Output 1 – 4

Carbon Reduction and Health Improvement by Retrofitting Biogas Plant in Tanzania

Table of Contents

List of figures

List of tables

List of Abbreviations

APQA	Animal and Plant Quarantine Agency
TMDA	Tanzania Medical Devices Authority
NM-AIST	Nelson Mandela African Institution of Science and Technology
PM	Particulate matter
WHO	World Health organization
TWA	Time-weighted average
BMP	Biogas methane potential
SBA	Specific biogas potential
VSS	Volatile suspended solids
COD	Chemical oxygen demand
FS	Fixed solids
TN	Total Nitrogen
NPK	Nitrogen Phosphorous Potassium
AMS	Animal manure management system

1. Introduction

Biogas is produced through the anaerobic digestion (AD) of organic materials such as biomass and waste. This renewable fuel can be used in a variety of ways: burned directly for energy, converted into electricity and heat via combined heat and power (CHP) systems, or upgraded to biomethane for injection into natural gas grids or use as vehicle fuel. Beyond its role as a clean energy source, biogas play an important part in sustainable waste management. The leftover digestate from AD is highly valued by agricultural communities, particularly for its ability to reduce dependence on synthetic fertilizers. With growing global efforts to cut greenhouse gas emissions in both the energy and agricultural sectors, biogas has emerged as a key component of renewable energy strategies aimed at decarbonizing energy systems, combating climate change, and decreasing reliance on fossil fuels.

Biogas is also recognized for its potential to advance Sustainable Development Goal 7.1.2, which focuses on ensuring that everyone has access to clean cooking fuels and technologies by 2030. This is especially important considering the limited progress so far in adopting and consistently using cleaner cooking methods. Additionally, there is an urgent need to address the serious health risks linked to indoor air pollution caused by burning traditional biomass. Each year, the use of charcoal and biomass for cooking is believed to contribute to around 4 million premature deaths, underscoring the importance of transitioning to cleaner alternatives like biogas. Therefore, because rural households use Biomass such as wood and coal for cooking, CO_2, the main greenhouse gas of global warming, is released into the atmosphere in large quantities. According to Tanzania's national energy policy, it is proposing a policy aimed at 60% of renewable energy as a whole by 2026. Investments are being made to replace biomass with natural energy to cope with climate change. However, most of the investment facilities are concentrated in cities, and investment is still insufficient in rural areas where greenhouse gases are emitted a lot, so climate change response is weak.

Therefore, because rural households use Biomass such as wood and coal for cooking, CO_2, the main greenhouse gas of global warming, is released into the atmosphere in large quantities. Indoor air pollution caused by biomass causes health and environmental problems at home. In Arusha Rural area, north of Tanzania, cooking fuel indoors shows that the level of smoke-exposure risk (SER) is 84.3%, higher than the urban area of 60.1%. Since the use of Biomass is high in rural households, personal hygiene problems such as respiratory diseases and eye diseases caused by fine particles are serious due to indoor air pollution caused by toxic gas. Rural families are also burdened by the cost of purchasing trees. Therefore, it is necessary to build an effective biogas plant at a lower cost which can be easily supported by residents. The main research model comprised of four phases: (i) On-site investigation off biogas plant, Arusha Tanzania, (ii) problem identification for low performance of the biogas plant, (iii) Sample analysis of digestate for biomethane potential, (iv) suggested retrofitting for the biogas plant with utilizing the digestate for phytotoxicity.

Summary report for Output 1

Meeting to discuss the problems mentioned in the CTCN request form and highlight the causes behind the low CH_4 efficiency of the biogas plant. Preparing a plan to visit Arusha, Tanzania and onsite biogas plant observations.

Activity 1.1. Introduction

An in-person kick-off meeting was held in Seoul, South Korea on June 3, 2024, to discuss the issues outlined in the CTCN request form, focusing on the low methane efficiency of the biogas plant in Arusha, Tanzania. The meeting was called by the investigation team and the title of meeting was "Carbon reduction and health improvement by retrofitting biogas plant in Tanzania".

Fig. 1. Details about the investigation team.

The meeting went for an hour and during that period Prof. Dong-Hoon Kim and his co-team investigator presented the importance of biogas, considering the limiting greenhouse gas emission, energy security, the current geopolitical instability and current scenario of biogas industry in South Korea. Later, the discussion was focused on the current scenario of biogas industries in Tanzania and the problems the country faces when to improve the biogas infrastructure. Furthermore, the focal point was low performance of biogas plant established and run by Gongali Model Co. Ltd, Njiro in Arusha, Tanzania was discussed and the possible suggestion based on the situation was suggested. The primary objective was to identify the root causes of the inefficiency and develop a plan to address them. Key problems identified during the discussion included sludge accumulation, temperature fluctuations, and biogas leakage. The panel agreed upon to investigate the reason behind low performance of biogas plant and suggestions based on the initial reports.

Table 1. List of Participants and their affiliation.

S. No.	Name of Participants	Affiliation	Gender
1	Prof. Dong-Hoon Kim (Lead investigator)	Inha University, South Korea	Male
2	Prof. Si-Kyung Cho (Co-Investigator)	Dongguk University, South Korea	Male
3	Dr. Chang-Kyu Lee	R.E.D Corp. South Korea	Male
4	Mr. Hoyoung Jo	Climate Technology Specialist, CTCN	Male
5	Dr. Gerald Kafuku	Tanzania Commission for Science and Technology (COSTECH)	Male
6	Prof. Askwar Hilonga	Nelson Mandela African Institution of Science and Technology	Male
7	Dr. Wona Lee	NCTCC, South Korea	Male
8	Dr. Seongwon Im	Suchon university	Male
9	Dr. Om Prakash	Inha University, South Korea	Male
10	Mr. Ali Ashraf Joolaei	Inha University, South Korea	Male
11	Dr. Min-Sang Kim	Dongguk University	Male

