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Assessing the Economic and Environmental Impacts of Anaerobic Digestion for Municipal Organic Waste: A Case Study of Minamisanriku Town, Japan

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Abstract: Anaerobic digestion (AD), or biogas technology, is an optimal method for municipal organic waste (MOW) treatment, recovering both material and energy. This study takes a life cycle assessment perspective and examines the economic and environmental impacts of a BIO facility in Minamisanriku Town, Japan, which has utilized MOW (kitchen/food waste and surplus sludge from sewage) as local biomass resources since 2012. Stakeholder interviews were conducted to gather data on material flows and impacts. Scenario analysis considered various conditions, such as pre- and post-operation of the BIO facility, the use and non-use of digestate as liquid fertilizer, and the facility's 100% operational efficiency. The results indicate that full operation of the BIO facility and marketing of value-added products, such as branded rice grown using liquid fertilizer, could significantly reduce greenhouse gas (GHG) emissions, lower integrated environmental costs, improve the regional economy, and increase net income. In the business as usual (BAU) scenario with a 56% operation rate of the BIO facility, there is a 13% improvement in both economic and environmental impacts compared to the pre-operation baseline. This study underscores the importance of maximizing biomass utilization to develop value-added uses by enhancing, extending, and expanding stakeholder collaboration.

Keywords: biomass utilization; stakeholder participation; regional revitalization; circular economy; life cycle assessment (LCA); LIME (life cycle impact assessment method based on endpoint modeling); sustainable development goals (SDGs)

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1. Introduction

Municipal organic waste (MOW), including kitchen waste and sewage sludge, poses significant environmental challenges but also offers substantial opportunities for resource recovery through anaerobic digestion (AD). Also known as biogas technology, AD is recognized as one of the most suitable alternatives for treating MOW due to its ability to recover both material (e.g., the solid fraction as soil conditioner or solid organic fertilizer, liquid fraction as fertigation water or liquid fertilizer) and energy (e.g., the gas can be upgraded to natural gas quality and used as vehicle fuel or converted into electricity) from municipal waste [1]. This multifaceted capability means that AD is highly ranked within the municipal waste management hierarchy [1], making it an excellent tool for creating a circular (bio-)economy [2,3] as well as achieving the 17 United Nations' Sustainable Development Goals (SDGs) [4].

As evidenced by numerous review papers, AD has been widely adopted globally. Europe, particularly Germany, the UK, and Italy, has taken the lead in AD deployment, driven by renewable energy policies, economic, environmental, and climate benefits, and technological advancements [4,5]. Torrijos reviewed the state of AD development in

Europe and concluded that while the industry has performed well since 2000, changes or cuts in support schemes around 2015 slowed the biogas market, despite ongoing policies favoring biogas [4]. Factors such as the acceptance of digestate as fertilizer, potential bans on landfilling, and limitations on incinerating organic waste could boost the biogas market. Scarlat et al. (2018) provide an overview of AD development in the EU, highlighting that economic issues are the key factor affecting biogas production [4]. Sustainability and challenges in developing countries have been reviewed [1,6] by Pandyaswargo et al. (2019) and Terrapon-Pfaff et al. (2014). Negri et al. (2020) reviewed factors favoring food waste for AD in China and Southeast Asia [7]. Additionally, domestic issues have been addressed for India [8], household biogas technologies in Pakistan [9], and rural Bangladesh [10].

In Japan, the promotion of biomass utilization has been underway since the "Biomass Nippon Comprehensive Strategy" was introduced in 2002. Recently, biomass utilization has gained significant attention for its potential contributions to achieving carbon neutrality, resource efficiency, and mitigating geopolitical risks. In 2010, the government formulated the "Basic Plan for Promoting Biomass Utilization," which set a goal for all prefectures and 600 municipalities to develop biomass utilization promotion plans by 2025. However, as of February 2023, only 19 prefectures and 74 municipalities had formulated such plans. Furthermore, even in regions with plans, biomass resources are not always fully utilized to create economic, environmental, and social value. Several practical barriers hinder the effective utilization of biomass resources in production areas. These barriers include a lack of stakeholder participation, difficulties in market and funding procurement, and imbalances between biomass feedstock supply and demand [11–13].

Given the significant attention to AD technology, numerous studies have addressed its technical aspects as well as the economic, environmental, and social dimensions both quantitatively and qualitatively [11–13]. A recent review paper presented a comprehensive literature review of previous studies on AD for MOW treatment, focusing on various approaches, including co-digestion, pre-treatment, recirculation, additive processes, and micro-aeration, evaluating their mechanisms and effectiveness in enhancing digestion performance [14]. Along with other review studies that advocate for improvements to make this technology more accessible and beneficial [15–18], there is a recognition that many analyses focus on AD technologies or individual projects. However, fewer studies provide comprehensive regional analysis that includes related ventures involved in biomass initiatives. Comprehensive analysis from a regional perspective, particularly practical analysis based on site-specific empirical data, is still lacking. Biomass projects require the participation of multiple stakeholders—municipalities, private companies, and citizens—from waste separation to the use of liquid fertilizer on farmland. AD technology must be sustainably managed within complex social systems. In such systems, indirect benefits such as bartering or self-consumption, often unrecorded in conventional accounting, can significantly contribute to the regional socio-economic landscape. Therefore, the current study aims to fill this research gap by providing a comprehensive regional analysis based on empirical data from Minamisanriku Town. This analysis includes economic, environmental, and social dimensions, and evaluates the benefits and challenges of AD technology's implementation from a regional perspective. By doing so, this study seeks to offer practical insights that can inform policy and decision-making processes for sustainable waste management and regional revitalization.

In the field of quantitative analysis, several life cycle assessment (LCA) studies have been conducted on AD for municipal waste [19,20]. However, most analyses tend to focus on the assessment of energy and greenhouse gas (GHG) emissions' impacts, with limited comprehensive quantitative evaluations involving digestate use. A review by Huttunen, Manninen, and Leskinen (2014) identified critical points related to biogas production by comparing LCA studies with actual decisions made at biogas plants in Finland through stakeholder interviews [21]. These critical points include the end use of biogas and digestate. Practical implementation and site-specific conditions of biogas plants can lead to significant differences in life cycle impacts. Thus, the importance of site-specific LCA studies for reliable impact assessments is emphasized, along with the incorporation of stakeholder interviews to support LCA at different stages and to better implement life cycle thinking into policy design.

Site-specific quantitative analysis from a regional standpoint can not only quantify the comprehensive socio-economic and environmental benefits but can also identify specific issues, providing insights for further optimization of local resource utilization to maximize local economic and environmental benefits. This study considers Minamisanriku Town, which has been practicing biomass resource utilization for over 10 years, as a case study and integrates site-specific LCA and economic analysis based on stakeholder interviews to evaluate the regional benefits of the biomass facility and to explore sustainable business models in collaboration with the local community. While our focus is quantitative, we also consider the subjective expectations and challenges of local stakeholders regarding the socio-economic impacts of AD, which provide valuable insights for improving biomass utilization and ensuring a more equitable distribution of benefits. By combining quantitative analysis with stakeholder perspectives, this study provides a comprehensive understanding of how the utilization of organic resources contributes to environmental, economic, and social sustainability at the regional level.

2. Case Study: Minamisanriku Town, Japan

Minamisanriku Town, the focus of this study, is located on the northeastern coast of Miyagi Prefecture in the Tohoku region of Japan (Figure 1, left), with a population of 11,888 and a total area of 16,340 hectares in 2022. The map on the right of Figure 1 provides a detailed land use classification of Minamisanriku in 2016. Different colors are used to represent various land use types. The map illustrates the preponderance of forested areas (depicted in green) and the distribution of land designated for agricultural and urban use. Forested areas (green; 12,562 ha) account for nearly 77% of the land, agricultural land (brown; 1023 ha) covers approximately 6%, and urban areas (red and orange) represent about 5%. Including other areas such as submerged regions and wasteland (beige and yellow), there is a potential to utilize liquid fertilizer (digestate from AD) on over 1000 hectares of land.

