HTP and FATEP are more significant than those in Scenario 0. In terms of acidification, Scenario 1 has double the impact of Scenario 0. Eutrophication potential is notably higher in Scenario 1 for both treatment and recycling phases.

For each impact category, the total emissions of each scenario are compared. The results indicate that GWP and resource use are the most significant indicators of environmental impacts in both scenarios (Figure 5). Scenario 0 has higher normalized values in acidification potential, eutrophication potential, and freshwater aquatic ecotoxicity, whereas Scenario 1 shows a negative value in climate change impact and resource use, indicating superior performance in these categories.

When comparing the impact assessment for the treatment options per tonne of waste, box composting has the highest greenhouse potential with a value of 19.15 kg CO_2-Eq, indicating significant greenhouse gas emissions during the composting process (Table 3). AD, on the other hand, has a negative value of -25.87 CO_2-Eq, indicating a net carbon sink effect. This is due to the production of biogas, which can replace fossil fuels and thus reduce greenhouse gas emissions. Additionally, the escaping gas in AD is stored as biogas, unlike in box composting, where it is filtered through biofilters and released into the air. This finding aligns with the study by (Neri et al. 2018), which demonstrates that integrating a biogas plant into a composting facility and expanding its capacity over seven years made fossil fuel depletion the primary environmental impact. Traditional composting is energy-intensive, primarily due to its high oxygen demand for microbial activity, making it dependent on external electricity sources. The electricity produced in AD scenarios exceeded internal energy needs, allowing surplus energy to be fed into the national grid, thereby reducing reliance on conventional power sources.

Box composting has a moderate acidification potential of 0.12 kg SO_2-Eq, while AD has a higher acidification potential of 0.34 kg SO_2-Eq, likely due to the release of acidic



(a)

	S0	S1
Landfill	10,7	10,7
Treament	753	-5295
Recycling	-1488	-1509
Transportation	15,9	12,6
Collection	757	764

(b)

	S0	S1
Landfill	526	526
Treament	1094365	300718
Recycling	-827388	-810963
Transportation	1862	1481
Collection	68837	69306

(c)

	S0	S1
Landfill	6787	6787
Treament	237940	51207
Recycling	985187	1001749
Transportation	762	633
Collection	98949	99083

(d)

	S0	S1
Landfill	2509	2509
Treament	40306	13088
Recycling	1032	50600
Transportation	160	133
Collection	33351	33351

(e)

	S0	S1
Landfill	3,84	3,84
Treament	4185	7910
Recycling	-1667	-1735
Transportation	9,5	7,64
Collection	277	278

(f)

	S0	S1
Landfill	1,39	1,39
Treament	1042	1628
Recycling	2506	2901
Transportation	1,78	1,44
Collection	45,5	45,7

FIGURE 4: Contribution analysis of the environmental impact indicators per scenarios: (a) Resource depletion, (b) Global Warming Potential (GWP), (c) Human Toxicity Potential (HTP), (d) Freshwater Aquatic Ecotoxicity Toxicity Potential (FAETP), (e) Acidification potential and (f) Eutrophication potential. Data are reported in t-Eq per year.

gases during the process. In terms of eutrophication potential, box composting shows a relatively low value of 0.03 kg PO4-Eq, whereas AD has a higher eutrophication potential of 0.06 kg PO4-Eq, which may be attributed to nutrient losses during the process. Box composting has a significant freshwater aquatic ecotoxicity potential of 1.92 kg 14-DCB-Eq, while AD shows a negative value of -3.19 kg 14-DCB-Eq, indicating possible health-promoting effects or avoidance of toxic emissions. Resource use is moderate in box composting, with a value of 0.06 kg Antimony-Eq, while AD shows a negative value of -0.28 kg Antimony-Eq, indicating that AD may save resources through the recovery of nutrients and energy.

The impact per tonne of waste for AD is lower than the results of (Castellani et al., 2023) which used the same software for the organic fraction of municipal waste on remote islands in Italy. This difference is due to variations in the electricity mix; in the Italian case study, diesel fuel was considered.