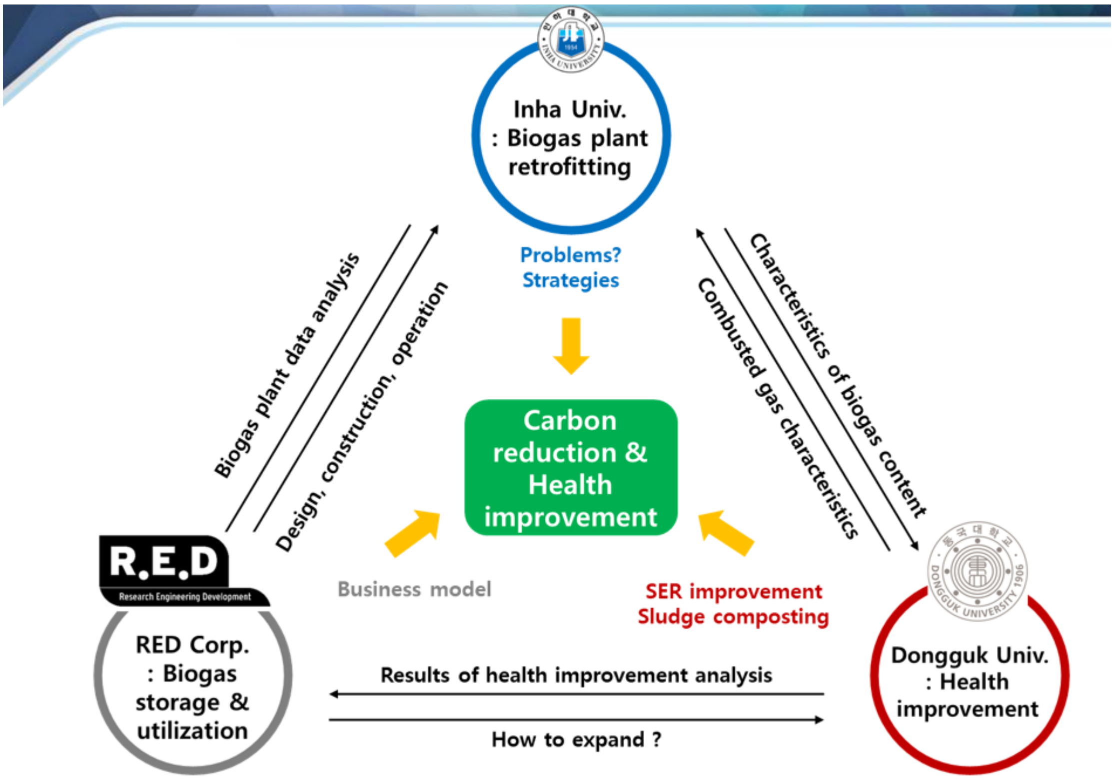


Fig. 2. The work distribution for each team.

Activity 1.2. Checking the possibilities of importing samples from Tanzania to South Korea for analysis

To better understand the technical issues, it was decided to analyze sludge samples from the digester tank. This required importing samples from Tanzania to South Korea for detailed laboratory testing, which included total solids, volatile solids, fixed solids, and microbial community analysis. The process involved coordinating with a logistics company in Tanzania to handle the export of samples and the document preparation was submitted by the end of July to clearance authority. An import clearance certificate could not be obtained to facilitate customs clearance in Tanzania. Additionally, the Animal and Plant Quarantine Agency (APQA) in South Korea denied the clearance for the manure samples. This step was critical to ensure the samples could be legally and safely transported for analysis. The samples were then analyzed n-site as mentioned in Output 3.

Activity 1.3. Buying chemicals and sensors to export from South Korea to Tanzania

For onsite analysis, chemicals and sensors needed to be exported from South Korea to Tanzania. This involved contacting logistics companies in South Korea to arrange the export of analytical chemicals and equipment. Clearance certificates were obtained from the Tanzania Medical Devices Authority (TMDA) to ensure compliance with local regulations. This step was essential to equip the team in Tanzania with the necessary tools for accurate diagnostics and problem-solving. The export of analytical chemicals was denied by the air transportation company (FedEx and DHL) in South Korea via due to the risks associated with transporting hazardous materials. Therefore, the chemicals were ordered to purchase locally in Tanzania instead.

Summary report for Output 2

Plan to visit Tanzania: Onsite biogas plant inspection and giving lecture regarding biogas basics, biogas industry in South Korea, and carbon emissions to university student

Activity 2.1. Onsite biogas investigation

A trip to Arusha, Tanzania was planned focuses on two primary objectives: Conducting an on-site inspection of biogas plants and delivering an educational lecture at the NM-AIST about basics of biogas, biogas industry scale in South Korea, taught about carbon emission calculation. The activities are designed to assess the performance of biogas plants, share knowledge about biogas technology, and evaluate the current state of biogas utilization in Tanzania. The trip was planned for 10 days and started from Aug 9, 2024, to Aug 19, 2024. An on-site inspection was done for the biogas plant situated at Njiro, Arusha, Tanzania. Additionally, a gas flow meter was also installed to check the biogas production on a daily basis. The methane content was below 20% in the biogas plant, which is very low compared the usual content (50-60% CH_4).

Activity 2.2. Lecture at Nelson-Mandela African Institution of Science and Technology (NM-AIST)

A lecture on the importance of biogas and its current scenario in South Korea was given to NM-AIST students. A total of 7 people were attended the seminar. Below the glance of the presentation files has been shown as figures.

The content of the lecture was:

(1) The importance of biogas as an energy source and reducing greenhouse gas emissions.

(2) Basics of anaerobic digestion to produce biogas using different organic waste.