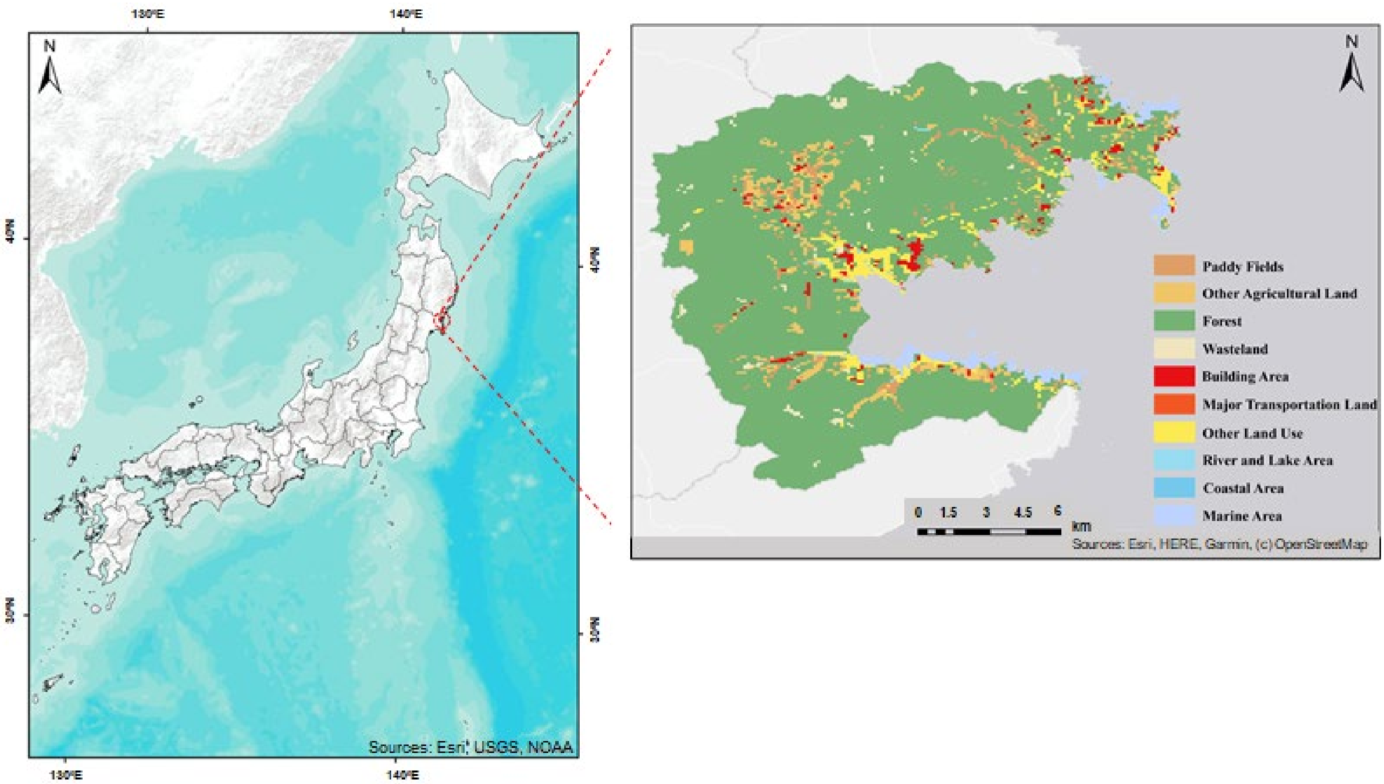


Figure 1. Study area. Paddy Fields: areas of rice paddies; Other Agricultural Land: farmland such as fields and orchards; Forest: areas densely populated with trees; Wasteland: land not used for agriculture or urban purposes; Building Area: land with buildings such as residential, commercial, and industrial areas; Major Transportation Land: land with major transportation infrastructure such as highways and railways; Other Land Use: land uses that do not fall into specific categories such as submerged regions; River and Lake Area: areas of water bodies such as rivers, lakes, and ponds; Coastal Area: land along the coastline; Marine Area: sea areas.

The town was severely damaged by the Great East Japan Earthquake on 11 March 2011. In response to the disaster, the Minamisanriku Biogas Facility, known as 'Minamisanriku BIO,' was established. Through this facility, kitchen/food waste and surplus sludge from the city are used as raw materials not only for power generation but also for the production of liquid fertilizer, which is then used on local farmland. This model aims to recycle organic resources in the region to produce rice and other agricultural products.

In the social context, Minamisanriku recognized the importance of establishing a system to secure the resources necessary for life within the local community, following the experience of severed lifelines during the disaster. This recognition was articulated in the 'Minamisanriku Town Disaster Recovery Plan' formulated in December 2011. The plan aims to establish an environmentally friendly lifestyle with reduced environmental impact by promoting the use of renewable energy, waste reduction, and recycling. Additionally, the town faced two major post-disaster challenges which catalyzed the establishment of the biomass gasification plant: (1) the lack of an incineration facility for waste disposal, relying on neighboring towns, and the urgent need to address imminent overflow at temporary storage sites for incinerator ash; (2) the non-functioning sewage treatment plants, necessitating a transition to combined sewage treatment tanks. Furthermore, the operational sanitary center was outdated with limited treatment capacity. These challenges underscored the need to build a self-sustaining decentralized social system using biomass resources.

In the aftermath of the disaster, numerous volunteer organizations, including the Amita Group specializing in circular society design projects aimed at achieving sustainability, came to Minamisanriku Town to offer their assistance. In 2012, the Amita Group conducted a demonstration experiment on waste sorting and liquid fertilizer utilization using general waste from households and businesses in Minamisanriku Town. Based on the results, the 'Minamisanriku Biomass Town Concept' was formulated. This concept aims to achieve energy self-sufficiency and promote creative recovery from the disaster by recycling local resources, and it received national certification in March 2014. Subsequently, an implementation agreement for the biomass gasification project was signed between Minamisanriku Town and Amita in July 2014, leading to the completion of Minamisanriku BIO on 16 October 2015. At that time, the BIO facility was expected to process 3.5 t/day of kitchen waste and 7 t/day of surplus sludge, totaling 10.5 t/day, to produce approximately 4500 t of liquid fertilizer and a maximum of 219,000 kWh of electricity (facility capacity) annually three years after its operation.

In addition to Amita BIO, various companies, residents, municipalities, and farmers collaborated, leading to spillover effects. For example, Yamafuji Transportation, originally responsible for transporting incineration waste from Minamisanriku to neighboring facilities, shifted its operations to transporting surplus sludge from the sanitary center to Minamisanriku BIO. Yamafuji Transportation also began distributing liquid fertilizer produced at Minamisanriku BIO onto farmlands using liquid fertilizer spreaders. Moreover, agricultural support services such as land cultivation using tractors were provided to assist elderly farmers in cultivating land after the application of liquid fertilizer. Efforts were also made to promote agricultural product branding using liquid fertilizer. Collaborative activities, such as residents' waste sorting and the utilization of liquid fertilizer in rice paddies, have continued since the 2012 demonstration experiment. Particularly, the increased demand for liquid fertilizer due to rising chemical fertilizer prices has resulted in a current supply shortage.

In 2018, Amita and NEC Solution Innovators collaborated to enhance kitchen waste collection in the town using Information and Communication Technology (ICT). They visualized kitchen waste sorting by district, analyzed contamination rates and collection amounts, and provided feedback to residents on waste sorting participation and the enforcement of rules. This initiative led to increased kitchen waste collection annually.