3.2 Evaluating Biogas and Compost Plants through a SWOT Analysis

This SWOT analysis aims to evaluate the potential of establishing a biogas plant versus a compost plant for the treatment of source-separated biowaste in a German city with a population of around 200,000. The goal is to determine which option provides better economic, environmental, and social benefits. Biogas plants have the significant advantage of producing renewable energy in the form of biogas, which can be converted into electricity, heat, and

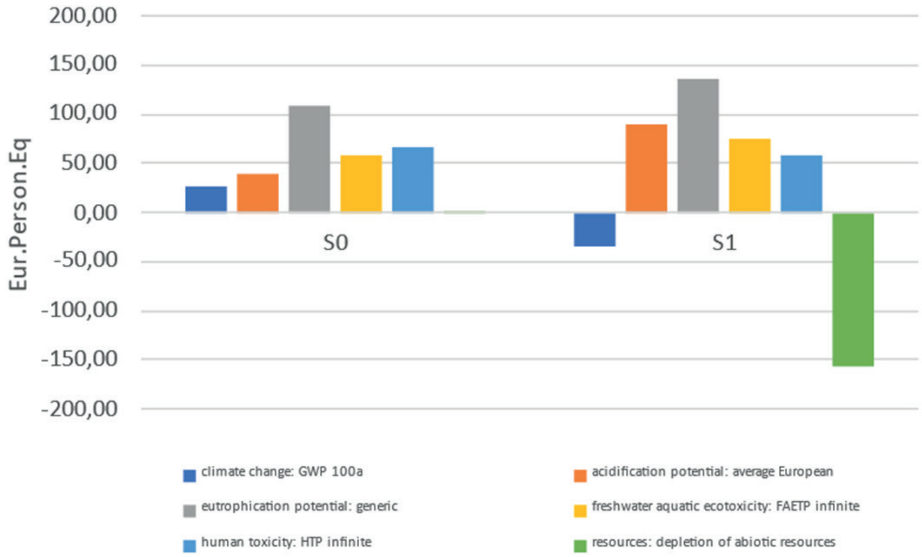


FIGURE 5: Environmental impact assessment of S0 and S1 (normalization in EP).

vehicle fuel. This contributes to the reduction of greenhouse gas emissions by capturing methane that would otherwise be released from waste decomposition in landfills (Gilbert et al., 2022). Additionally, the process generates nutrient-rich digestate, which serves as an effective fertilizer (Gilbert et al., 2022). As a result, more biogas plants were constructed for the treatment of source-separated biowaste. In 2022, for the first time, more biowaste was treated in biogas plants than in composting plants (Figure 6).

Despite their benefits, biogas plants require substantial initial investment for construction and equipment (Walk and Gambini 2024). Their operational complexity necessitates skilled labor for efficient management and maintenance. Biogas plants depend heavily on a continuous and reliable supply of biowaste, making their operation vulnerable to feedstock composition and physical contamination (Walk and Gambini, 2024). The potential for partnerships with agricultural and food industries for feedstock supply and integration with other waste management solutions presents opportunities (Figure 7).

However, biogas plants face several threats, such as potential regulatory changes that could impact their operations. Market fluctuations, particularly in energy prices and demand, can affect profitability. Competition from other renewable energy sources and waste management solutions adds to the risks.

Compost plants, on the other hand, are characterized by their lower initial investment and simpler technology, making them easier to operate and maintain (Walk and Gambini, 2024). They produce high-quality compost, providing significant environmental benefits by reducing landfill usage and associated methane emissions (Gilbert et al., 2022). However, compost plants do not recover energy and require effective odor management and significant land area for operations. Their processes can also be affected by weather conditions (Walk and Gambini, 2024).

The opportunities for compost plants include a growing market demand for organic products, local job creation, and potential partnerships with farmers and gardeners. Increasing public awareness of composting benefits also presents a positive outlook. Nonetheless, they face threats from potential regulatory changes, competition from cheaper synthetic fertilizers, challenges in market acceptance, and environmental concerns related to leachate and odor if not properly managed.