(3) Potential of biogas industry in South Korea

(4) Potential and utilization of animal manure for biogas generation

Introduction of Biogas Industry in Korea (1)

Number and capacity of biogas plants in Korea

*(Number of unit) (ton/d)

Year	Food waste	Livestock manure	Sewage sludge	Integrated Digestion	Etc.	Total
2021	(25) (5,463)*	(3) (380)	28 (16,510)	**53** (45,931)	1 (28,000)	**110** (96,284)
2020	(26) (6,123)	(5) (630)	33 (23,023)	46 (37,673)	-	110 (67,450)
2019	(21) (5,084)	(4) (480)	32 (21,355)	44 (37,517)	-	101 (64,436)
2018	(21) (5,084)	(4) (480)	32 (21,355)	43 (37,427)	-	100 (64,346)

Current status of biogas production and utilization

**(x10^6 m^3) (%)

Year	Production	Utilization							Combustion (Unused)
		In-situ (53.9%)		Ex-situ (30.8%)					
		Electricity generation	Heating	Electricity generation	Gas	CNG	Heating	Subtotal	
2021	(375) (100)**	(46) (**12.3**)	(156) **(41.6)**	(38) (10.2)	(34) (9.1)	(6) (1.5)	(38) (**10.1**)	(318) (84.7)	(57) (**15.3**)

Year	Production	Utilization					Combustion (Unused)
		Electricity generation	Ex-situ	In-situ	Steam gas	Subtotal	
2020	(362) (100)	(50) (13.8)	(100) (27.6)	(114) (31.4)	(38) (10.5)	(302) (83.2)	(61) (16.8)
2019	(351) (100)	(65) (18.5)	(90) (25.6)	(106) (30.1)	(33) (9.3)	(293) (83.5)	(58) (16.5)
2018	(354) (100)	(62) (17.6)	(98) (27.6)	(95) (26.8)	(31) (8.7)	(286) (80.7)	(68) (19.3)

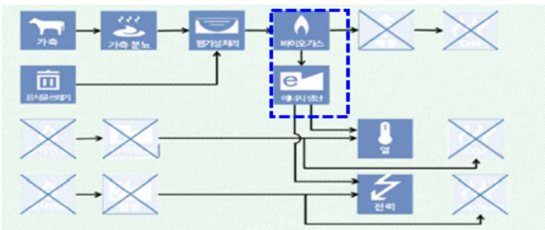
3

Introduction of Biogas Industry in Korea (2)

<Biogas plant expectation until 2030>

Year	Num.	FW	LM	Sludge	Co-digestion
2008	35	5	6	17	10
2013	61	16	7	20	18
2020	110	26	5	33	46
2030	200	+20	+30	+10	+30

<Development of Korea own methodology for proving GHGs reduction – Tier 2,3>



- **Legal announcement** for "facilitating biogas production and use" in March 2021 from the congress.
  - Number of biogas plant ↑ **+ 90 until 2030**
  - Current purification system for LM → **First, biogas and further resource (N and P) recovery**
  - Planning to treat all food waste in **Seoul by co-digestion** in WWTP until 2030.
- "**Biogas law**" passed at the congress in Dec 2023.
  - Setting the target on how much **amount of biogas** should be produced in each region. This will be activated from **Jan 2025**.
  - **2025~2030: Half of the potential**, 2040: 70% of the potential, 2050: 80% of the max. potential
  - **Penalty** and **incentives**

4

Fig. 3. The screenshots of contents presented before students. It showed the biogas industry status in South Korea.

Biogas potential in Korea

Index	Water content (%)	VS content (VS/TS, %)	COD /VS	Theoretical maximum* (m^3/ton)	Digestion efficiency (%)	Practical value (m^3/ton)	Waste generation (10^6 ton/y)	Biogas Production (10^6 m^3/y)
Food waste	83	95	1.5	170	70	119	5.5	653
Sewage sludge (cake)	80	90	1.3	164	50	82	3.5	287
Livestock manure	90	90	1.3	82	40	33	65.3	2,139
Unused biomass	85	90	1.5	142	60	85	1.8	153

* Theoretically, 1 kg COD = 0.35 m^3, CH_4 = 0.7 m^3 biogas (CH_4 = 50%)

Food waste → 1 ton × 1,000 kg/ton × 0.17 × 0.95 × 1.5 × 0.7 m^3 biogas

3,232 × 10^6 m^3 = 1,616 × 10^6 m^3 CH_4 = 64,637 × 10^6 MJ = 15,390 × 10^6 Mcal

= 1,538,968 TOE

(0.5% total primary energy supply in Korea 2020) (40 MJ/m^3 CH_4, 1 TOE: 10^4 Mcal)