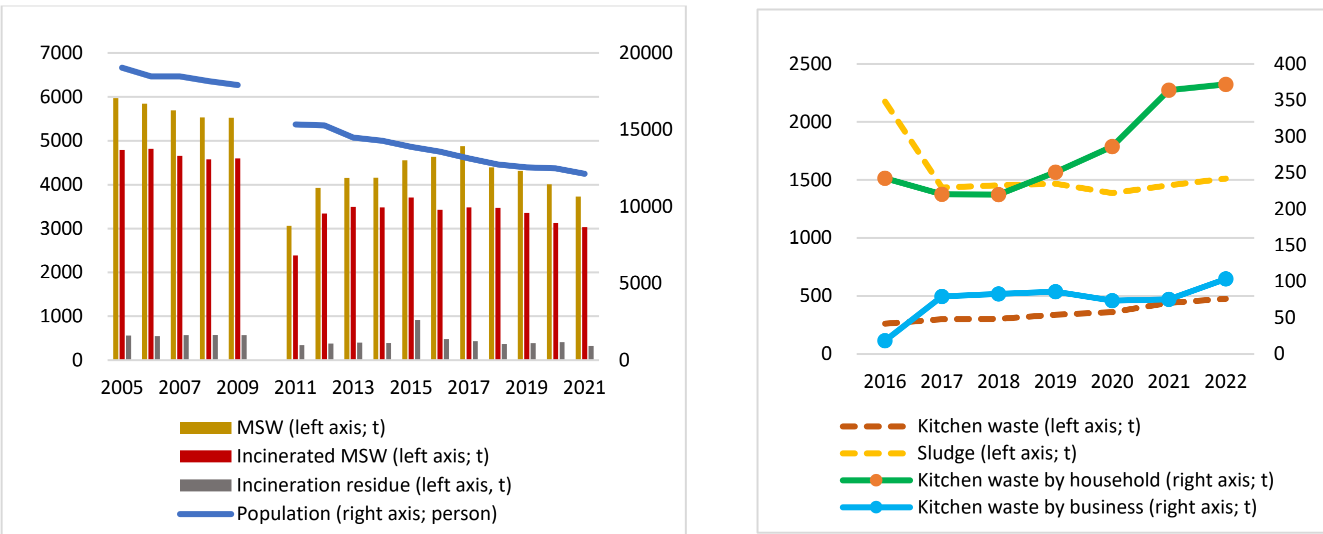
The main related policies and issues addressing the step-by-step implementation of the Minamisanriku Biomass Cyclization are summarized in Table 1.

Table 1. Related policies and issues to address the Minamisanriku Biomass Cyclization step-by-step.

Actor	Year	Content
Municipality	December 2011	"Minamisanriku Town Disaster Recovery Plan" formulated.
	2013	"Minamisanriku Biomass Town Concept" proposed.
	May 2014	Minamisanriku Liquid Fertilizer Utilization Promotion Council established. The council aims to promote environmentally sustainable agriculture through resource circulation by utilizing liquid fertilizer on farmland, and to achieve sustainable agriculture. It consists of a total of 16 members, including representatives from local farming cooperatives, practitioners of liquid fertilizer utilization, Minamisanriku Agricultural Cooperative, municipal government officials, and Amita Corporation, the operator of the biomass plant.
Main project (BIO)	November 2012–March 2013	Demonstration experiment conducted on waste separation and the utilization of liquid fertilizer.
	July 2014	Implementation agreement concluded for biogas project (Minamisanriku BIO) with Minamisanriku Town under public–private participation (the outsourcing of local government operations to private entities).
	October 2015	Minamisanriku BIO began operations. Information sessions on household waste separation conducted in 60 administrative districts, and household waste separation collection began.
	May 2016	Demonstration experiments conducted on the resource utilization of aquatic waste.

	June 2016	New permits for general waste disposal business were obtained, and efforts were made to promote resource utilization of food waste from hotels, restaurants, and other establishments within the town.
	2016	Registration of liquid fertilizer by Minamisanriku BIO
	September 2018	In collaboration with NEC Solution Innovators, an experiment was conducted on visualization of participation in household waste separation using ICT at 42 randomly selected locations out of 261 household waste collection sites established in the town. The experiment involved providing feedback to residents on their participation in waste separation using ICT, and comparing the quantity and quality of waste collection and separation before and after the feedback to verify how residents' awareness was changing.
	2021	Registration of trademark of Megurin Rice produced by BIO liquid fertilizer
Spillover business (Yamafuji Transportation)	October 2015	Transportation of surplus sludge from the sanitary center to Minamisanriku BIO commenced.
	April 2016	Commencement of liquid fertilizer spreading on farmland.
Farmers	2012	Some farmers participated in liquid fertilizer demonstration experiment.
	2016	Requests for purchase and spreading of liquid fertilizer made through JA (Japan Agricultural Cooperatives).
Residents	October 2015	Household waste sorted into collection buckets installed at each collection site the day before the collection day (twice a week).
	September 2020	Collection buckets permanently installed in all areas to enable residents to dispose of household waste at any time.

The temporal changes in municipal solid waste (MSW) generation, incinerated MSW, incineration residue, and population from 2005 to 2021 are shown in Figure 2a. Following the 2011 Great East Japan Earthquake, there was a significant temporary fluctuation; however, the total MSW generation showed a long-term decline, decreasing by 38% from 5972 t in 2005 to approximately 3729 t in 2021. Post-earthquake, there was a temporary increase in MSW until peaking in 2017, followed by a gradual decline, indicating stabilization of and improvement in waste management practices. The population of Minamisanriku had been gradually decreasing before the earthquake, but this accelerated its decline afterward, declining by 36% from 19,042 people in 2005 to 12,135 people by 2021. Per capita MSW generation decreased from 859 g per person per day in 2005 (621 g from households and 238 g from businesses) to 842 g per person per day in 2021 (636 g from households and 206 g from businesses). Since the operation of the BIO facility began in 2015, direct incineration volumes and incineration ash have decreased.



(**a**) MSW generation and population (**b**) Local MOW utilized

Figure 2. Changes in MSW generation and organic resources' utilization. The absence of data for the 2010 fiscal year in (a) results from the Great East Japan Earthquake of 2011.

Temporal changes in organic resources utilized by Minamisanriku BIO from 2016 to 2022 are shown in Figure 2b. Since the ratio of kitchen waste to sludge ideally should be 3:7, both have shown stable increases since 2020. Particularly, promoting household kitchen waste separation since 2018 has increased the collected amount from households, rising from 220 t in 2018 to 372 t in 2022, marking a nearly 70% increase. However, despite continuous increases in kitchen waste separation, its proportion to total MSW remains approximately 12% (13% from households and 8% from businesses) in 2021. Furthermore, although the utilization rate of the BIO facility has shown improvement, it still remains at approximately 66% as of 2022, indicating that several challenges remain unresolved.

3. Methodology

In this section, we outline the methodological framework employed in the study to assess the economic and environmental impacts of AD for MOW in Minamisanriku Town. The methodology encompasses a series of analytical steps, including boundary setting, scenario setting, information collection, and quantifying economic and environmental impact analysis, as well as the application of specific LCA tools to evaluate the various dimensions of AD implementation.