In the case of our study area, a mid-sized town, the potential benefit includes a reduced carbon footprint associated with renewable energy production. In terms of weakness and threats, impurities and the potential of biogas production from the input feedstocks are relevant. The biological treatment of organic waste, particularly biowaste, has proven challenging because the collected ma-

TABLE 3: Environmental impact assessment for the treatment options per tonne of waste.

Impacts	Unit	Box	AD	Impacts per tonnes waste	
				Box	AD
Climate change	kg CO2-Eq	339619	-458690	19,15	-25,87
Acidification potential	kg SO2-Eq	2210	5961	0,12	0,34
Eutrophication potential	kg PO4-Eq	539	1131	0,03	0,06
Freshwater aquatic ecotoxicity	kg 1,4-DCB-Eq	34092	6722	1,92	0,38
Human toxicity	kg 1,4-DCB-Eq	131042	-56518	7,39	-3,19
Depletion of abiotic resources	kg antimony-Eq	1141	-4944	0,06	-0,28

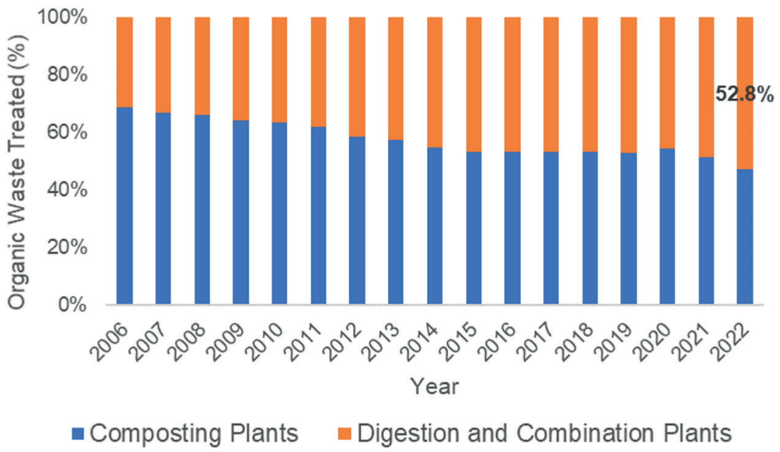


FIGURE 6: Ratio of Biowaste treated in biological facilities in Germany (German Environment Agency, 2024).