5

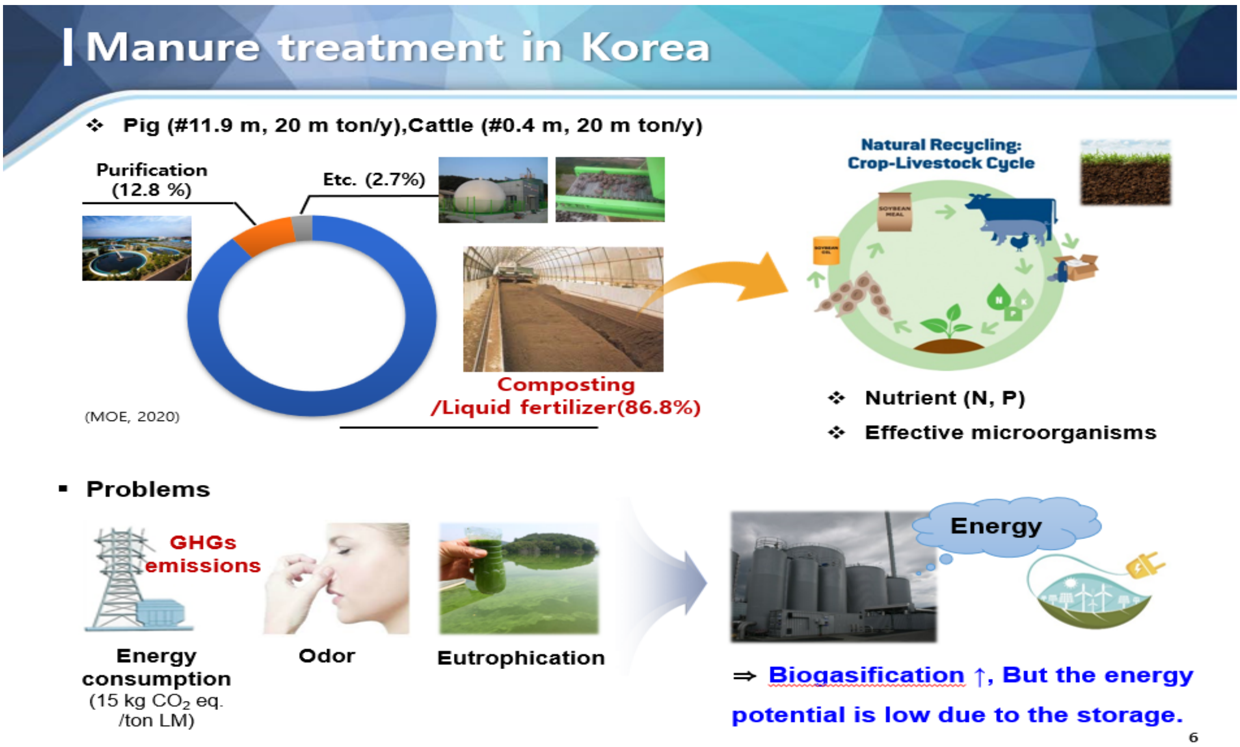


Fig. 4. Total biogas potential in South Korea and potential from manure was shown.

Fig. 5. On-site inspection of the biogas plant in Arusha, Tanzania and delivering lectures to students working on biogas generation.

Problem identification and comparison with previous studies.

A study has been conducted to find the possible factors behind high rate of biogas plant failure in Tanzania. Based on the literature[1] (Hewitt et al., 2022), the main reason for failure of biogas plants in rural Tanzania were shortlisted and presented here:

1. Poor quality installation including the use of inappropriate technology (ex. Unscientific operational parameters, such as feed to water ratio, feeding intervals, pH parameters, insufficient/no mixing inside digester tank, cracking and leaks in the digester etc.).

2. Irresponsible and lack of proper training in operation and maintenance issues due to unawareness of basic knowledge and poor troubleshooting decisions.

3. Irregular and untimely feeding throughout the operational period in different seasons, high temperature variations in mountainous regions, and less water availability during the dry seasons.

4. Improper maintenance and labor shortage are another reasons for failure of biogas plants in rural Tanzania.

Activity 2.3. Comparison of indoor dust concentration

2.3.1. Indoor air quality measurement methodology

Indoor air quality assessment is essential to ensure a healthy and safe environment for occupants. Poor indoor air can cause various health issues, including respiratory problems, allergies, fatigue, and long-term illnesses. By conducting an assessment, it is possible to identify and measure harmful pollutants such as particulate matter, volatile organic compounds, carbon monoxide, mold, and other biological contaminants. The Indoor air quality assessments were conducted in two households in the Arusha region—one using biomass and the other using biogas for cooking. PM_{10} concentrations were measured in the cooking areas within each kitchen. For particulate matter collection, cellulose thimble filters (30 × 80 mm) resistant to temperatures up to 200 °C were used. Prior to sampling, each thimble filter was dried at 105 °C for 2 hours and weighed to obtain the initial mass. PM_{10} was collected by drawing air through the filter using a vacuum pump at a flow rate of 35 L/min. Filters were replaced every 15 minutes over a 1-hour sampling period, aligned with typical cooking durations. After sampling, the thimble filters were again dried at 105 °C and reweighed to determine the amount of PM_{10} collected. The PM_{10} mass was then calculated and analyzed. The measured concentrations were compared against the WHO indoor air quality guidelines to assess potential health risks. Additionally, a TWA was used to evaluate the risk associated with prolonged PM_{10} exposure.

2.3.2. Air quality monitoring results

The results were extrapolated to simulate a household cooking three times a day for one hour per session. The calculations indicated that using biogas resulted in no dust production from the fireplace or cooking environment. In contrast, kitchens utilizing biomass produced a significant amount of dust, with an average dust concentration of 16,452.21 μg/m^3 over 24 hours. This value is 365 times higher than the WHO guideline limit of 45 μg/m^3. On 15 min mark for biomass utilizing household, it has shown that 128,676μg/m3 of dust was produced within cooking environment. These findings highlight the severe health risks associated with biomass use in household kitchens, emphasizing the need for cleaner cooking alternatives.

Fig. 6. Smoke collection from biomass (left) and biogas (right).

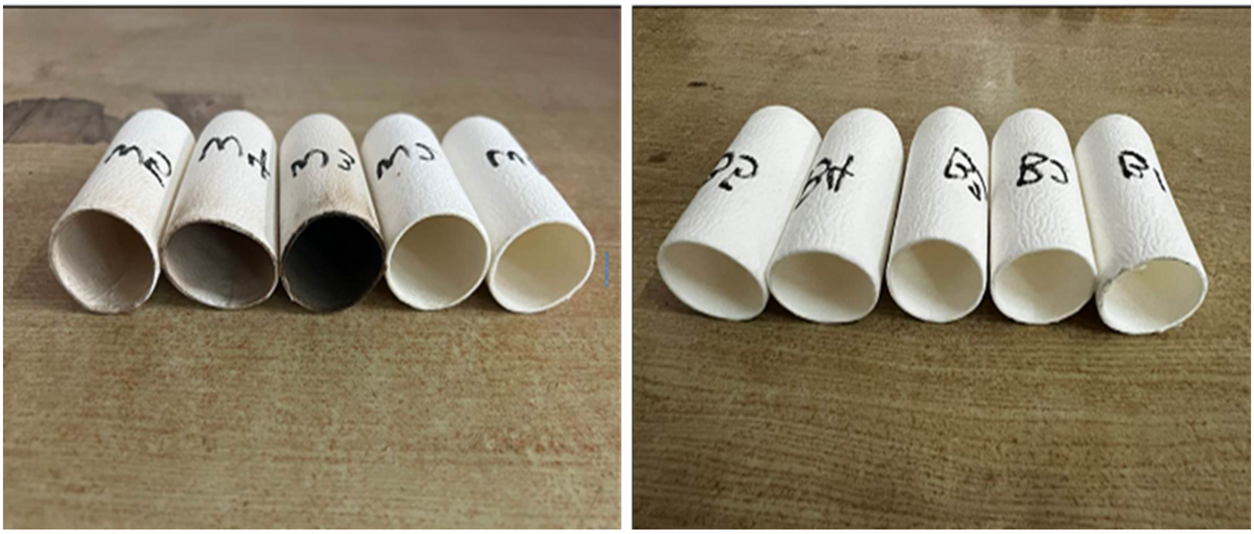


Fig. 7. Smoke collected samples from biomass (left) and biogas (right).