3.1. Boundary Setting

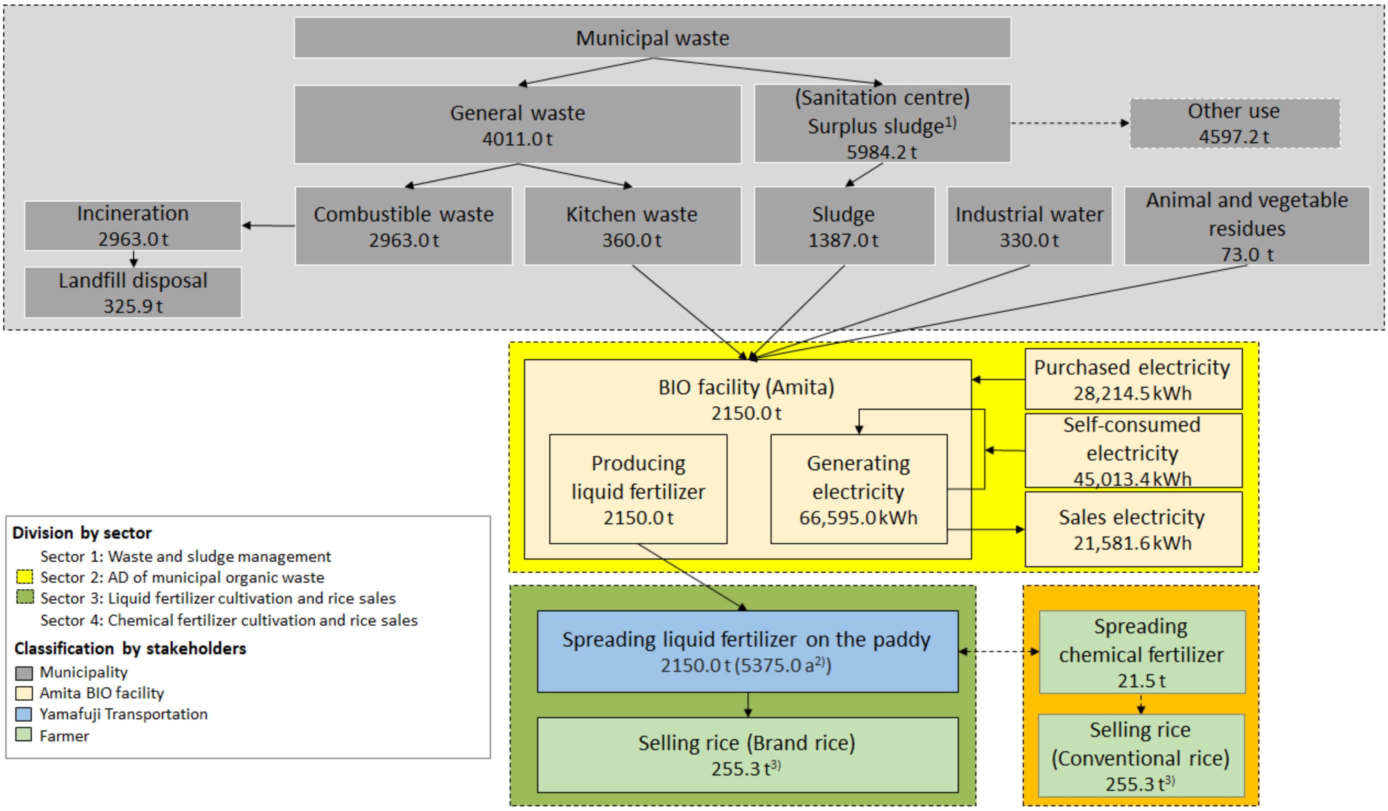
Figure 3 shows the scope of analysis boundary related to MOW utilization in Minamisanriku Town. It includes four main sectors involved in the collection, processing, and utilization of MOW/local resources. Sector 1 includes the collection and treatment of municipal waste such as household waste, commercial waste, and surplus sludge. Most of the municipal waste is incinerated and finally disposed of in landfills. Meanwhile, the sorted kitchen waste is transported to the Amita BIO facility along with surplus sludge and other residues. In Sector 2, the process involves utilizing the kitchen waste, surplus sludge, and other organic residues at the Amita BIO facility to produce liquid fertilizer and generate electricity. Liquid fertilizer can serve as an alternative to chemical fertilizers but may also be discharged into sewage if not utilized. Some of the electricity generated within the facility is either consumed internally during operations or sold externally. Moreover, a specific amount of electricity is purchased to facilitate the operation of the facility. Sectors 3 and 4 are involved in the process of spreading fertilizer for growing crops and selling the harvested crops. Here, based on the utilization of liquid fertilizer, either Sector 3 or Sector 4 is chosen accordingly. In practice, liquid fertilizer is utilized for the harvest of various crops, but for the efficiency of analysis in this study, crops were simplified to rice. Concretely, sector 3 involves the process of distributing the liquid fertilizer produced at the Amita facility onto rice fields for rice cultivation, followed by the sale of the resulting high-value organic produce as branded rice. Sector 4 encompasses the process of producing and selling rice using chemical fertilizers in the conventional way, describing the situation when the liquid fertilizer produced at the Amita facility is not effectively utilized. The rice harvested in this process is marketed as conventional rice.

The stakeholders involved in facilitating the effective utilization of biomass waste are clearly delineated by sector: the municipality is responsible for the management of municipal waste and surplus sludge in Sector 1, Amita is responsible for the conversion of food waste and surplus sludge into resources in Sector 2, Yamafuji Transportation is responsible for transporting and spreading liquid fertilizer, and farmers are responsible for selling rice in Sector 3, and then farmers are in charge of spreading chemical fertilizers and selling rice in Sector 4.

Meanwhile, the situation of material flow related to MOW utilization in Minamisanriku Town as of 2020 is shown in Figure 3. Municipal waste begins with the collection of 4011.0 t of MSW, which includes 2963.0 t of combustible waste and 360.0 t of kitchen waste, alongside the treatment of 5984.2 t of surplus sludge, reaching a total of 9995.2 t of targeted waste. Out of general waste, 2963.0 t of combustible waste are incinerated, resulting in 325.9 t of landfill disposal, which corresponds to 11%. Of surplus sludge, 1387.0 t are transported to the BIO facility, while 4597.2 t are utilized for other purposes (Sector 1).

The AD process at the Amita BIO facility handles 360.0 t of kitchen waste, 1387.0 t of surplus sludge, 330.0 t of industrial water, and 73.0 t of other organic residues, producing 2150.0 t of liquid fertilizer and generating 66,595.0 kWh of electricity (Sector 2). A significant portion of the electricity (45,013.4 kWh per year) is self-consumed by the facility, with 21,581.6 kWh per year sold externally. The facility also consumes 28,214.5 kWh of purchased electricity per year. If the BIO facility were to operate at maximum capacity, the processing capability would be 10.5 t per day, amounting to a total of 3832.5 t annually. Of this quantity, 1149.7 t would be solid organic waste, while 2682.7 t would be liquid (including surplus sludge and industrial water).

For the sake of calculation convenience, it is assumed that the produced 2150.0 t of liquid fertilizer are used on a maximum of 5375.0 a (100 m^2) of paddy fields (approximately 80% of the liquid fertilizer is actually used on paddy fields, with the remaining 20% used on pasture and fields). This application is estimated to result in the production of 255.3 t of branded rice (Sector 3). In contrast, conventional rice cultivation using chemical fertilizers requires approximately 21.5 t of chemical fertilizers (Sector 4).



1) Only treatment costs/energy within the sanitation center and BIO facility, as well as transportation costs/energy from the sanitation center to the BIO facility, are included.
2) 1 are (a)=100 m^2. The amount of liquid fertilizer applied is assumed to be 4 t per 10 ares.
3) The yield of brown rice is assumed to be 475 kg per 10 ares, regardless of the type of fertilizer used, including chemical and liquid fertilizers.

Figure 3. The boundary of material flow (as of 2020) related to MOW utilization in Minamisanriku Town.