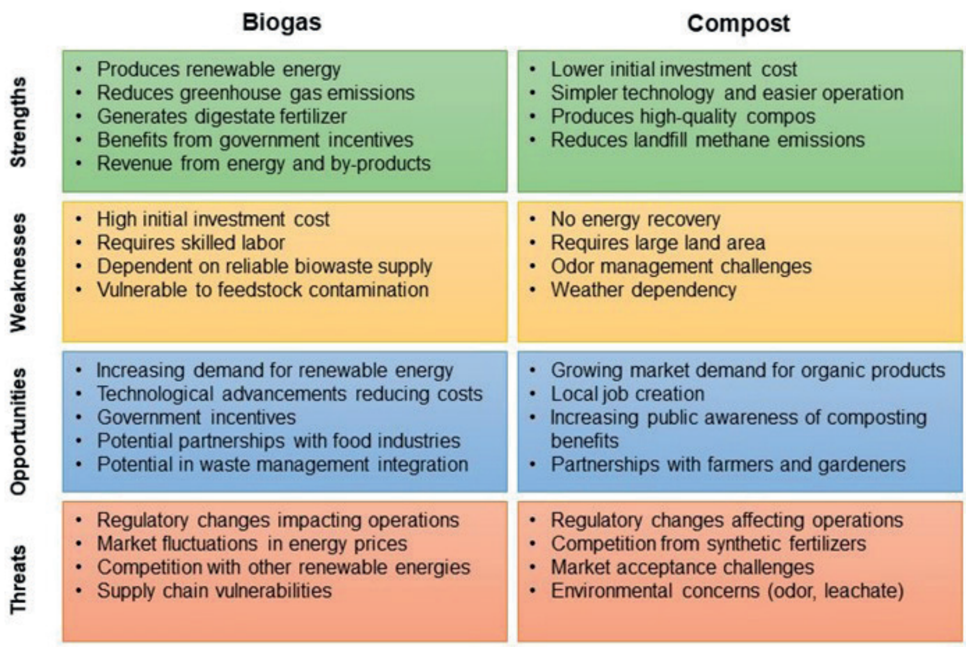


FIGURE 7: Strengths, Weaknesses, Opportunities, and Threats (SWOT) analysis for compost and biogas technology.

terial often contains various impurities and foreign matter. Depending on its quality, residual impurities in biowaste can lead to additional costs for digestate treatment. Despite processing efforts, it is not possible to completely remove these impurities, which reduces the quality of the end products and lowers the potential revenue from the commercialization of digestate and compost. This makes the biogas option even more expensive.

The quality and quantity of biowaste also vary across seasons due to changes in temperature and solar radiation. A study conducted by (Sprafke et al. 2020) estimated the specific biogas yield based on material availability in different seasons within the study area. The biogas yield ranged from 91 to 160 m³ per Mg, with seasonal fluctuations affecting waste volume, thereby making it challenging to maintain a consistent supply of biogas or biomethane. In winter, biogas production can drop to 52% of the maximum volume, leading to a CHP utilization rate of 72% without co-substrates. A common practice for optimizing plant operation is the use of co-substrates or biowaste from periods with increased biowaste volumes. However, German regulations impose limitations on the use of co-substrates up to 10% (Federal Office of Justice 2023). Additionally, storage is not a viable option, as biowaste is subject to biodegradation processes. Consequently, the volatile nature of biowaste and the uncertain availability of co-substrates present significant challenges for optimizing plant operations from a techno-economic perspective. The risks associated with biogas potential are a significant drawback. In contrast, composting is more adaptable to fluctuations in both quality and quantity. Composting is the more cost-effective option, as the town already has a compost plant that can be upgraded to accommodate the new facility.

These findings align with existing literature. Biogas plants with improved environmental and economic performance typically have a capacity exceeding 40,000 tonnes per year (Lewerenz et al., 2023; Mayer et al. 2020). The reported feedstock for these facilities contains a higher proportion of food waste than lignocellulosic material (Neri et al. 2018). However, if increasing plant capacity—whether in quantity or quality—requires extensive biowaste transportation, a smaller plant (such as this study's approximately 20,000-tonne facility for both green and organic waste) with simple technology and well emission strategies (Essonanawe Edjabou and Scheutz 2023; Bong et al. 2017) is a more environmentally friendly option than a larger, more advanced plant (Lewerenz et al., 2023).

4. CONCLUSIONS

The comparative analysis of biogas and compost plants for source-separated biowaste treatment reveals distinct differences in their environmental impacts across various categories. LCA indicates that AD has a more favorable outcome in terms of GWP, showing a net reduction of -25.87 kg CO2-equivalent per tonne of waste, which is over 200% lower than the 19.15 kg CO2-equivalent emissions from composting. This significant reduction is primarily due to the biogas produced during AD, which can replace fossil fuels and thus lower overall greenhouse gas emissions.

A SWOT analysis was used to compare the main benefits of biogas, such as renewable energy production and government incentives, with the challenges of operational complexity and national regulations. Since German regulations do not allow more than 10% co-substrate for biogas plants receiving biowaste, and the availability of biowaste in winter is low in the study area—potentially dropping to 52% of the maximum volume—it is not feasible to establish a biogas plant. Additionally, impurities in the biowaste pose a challenge, as their removal from the digestate increases the overall cost of biogas technology.

Opting for a composting plant offers advantages such as lower initial costs and simpler technology while producing a high-quality final product and reducing landfill use. The facility has over 20 years of experience in operating a composting plant, and within a new setting, improved emission control measures can be implemented to increase efficiency.

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