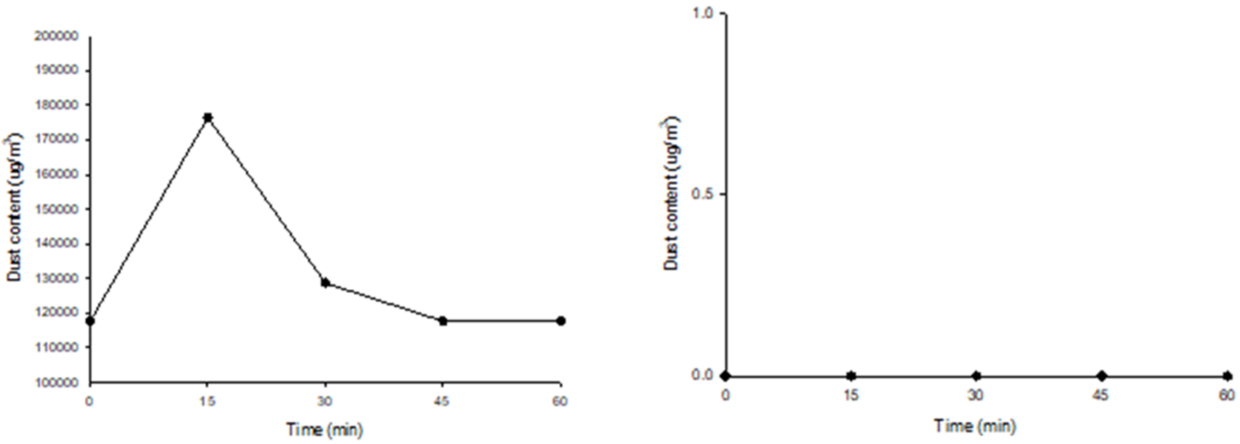


Fig. 8. Dust content from biomass burning (biomass burning) vs biogas burning (right).

Summary report for Output 3

Second visit to Tanzania: Retrofitting of digester tank, biogas leakage fix, optimization of feeding process, and teaching methane potential calculation to NM-AIST students

Activity 3.1. Preparation of buying chemicals for physico-chemicals analysis, biochemical methane potential (BMP) test

Before the second visit of Tanzania, a zoom meeting was organized in October 2024 and headed by Prof. Dong-Hoon Kim and all the paprticipants were attended as shown in Table 2. The discussion was based regarding the retrofitting of biogas plant and chemicals purchasing directly in Tanzania.

Table 2. List of participants.

S. No.	Name of Participants	Affiliation	Gender
1	Prof. Dong-Hoon Kim (Lead investigator)	Inha University, South Korea	Male
2	Prof. Si-Kyung Cho (Co-Investigator)	Dongguk University, South Korea	Male
3	Dr. Chang-Kyu Lee	R.E.D Corp. South Korea	Male
4	Mr. Hoyoung Jo	Climate Technology Specialist, CTCN	Male
5	Dr. Gerald Kafuku	Tanzania Commission for Science and Technology (COSTECH)	Male
6	Prof. Askwar Hilonga	Nelson Mandela African Institution of Science and Technology	Male
7	Dr. Wona Lee	NCTCC, South Korea	Male
8	Dr. Seongwon Im	Suchon university	Male
9	Dr. Om Prakash	Inha University, South Korea	Male
10	Mr. Ali Ashraf Joolaei	Inha University, South Korea	Male
11	Dr. Min-Sang Kim	Dongguk University	Male

The second visit to Arusha, Tanzania was aimed at enhancing the efficiency and functionality of biogas plants through retrofitting, addressing biogas leakage, optimizing feeding processes, and providing advanced training to students at the NM-AIST. This visit built on the previous efforts to improve biogas technology and promote sustainable energy solutions in Tanzania. The first activity involved preparing for the purchase of chemicals required for physico-chemical analysis and BMP testing of feedstock and digestate samples. The Tanzanian team arranged the procurement of these chemicals, with funding provided by the Korean team. This step was crucial for conducting accurate analyses and ensuring the effectiveness of the biogas production process.

3.1.1. Methodology for BMP

For the Biogas potential test and SBA, 270 mL glass bottles with a working volume of 200 mL were used, and all tests were triplicate under mesophilic conditions (35 ± 1 °C). The tests were carried out with feedstock (fresh cattle manure) and fresh effluent as inoculum while the SBA test were performed with old digestate and fresh digestate (new effluent) as inoculum and acetic acid as the sole carbon source, the nutrients were added based on Kim et al. (2021). The inoculum-to-substrate ratio and substrate concentration were 2 g VSS/g COD and 5 g COD/L based on the sludge characteristics as shown in Table 2, for biogas potential and SBA respectively. The initial pH was set at 7.8 ± 0.05 using a 1 N KOH solution, and the bottles were purged with nitrogen gas for 10 min to provide anaerobic conditions as shown in Fig. 9. The bottles were then placed in an incubator (VS-8480SR, Vision Scientific) and degassed after 1 h. After deducting the biogas amount from the control (inoculum only), the cumulative biogas production was fitted using the modified Gompertz equation (Eq. (1)), and its kinetic parameters were calculated using Sigma Plot version 10.0.

where, V(t) is the cumulative biogas production (mL) at the time t (d), P_{max} is the final biogas produced in (mL), λ is the lag period (d), and R_{max} is the biogas production rate (mL biogas/d). biogas production efficiency was then calculated based on 1 g COD = 530 mL biogas (CH_4 = 65%).

$$V(t) = P_{\max} \times \exp\left[-\exp\left(\frac{(R_{(\max)} \times \exp(1))}{P_{\max}} \times (\lambda - t) + 1\right)\right] \quad (1)$$

Fig. 9. Experimental work performed at NM-AIST university, Arusha, Tanzania.