3.2. Scenario Setting

The biomass utilization in Minamisanriku Town is implemented through collaboration among various stakeholders. Factors such as the operation status of the BIO facility, its operational rate (indicating the intensity of collaboration), and the use of liquid fertilizer as a substitute for chemical fertilizers are considered significant elements influencing the local economy and environment. Therefore, considering these factors, eight scenario options are assumed to quantitatively evaluate and compare the impact of biomass utilization on the economy and environment in the region (Table 2). It should be noted that variations in the operational rate of the Amita BIO facility result in changes in the input of biomass waste, the production of liquid fertilizer, as well as rice production. Therefore, this study divides scenarios into roughly two categories (A and B) based on changes in the operational rate. Specifically, three scenarios related to A assume an operational rate of 56% (as of 2020; 2150.0/3832.5=56%), while five scenarios related to B assume an operational rate of 100%. The specific settings for each scenario are as follows:

Scenario A1; Scenario B1: Without the Amita BIO facility, conventional rice cultivation methods are employed, relying on chemical fertilizers. In these scenarios, MOW is incinerated and subsequently landfilled with other general municipal waste. The rice production sector (Sector 4) operates under the assumption of conventional cultivation and sales practices, without the utilization of digestate by-product as liquid fertilizer.

Scenario A2; Scenario B2: The Amita BIO facility is operational, converting MOW into electricity. This energy is utilized internally or sold externally in cases of excess. These scenarios show a reduction in the volume of waste requiring incineration or landfilling due to the resource recovery from MOW. However, the digestate by-product is not repurposed as liquid fertilizer but is treated as wastewater.

Scenario A3; Scenario B3: Building on the operational status described in Scenario A2 and Scenario B2, these scenarios utilize the BIO digestates as liquid fertilizer for rice cultivation, replacing chemical fertilizers. Additionally, branded rice—a value-added product cultivated using liquid fertilizer—is produced and sold. Scenario A3 reflects the situation of business as usual (BAU).

Scenario B4; Scenario B5: Building on the operational status described in Scenario B2 and Scenario B3, these scenarios assume ideal operational conditions for electricity generation at the Amita BIO facility. They are based on the premise that the electricity output matches the optimal values (219,000 kWh annually) anticipated during the planning and design stages, which are higher than the actual operational values.

Table 2. Scenario setting.

Scenarios	Operating Ratio	Contents
Scenario A1. (A1)	56%	In the absence of BIO facilities (control)
Scenario A2. (A2)		BIO facilities in operation; no liquid fertilizer use
Scenario A3. (A3)		BIO facilities in operation; liquid fertilizer utilization (BAU)
Scenario B1. (B1)	100%	In the absence of BIO facilities (control)
Scenario B2. (B2)		BIO facilities in operation; no liquid fertilizer use
Scenario B3. (B3)		BIO facilities in operation; use of liquid fertilizers.
Scenario B4. (B4)		BIO facilities in operation; no liquid fertilizer use; power generation (facility capacity ideal value)
Scenario B5. (B5)		BIO facilities in operation; use of liquid fertilizer; power generation (facility capacity ideal value)

3.3. Information Collection

In this study, to quantitatively analyze the effects of biomass utilization on local revitalization, we conducted semi-structured interviews with key stakeholders, including local governments, the Amita BIO facility, Yamafuji Transportation (responsible for transporting liquid fertilizer), Sanitation Center, farmers, and residents, to obtain site-specific empirical data. The interview surveys were conducted through three rounds of face-to-face interviews in November 2023, February 2024, and May 2024, supplemented by several telephone and online surveys. Each stakeholder was surveyed about their motivations, dynamics, experiences, perceptions, and challenges regarding biomass utilization. The main topics covered in the interviews were as follows:

1. Municipality:
    - Information on the flow of waste and waste water treatment;
    - Details of waste treatment (the volume of each type of waste, waste treatment and costs, transportation, incineration, landfilling, and sewage treatment, etc.);
    - Background leading to the introduction of BIO facilities;
    - Administrative challenges and future plans.
2. Amita BIO Facility:
    - Collection and processing volumes of food waste (household waste and commercial waste), surplus sludge, and other materials;
    - Waste processing commission fees;
    - Energy consumption data (electricity);
    - Production, consumption, purchases, sales volumes, and sales revenue of electricity and liquid fertilizer;
    - Status of wastewater treatment and other waste disposal processes;
    - Initial cost for construction (actual expenses, subsidies);
    - Annual operational running cost (personnel expenses, annual subsidy).
3. Yamafuji Transportation (Liquid Fertilizer Transport Company):
    - How and why the company entered this business;
    - Changes in operations and finances due to the transition to liquid fertilizer;
    - Details regarding the application of liquid fertilizer in rice fields (types of machinery used, fuel consumption per unit, and application area).
4. Farmers:
    - Criteria for fertilizer selection and reasons for using liquid fertilizer;
    - Amount of liquid and chemical fertilizer applied per unit area, fertilizing cost, and application area;
    - Application method of liquid and chemical fertilizer (amount per unit area, fertilizing cost, and application area);
    - Amount of liquid and chemical fertilizer applied per area, fertilizing cost, and application area;
    - Harvest-related information: rice yield per unit area;
    - Sales revenue of branded rice (with liquid fertilizer usage) and conventional rice (with chemical fertilizer usage);
    - Distribution channels of agricultural products and challenges and perceptions related to liquid fertilizer use.
5. Others (community residents who provide household waste and concurrently utilize liquid fertilizer):
    - Motivation and methods for segregating household waste, along with segregation rates;
    - Utilization and feedback regarding liquid fertilizer;
    - Opinions and proposals for improving waste segregation and supporting liquid fertilizer use.

The insights gathered from the interviews not only provide site-specific input data for LCA quantitative analysis but also serve as crucial elements in advancing improvement strategies for biomass utilization in the region. The stakeholders' perspectives and perceptions revealed through the interviews are vital for fostering actions toward regional goals and encouraging measures for enhancing biomass utilization. These insights not only clarify specific challenges and needs within the region but also serve as significant guidelines for future policy recommendations.

Additionally, data such as sewage treatment fees, and electricity purchase and sales prices, which can be obtained through officially published sources, were acquired using the tariff rates set by the relevant authorities for sewage and electricity in Minamisanriku Town [19,20]. The price of diesel fuel utilized retail price data from refueling stations [20].

3.4. Quantifying Economic and Environmental Impact

The material flows, income, and expenditure per amount of targeted waste (general waste and surplus sludge from human waste and sewage treatment) unit, and GHG emission factor per material unit, categorized by scenario, utilized in the quantitative analysis of the economic and environmental impacts of the utilization of local organic biomass, are summarized in Table S1. The numerical values by scenario were organized into sectors from an LCA perspective.

The costs and expenses (E_c) and amount of GHG emissions (G_c) of each scenario (c) can be calculated using the following Equations (1) and (2).

$$E_c = v_c \times e \tag{1}$$

$$G_c = v_c \times g \tag{2}$$

Here, changes in costs and expenses are calculated by multiplying the volume or amount of material flow in each scenario (v_c) by the unit value in the expense and income (e), which are obtained based on the results of the in-depth interviews and related information. The amount of GHG emissions are calculated by multiplying the volume or amount of material flow in each scenario (v_c) by the GHG emission factor (g). Furthermore, the amounts of income and expenses or GHG emissions by scenario were obtained from the subtotals for each sector (1–4) or the total for all sectors. The GHG emission factor of each energy type, related material, and waste activities make use of data from the Inventory Database for Environmental Analysis (IDEA, v.3.2), a Japanese LCI database. GHG emissions are calculated as the sum of CO_2, CH_4, N_2O, and other emissions, which are converted to metric tons of CO_2 equivalent based on the 100-year time horizon Global Warming Potentials, as accepted in the IPCC Fourth Assessment Report (IDEA guideline).

Moreover, this study employed the evaluation framework of Endpoint Modeling 2 (LIME2, Life Cycle Impact Assessment Method based on Endpoint modeling) to conduct a Life Cycle Impact Assessment (LCIA). LIME is a methodology developed to assess environmental impacts through LCA. The first version, LIME-1, was created between 1998 and 2000 under a national project supported by the Ministry of Economy, Trade and Industry (METI) of Japan. LIME-1 established a basic methodology consisting of three steps: characterization, damage assessment, and weighting, with conjoint analysis used for weighting. It included 11 impact categories: air pollution, human toxicity, ozone layer depletion, global warming, ecotoxicity, acidification, eutrophication, ozone creation, land use, solid waste, and resource consumption, along with four endpoints: human health, social assets, biodiversity, and primary production. LIME-2, developed between 2004 and 2006 in the second national LCA project, introduced additional impact categories: indoor air pollution and noise. This version involved conjoint analysis conducted with nearly 1000 respondents from across Japan, reflecting a wide range of environmental considerations and societal values specific to Japan. Moreover, by aggregating the integration coefficients for four endpoints as protection categories, the "Integration" (unit: JPY) was derived, enabling a comprehensive assessment of environmental impacts. By utilizing LIME2, this research calculated "integration", incorporating not only climate change but also biodiversity, health impacts, and social capital based on material flows in each scenario.

4. Results

4.1. Changes in Income and Expenses of Each Sector across Scenarios

Figure 4 shows the economic benefits of MOW utilization in Minamisanriku Town for the year 2020 across different sectors. These economic benefits include saving on waste disposal costs due to reduced incineration and landfill use, income from the sale of liquid fertilizer produced by the AD process, income from electricity generation and sales, and profits from the sale of branded rice grown using the liquid fertilizer. In Scenario A (A1, A2, A3), which reflect an operating rate of 56%, the net income for the town has changed: in Scenario A1, the net income is −6791 JPY/t, indicating a deficit in the absence of BIO-related activities. In Scenario A2, the net income is approximately −12,918 JPY/t due to the increased expenditure by Sector 1 on BIO facilities for the treatment of kitchen waste and sludge alone, which places a greater financial burden on local communities. Scenario A3 (BAU) results in a net benefit of −5906 JPY/t, reflecting a 13.0% increase in income compared to Scenario A1, due to the sale of value-added products such as branded rice grown with liquid fertilizer.

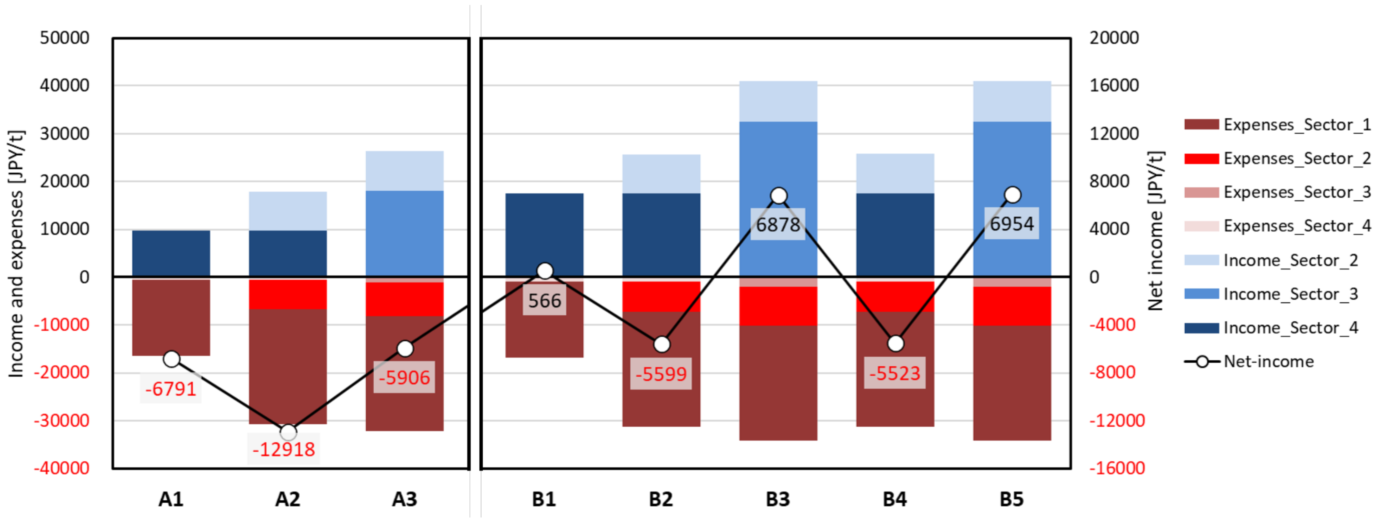


Figure 4. Income and expenses of each sector in scenarios.

Scenario B (B1, B2, B3, B4, B5), which represents a 100% operation rate of BIO facilities, shows significant increases in net income. In Scenario B3, which focuses on increased sales of rice produced with liquid fertilizer, net income increases by approximately 216.5% compared to Scenario A3, reaching a positive 6878 JPY/t. This represents an 11.2-fold increase compared to the baseline Scenario B1, which does not include BIO facility operations. In addition, in Scenario B5, where the electricity production targets are achieved at the planned level, the increased income from the sale of self-generated electricity in Sector 2 leads to a further increase in net benefits of 1.3% to 6954 JPY/t compared to Scenario B3.

4.2. GHG Emissions Reduction in Various Scenarios

Figure 5 illustrates the reduction in GHG emissions achieved through the utilization of MOW in Minamisanriku Town in 2020, emphasizing environmental benefits. This primarily includes reductions in GHG emissions from reduced waste incineration and landfill, reduced sludge treatment, decreased reliance on chemical fertilizers through the use of liquid fertilizer, and GHG reductions from the use of electricity generated by the BIO facility. However, it also accounts for increased GHG emissions from energy consumption in BIO facility operations and energy consumption during liquid fertilizer application. As a result, scenarios where BIO-related activities are not implemented, such as Scenarios A1 (170.9 kg-CO_2eq/t) and B1 (172.4 kg-CO_2eq/t), exhibit higher GHG emissions compared to other scenarios, demonstrating the contribution of BIO facility operations to GHG emissions reduction.