Activity 3.2. Data accumulation

The data showed that the FS percentage for the bottom part of the old digestate was 73.2% of the total solids which was 49% higher than the FS of top part of the old digestate sludge. These results showed that there was high accumulation of silt and sand at the bottom part of the digester tank which downgrades the performance for biogas plant. The COD of fresh digestate sludge was quite low, just 9% of the TS, which showed that it contains a very high percentage of VS which is convertible to biogas. If it has been seen in number, then the VS of fresh digestate was 90% of the TS, which was 246% higher than the bottom part of the old digestate sludge. In terms of COD, the COD of fresh digestate was 169.5 g COD/L, which was 28% lower than, the main reason behind such low concentration was settling down of settleable solids into the digester tank, not because of biogas production. Since when the measurement was done no biogas production was recorded.

Activity 3.3. Complete retrofitting of digester tank

A key component of this visit was the complete retrofitting of the digester tank to address issues such as the removal of silt and sludge accumulated inside the digester responsible for inefficiencies. This process involved removing settled sediment from the biogas reactor, evaluating feedstock and digestate characteristics, observing temperature variations and biogas production rates. These measures aimed to retrieve the performance of the biogas plant and ensure its long-term sustainability. The study was conducted on the sludge digestate taken from the digester tank to analyze its characteristics. It was hypothesized that the primary reason behind biogas plant failure was silt and sludge accumulation. Feedstock characteristics displayed very high organic content, but the biogas potential results showed only 32% conversion efficiency, which is lower than expected.

Fig. 10. The retrofitting of the biogas plant initiated with cleaning of digester tank.

Fig. 11. Delivering lectures for master's and PhD student at NM-AIST, Arusha, Tanzania.

Activity 3.4. Lecture to NM-AIST students

The second lecture about the importance of biogas was delivered and the topic of the lecture was about the basics of microbiology and microbiology involved in anaerobic digestion. The lecture period lasted for an hour and 30 minutes and was attended by 10 students from master's degree and PhD. The fourth activity involved delivering a lecture to NM-AIST students on advanced topics related to biogas technology. The training covered methane potential calculation, carbon reduction calculation, the basics of the anaerobic digestion process, and the utilization of sludge waste. This educational initiative aimed to build local expertise and foster innovation in biogas technology.

Fundamentals of microbiology:

For cells to function they must have:

- ❑ Energy
- ❑ Carbon for the synthesis of new cellular material.
- ❑ Inorganic elements (nitrogen and phosphorus), other trace elements such as sulfur, potassium, calcium, and magnesium.

$$\text{Organic material} + O_2 + NH_3 + PO_4^{3-} \xrightarrow{\text{Microbes}} \text{New cells} + CO_2 + H_2O + NO_2^-/NO_3^- \longrightarrow N_2$$

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Nutritional types of micro-organisms (2):

Nutritional type	Sources of energy, hydrogen/ electrons and carbon	Representative microorganisms
Photolithoautotrophy	Light, inorganic H/e^- donor, CO_2	Algae, Purple and green sulfur bacteria, Cyanobacteria
Photoorganoheterotrophy	Light, organic H/e^- donor, Organic carbon source (CO_2 sometimes)	Purple and green non-sulfur bacteria
Chemolithoautotrophy	Chemical energy source (inorganic), inorganic H/e^- donor, CO_2	Sulfur-oxidizing bacteria, H_2 bacteria, Nitrifying bacteria, Iron-oxidizing bacteria
Chemoorganoheterotrophy	Chemical energy source (organic), organic H/e^- donor, organic carbon source	Protozoa, Fungi, non-photosynthetic bacteria

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Fig. 12. Basics of microbiology delivered for the lecture.

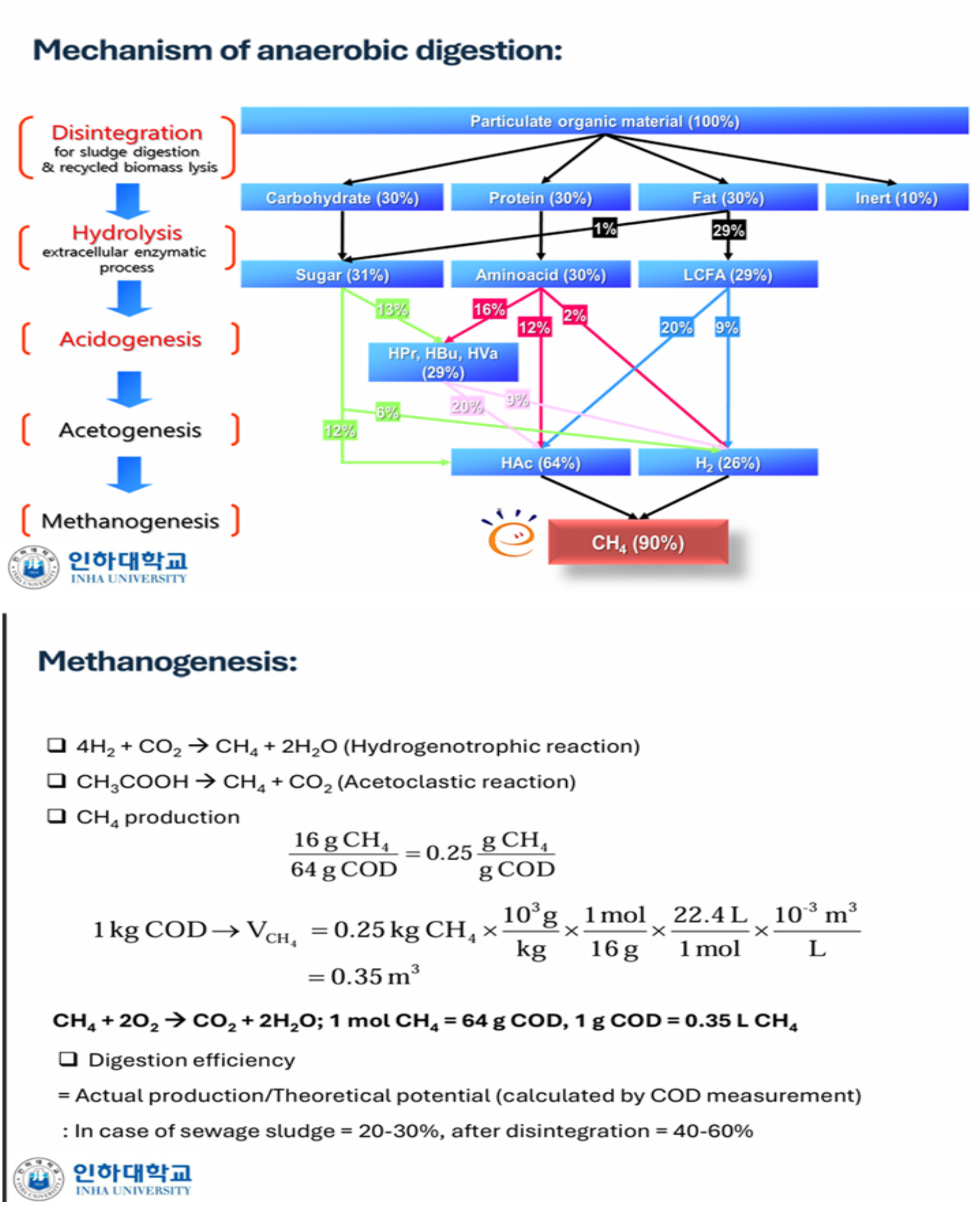

Fig. 13. Mechanism of anaerobic digestion and methanogenesis.

Activity 3.5. Sample collection for COD, TN, and ammonia analysis

The samples were collected from the digester tank and were divided into two parts, top and bottom. The reason behind this partition was to analyze the percentage of fixed solids, since according to the hypothesis, more sediment and silt would have been settled at the bottom of the digester. It was expected that the percentage of silt would be higher in the bottom samples compared to samples collected from the top. The results showed that bottom samples had 49% more fixed solids than top part. This could be one of the reasons for high inefficiencies. The experiment was performed such as estimation of total solids, volatile solids, and fixed solids. It was found that the sludge taken from the bottom part of the digester tank had 74% fixed solids compared to the sludge taken from top part of the digester. It reveals the more than 1/3 of the digester tank was full of silt and sediment which might have been accumulated during the long operation. The data has been provided in Table 3.

Table 3. Characteristics of old digestate taken out from the digester tank and cow dung.

Samples	**TS (% of FW)**	**VS (% of TS)**	**FS (% of TS)**	**COD (g/L)**	**TN (g/L)**	**Ammonia (g/L)**
Feedstock (cow dung)	18.32±0.49	92.46±3.49	7.53±0.43	236.65±6.80	4.36±0.13	1.36±0.11
Old digestate (top part)	16.91±0.36	50.61±4.23	49.39±2.59	113.85±3.80	2.37±0.30	1.75±0.12
Old digestate (bottom part)	28.99±0.50	26.76±2.11	**73.24±3.22**	102.48±2.18	2.45±0.18	1.89±0.14
Fresh digestate	12.24±0.29	90.93±3.56	9.07±0.27	169.48±4.15	3.42±0.16	1.41±0.14

Activity 3.6. Utilization of sludge waste for fertilizer

3.6.1. Methodology for plant growth using digestate sludge

A crop growth experiment was conducted using excess sludge collected from the sludge tank of a biogas digester. The sludge was applied as organic fertilizer, and the experiment was carried out in 10-liter plastic pots. Each pot represented one treatment condition, and a total of six conditions were established: a control (no fertilizer), chemical fertilizer only, digestate only, and three mixed treatments combining organic and chemical fertilizers at ratios of 9:1, 7:3, and

5:5. Lettuce (Lactuca sativa), one of the most commonly cultivated crops in Tanzania, was selected for this experiment, and NPK fertilizer, the most commonly used chemical fertilizer, was used as the inorganic treatment. For each treatment, five replicate pots were prepared, all filled with the same locally sourced soil. The application rates were 60 kg/acre for the chemical fertilizer and 8 tons/acre for the digestate. All pots were irrigated once daily with a fixed volume of water. The cultivation period lasted for two weeks, and plant growth was assessed both before and after the experiment by measuring leaf width, leaf length, number of surviving leaves, plant height, and root length.

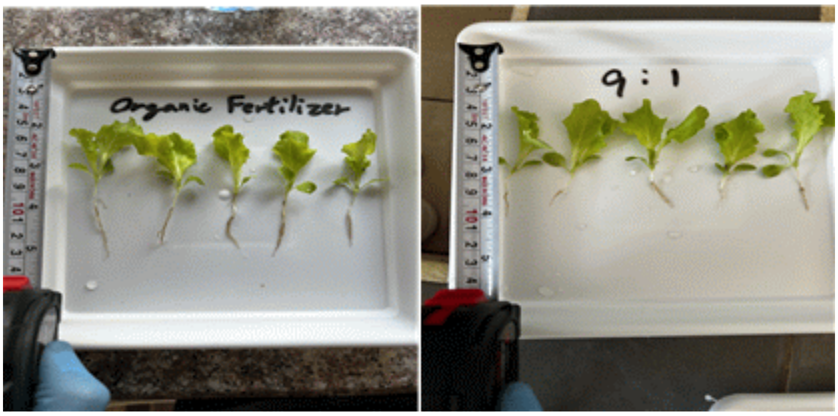

Fig. 14. Early plant measurement photos by condition.

A second study was conducted to evaluate the utilization of digestate from a biogas reactor. The experiment was designed to compare the effects of inorganic fertilizer and digestate on plant growth and inhibition. Additionally, different combinations of digestate and inorganic fertilizer in 50:50, 75:25, and 90:10 ratios were tested for potential application. Lettuce seedlings were chosen for the test, and the experimental conditions included control, inorganic fertilizer, digestate, 50:50, 75:25, and 90:10 treatments. Each condition was tested using five lettuce seedlings grown in separate pots, and the physical properties of the seedlings were measured before planting. The application rates were 60 kg/acre for inorganic fertilizer and 8 tons/acre for digestate.