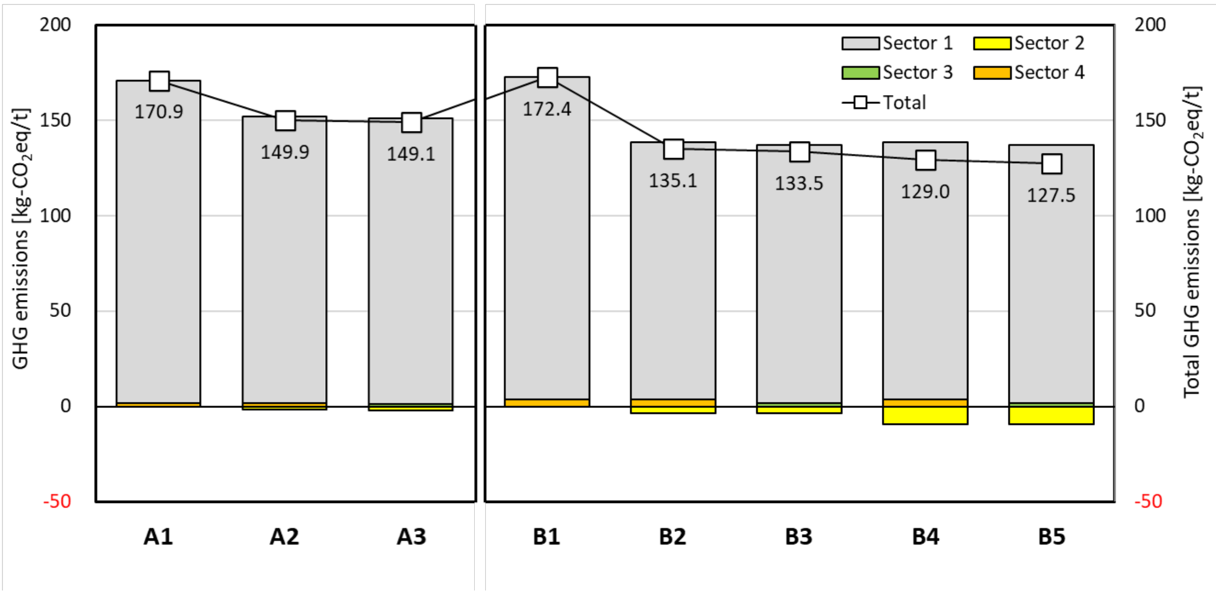
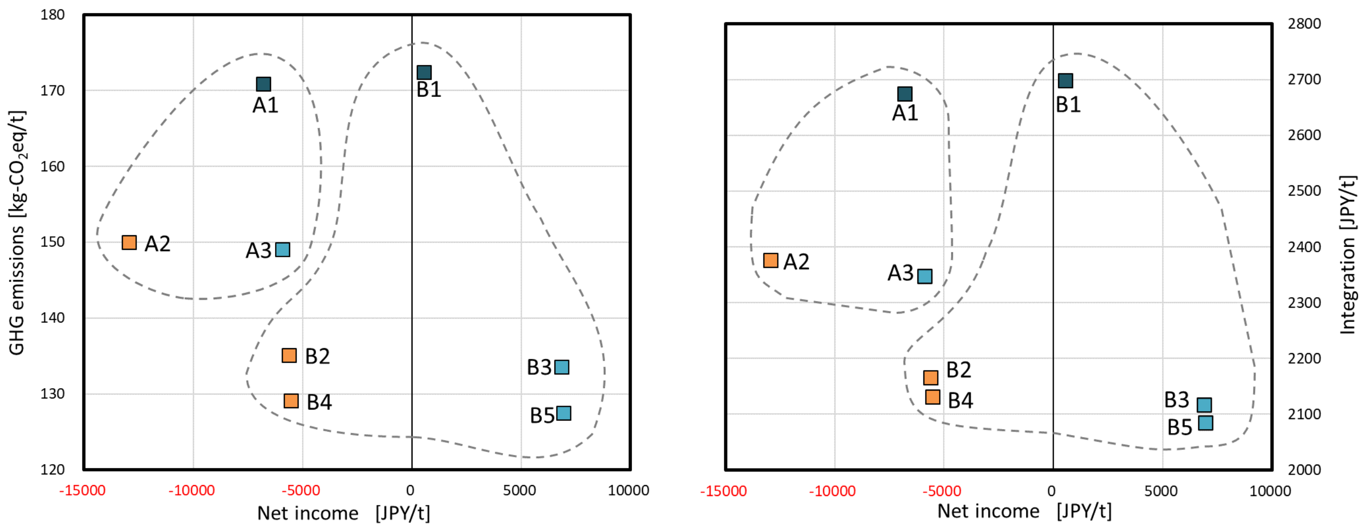


Figure 5. GHG emissions across various sectors for each scenario.

Under the scenario based on a 56% operational rate, Scenario A1, reductions of 12.2% and 12.8% are achieved in Scenario A2 (BIO facility operation focusing on MOW) and Scenario A3 (liquid fertilizer utilization), respectively. Similarly, under the scenario based on a 100% operational rate, Scenario B1, reductions of 21.6% (135.1 kg-CO_2eq/t) and 22.6% (133.5 kg-CO_2eq/t) are observed in Scenario B2 and Scenario B3, respectively. These scenarios demonstrate a decreasing trend in GHG emissions associated with the increased utilization of biomass. Furthermore, in Scenario B4 and Scenario B5, GHG emissions further decrease to 129.0 kg-CO_2eq/t and 127.5 kg-CO_2eq/t, respectively, representing approximately a 3.5% reduction compared to Scenarios B2 and Scenario B3, due to increased electricity generation. Therefore, it is evident that increasing the operational rate and efficiency of BIO facilities, as well as enhancing the utilization rate of liquid fertilizer, contribute significantly to reducing GHG emissions. Increased operational rates particularly demonstrate higher contributions to GHG reduction.

4.3. Multifaceted Environmental Evaluation

Figure 6 shows the relationship between net income and environmental impact of the biomass utilization system under different scenarios. The horizontal axis represents net income, the left vertical axis represents GHG emissions, and the right vertical axis represents the LIME2 integration index that indicates the environmental impact cost.



(**a**) Net income vs. GHG emissions (**b**) Net income vs. LIME2 integration

Figure 6. Relationship between net income and GHG emissions and LIME2 integration score across scenarios in biomass utilization system.

Firstly, examining the relationship between net income per metric ton of waste and GHG emissions (Figure 6a), the scenarios considering only the operation of the BIO facility (A2 and B2) show a significant reduction in GHG emissions compared to the baseline scenarios before the BIO facility operation (A1 and B1). For instance, GHG emissions in Scenario A2 decrease by 12.2% compared to Scenario A1, and in Scenario B2, they decrease by 21.6% compared to Scenario B1. However, net income also decreases. Scenario A2 shows a 90.2% increase in economic burden compared to Scenario A1, and Scenario B2 shifts from positive to negative net income compared to Scenario B1. The reduction in GHG emissions is primarily due to decreased waste incineration and the self-consumption and sale of electricity produced on-site by the BIO facility. The decrease in net income is mainly due to the operational and management costs of the facility, which impose a local economic burden.

In Scenario A3 and Scenario B3, both the operation of the BIO facility and the revenue from value-added products (such as branded rice) generated through the effective use of liquid fertilizer occur simultaneously. This results in the co-benefit of a reduction in GHG emissions and an increase in net income. Specifically, Scenario A3 shows a 12.8% reduction in GHG emissions compared to Scenario A1 (0.6% reduction compared to Scenario A2), and Scenario B3 shows a 22.6% reduction compared to Scenario B1 (1.2% reduction compared to Scenario B2). Net income increases by 13.0% in Scenario A3 compared to Scenario A1 and by roughly 11 times in Scenario B3 compared to Scenario B1.

Moreover, in Scenario B4 and Scenario B5, both GHG emissions and net income improve further compared to Scenario B2 and Scenario B3. GHG emissions decrease by approximately 4.5%, and net income increases by about 1%.

Similarly, the relationship between net income and the LIME2 integration index (Figure 6b) shows a similar trend to that between net income and GHG emissions. In Scenarios A3 and B3, net income increases by 13.0% and roughly 11 times, respectively, compared to the baseline Scenarios A1 and B1. The environmental impact cost (LIME2 Integration) decreases by 12.2% and 21.6%, respectively. In optimal Scenario B5, if the BIO facility operates fully, generating electricity completely, and all liquid fertilizer is used for producing branded rice, the net income per metric ton for the region increases from JPY 566 in the baseline Scenario B1 to JPY 6954, approximately 11 times. Simultaneously, the environmental impact cost decreases from 2698 JPY/t to 2085 JPY/t, a reduction of 613 JPY/t or 22.7%.

The above results align with multiple of the United Nations' Sustainable Development Goals (SDGs), demonstrating significant progress such as improved agricultural productivity (SDG 2), promotion of renewable energy usage and reduced reliance on fossil fuels (SDG 7), economic growth (SDG 8), industry innovation and infrastructure (SDG 9), advancements in education and gender equality (SDGs 4, 5), sustainable consumption and production (SDG 12), mitigation of climate change (SDG 13), transformation of cities into sustainable environments (SDGs 11, 16, 17), and reduction in environmental pollution (SDGs 3, 6, 12, 14, 15).

5. Discussion

The results indicate that the BIO system in Minamisanriku Town has contributed to both economic and environmental sustainability by reducing waste incineration and landfilling, and significantly cutting GHG emissions. However, the low collection rate of kitchen and food waste and the 56% operational rate of the BIO facility highlight areas for improvement. This section will look at the challenges identified and explore strategies to optimize the BIO system's benefits, drawing on insights from our quantitative analysis and stakeholder interviews.

5.1. Challenges in Making BIO Facilities Operate More Effectively

This study highlights the important role played by stakeholder cooperation in the production of high value-added products through the circular use of MOW in the community: in Scenario A3 (BAU), the BIO facility is 56% operational compared to Scenario A1 before the facility was operational; moreover, the economic and environmental impact has improved by 13%. In particular, the reduction in waste incineration and the improvement in the wastewater sludge treatment process have resulted in a significant reduction in GHG emissions. However, the operation of the BIO facility alone does not provide economic benefits due to the operational costs involved (Scenarios A2 and B2). The development of high value-added products through stakeholder collaboration (Scenarios A3 and B3) can greatly accelerate sustainable local development in both environmental and economic terms.

Despite the identified benefits, the collection rate of kitchen and food waste remains low, at approximately 12% of total waste, and the utilization rate of the BIO facility is less than 60%, suggesting significant room for improvement. Enhancing the operation of the BIO facility and promoting high-value agricultural products using BIO-derived fertilizers could potentially lead to greater reductions in GHG emissions as well as environmental burdens and thus substantial economic benefits for the local community. However, several challenges hinder the optimal utilization of the BIO facility:

1. Institutional constraints: For example, the current municipal waste management contract may restrict BIO facility operators from freely selling liquid fertilizer as a commercial product, resulting in reliance solely on the town's waste disposal business fee for revenue. Also, rice produced with the liquid fertilizer can be priced high if sold through independent sales channels, but if sold through agricultural cooperative, it will be priced low, the same as other rice.
2. Insufficient organic waste collection: The current collection rate does not fully utilize the BIO facility's capacity. This is due to inadequate cooperation in organic waste segregation, particularly from larger hotels. Meanwhile, the development of other organic resources, such as the seafood processing industry, should also be considered.
3. Technical limitations: The current BIO facility is configured to process kitchen waste and sludge from sanitation centers in a 3:7 ratio. This ratio has been established based on optimal processing conditions for these materials. However, due to the limited amount of collected kitchen waste, adhering to this fixed ratio results in an excess of sludge from the sanitation centers. Sticking to this ratio not only restricts opportunities for utilizing other available organic resources in the region but also misses the

potential benefits of combining different organic materials, such as increased biogas production and cost reduction. Therefore, implementing a more flexible processing ratio is crucial for optimizing resource utilization according to regional characteristics. Additionally, demographic decline and the widespread use of septic tanks may lead to competition for sludge from sanitation centers. Furthermore, the mountainous terrain in Minamisanriku presents challenges, as many areas make the mechanical application of liquid fertilizer impractical or inefficient, which must be carefully considered from a technical perspective.

To fully capitalize on the BIO facility's potential, immediate measures are required to address the institutional restrictions imposed by the "waste management project" classification and to enhance organic waste collection rates, especially from commercial sources such as hotels and restaurants, while considering the overall regional material flow balance. These steps are critical to improving the facility's efficiency and maximizing its contributions to the local community's economic and environmental sustainability.

5.2. Need for Reconfiguration to Realize Medium- to Long-Term Benefits for the Community as a Whole

Increasing the utilization rate of the BIO facility alone does not guarantee all the benefits that the BIO system offers to local communities. It is crucial for all stakeholders—BIO facility operators, farmers using liquid fertilizer, government officials, and waste-generating households—to understand the environmental and economic benefits of this initiative and engage in a bottom-up co-design and co-evolution process. The BIO mechanism has the potential to play a vital role in achieving long-term socio-economic sustainability in the Minamisanriku region. Interviews with key stakeholders reveal several challenges in positioning BIO as part of the region's transition to mid- and long-term sustainability.

1. Linking short-term benefits with medium- to long-term benefits for each stakeholder

The biomass initiative in Minamisanriku Town has shown some direct benefits but falls short of stakeholders' long-term goals. For example, farmers using liquid fertilizer from organic waste report high-quality crops selling at premium prices, even though distribution is limited to out-of-town consumers. Residents appreciate the convenience of 24/7 organic waste disposal, and the local government benefits from reduced waste management costs. However, the initiative's full potential remains unrealized. Early adopters hoped to revitalize the local agricultural industry and instill community pride but face challenges in achieving organic certification and local distribution. There is a disconnect between household waste separation and the local consumption of rice products derived from liquid fertilizer, which has resulted in missed opportunities for broader community engagement in the circular economy. Additionally, while businesses aimed to establish a sustainable community with "decentralized, autonomous, and regionally complete agriculture," the current production levels fall short of these ideal scenarios.

2. Designing a mechanism to share the vision of community-wide transformation

To maximize the initiative's potential, it is crucial to extend beyond immediate individual benefits and promote medium- and long-term community-wide advantages. This involves broadening public understanding beyond waste reduction to recognize the connection between this system and valuable local food production, landscape preservation, and the role of public cooperation. Sharing knowledge across all community sectors is vital, including creating opportunities for non-farming residents to engage with the process and developing a compelling narrative about community resource circulation. Addressing challenges such as high prices, procedural hurdles, and Minamisanriku's limitations as a mid-mountainous area with restricted cultivation capacity will be key to fully realizing the potential of this biomass initiative.

6. Conclusions

This study investigates the economic and environmental benefits of utilizing AD for MOW in Minamisanriku Town. The introduction of the BIO system demonstrates significant potential to transition the local business environment toward a more resource-efficient circular economy. Utilizing MOW as liquid fertilizer, as well as for energy production and other high-value products, has been shown to greatly promote the sustainable use of local resources, reduce incineration and landfill waste, support organic agriculture, and contribute to the development of a self-sufficient and resilient local community.

To fully realize these benefits, it is essential to address challenges such as low collection rates of organic waste and facility utilization. Maintaining and enhancing the capacity of the BIO system requires active participation from local government, businesses, and citizens. Governments should commit to long-term investments and policy adjustments, while businesses must innovate their business models, implement more flexible processing ratios to optimize local organic resource utilization, and explore diverse funding sources. Currently, the system relies heavily on municipal waste processing fees, but there is significant potential to commercialize liquid fertilizer and seek alternative funding sources, such as carbon credits. Such investments and business model innovations are crucial for fostering long-term community resilience and advancing transitions toward a decarbonized, circular, and nature-inclusive society.

Initial findings suggest that community engagement is critical for the success of the BIO system. While individual stakeholders benefit from the biomass initiative, broader contributions to the community's medium- to long-term development appear limited. There is a notable gap between the current state and the anticipated benefits, such as the maintenance of agricultural landscapes and the revitalization of community through integrated food and agriculture cycles. We hypothesize that closing this gap will require innovative collaboration among various stakeholders. Preliminary observations indicate that providing feedback to residents and businesses about benefits and outcomes may foster ownership and cooperation. Additionally, partnerships with local schools for meal programs and food-related businesses could optimize system efficiency and promote sustainable practices across the community. However, these are preliminary considerations based on initial investigations and require further exploration.

The study has several limitations that should be acknowledged. First, this research is based on a case study from Minamisanriku Town, which may limit the ability to apply the findings to other regions with different environmental, economic, and social contexts. Additionally, the analysis did not incorporate a sensitivity analysis to account for variations in key parameters, such as waste collection rates and fertilizer/rice market conditions, which could impact the overall outcomes. Future research should include a sensitivity analysis to explore how changes in these parameters might affect the economic and environmental benefits of the BIO system. Moreover, the applicability of these strategies to other communities with diverse environmental and socio-economic conditions should be examined to enhance the robustness and applicability of the findings. Future studies will delve deeper into these aspects and explore strategies for achieving community-wide benefits and fostering truly integrated and sustainable regional ecosystems.

Supplementary Materials: The following supporting information can be downloaded at: www.mdpi.com/xxx/s1, Table S1: Parameters for calculating expenses and income, and GHG emissions [22,23].

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