Summary report for Output 4

Continuous data collection for performance analysis of the retrofitted biogas plant in terms of CH_4 yield and carbon reduction calculation

Activity 4.1. Continuous data collection from the retrofitted biogas plant and BMP

The biogas potential and specific biogas activity was conducted to evaluate the biogas production potential of feedstock (which was cow dung), and methanogenic activity of the old digestate and new effluent and the results were shown in Fig. 15. The reason before this experiment was to check that rate and efficiency of conversions of organic matter present into the feedstock to biogas production. The SBA of old digestate and new effluent indicates rate of fermentation and anaerobic digestion by microorganism. Continuous data on biogas production, methane content, and sludge characteristics was collected from retrofitted biogas plants. The methane content the biogas digester tank was estimated to be >50%, since the methane content at the headspace of effluent collection tank was 45-47%. The SBA for old digestate was 18.0 mL biogas/d and for new effluent it was obtained as 23.0 mL biogas/d. It means that the rate of biogas production increased by 23% and the microbial activity of new effluent was better than old digestate. The low microbial activity of old digestate could also be one of the reasons for low biogas efficiencies of the digester.

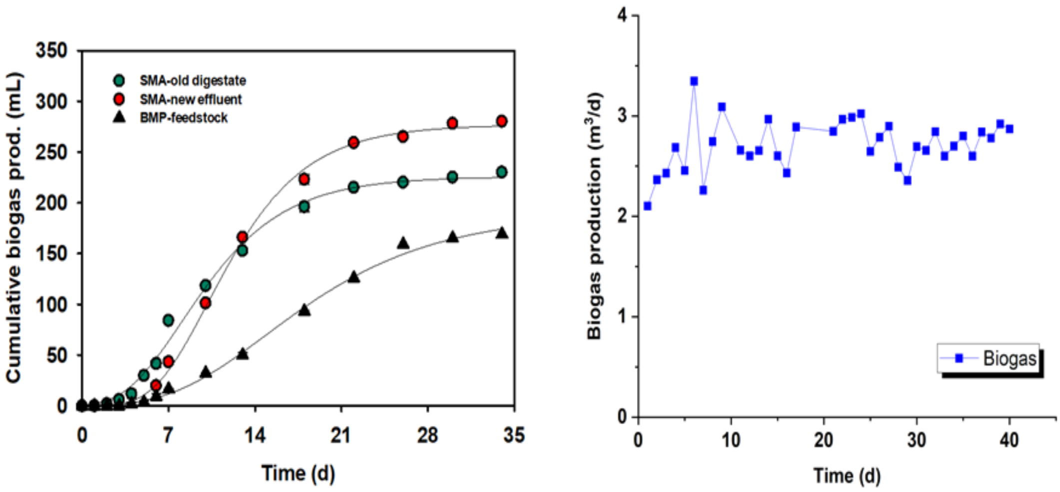

Fig. 15. Daily biogas production from the biogas plant after retrofitting.

Table 4. Biogas potential and SBA results

Samples	Cumulative biogas prod. (mL)	Biogas yield (mL biogas/g COD)	Efficiency (%)	SBA value (mL biogas/d)
SBA-old digestate	225.6	225.6	38.6	18.0
SBA-new effluent	276.7	276.7	47.4	23.0
Biogas Potential feedstock	185.7	185.7	31.8	-

After retrofitting the digester tank, cow dung was fed into the reactor until it was full and then left for 3-4 weeks to allow microorganism activation and the initiation of the fermentation process.

The continuous biogas measurement was initiated using the gas flow meter installed near the gas burner in January 2025, and it was found that it produces almost 2.5 m^3 biogas/d as shown in Fig. 15. The biogas generation before retrofitting was at 45 m^3 in three months, which corresponds to a daily generation of only 0.5 m^3 biogas/d. Based on the above values it can be concluded that the biogas production was enhanced by 400%. The total biogas generated during the four months after installing the gas flow meter in August, 2024 showed 45 m^3 biogas production over three months before the retrofitting, conversely and a total 63 m^3 biogas generated in just one month after retrofitting.

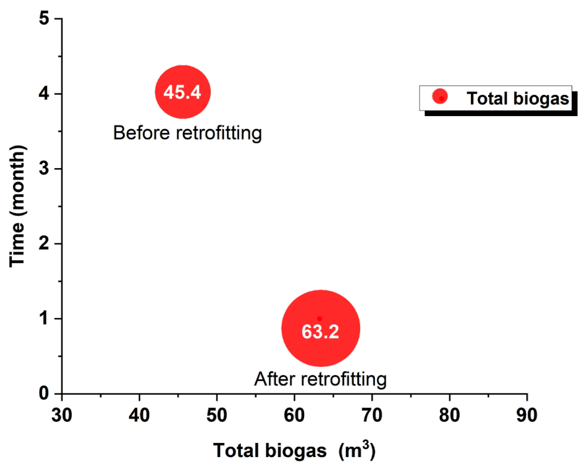

Fig. 16. Total biogas generated before (in four month) and after (in one month) retrofitting.

Activity 4.2. Collaborative biogas experiment and carbon emission reductions

Carbon credits or carbon offsets can potentially be earned by utilizing the produced biogas for producing energy. For example, when generating electricity from biogas, the following two international methodologies can be used: a) AMS-III.D. Methane recovery in animal manure management systems, and b) AMS-I.D. Grid connected renewable electricity generation. Generally, AMS-III.D is applicable for slurry manure, which is commonly stored under anaerobic conditions; however, it may also be used for cow dung since CH_4 is produced from cow dung during storage. Therefore, AMS-III.D was included for the calculation of carbon reduction in here. With the experimental data obtained from the operation of the retrofitted continuous anaerobic digester, the total carbon reduction is calculated to be 1.0 ton CO_2 eq./y (a) Methane recovery-0.23 ton CO_2 eq./y (0.03 ton/d × 169.4 kg VS/ton × 4.4 g CH_4/kg VS (CH_4 emissions factor for cattle, IPCC guideline) × 28 (CH_4 GWP) × 1/1000 × 365) and b) Electricity generation-0.77 ton CO_2 eq./y ((2.5 m^3 biogas/d × 0.6 (CH_4 content assumption) × 35.7 MJ/m^3 CH_4 × 0.278 kWh/MJ × 0.3 (Electricity conversion efficiency) × 0.467 kg CO_2 eq./kWh × 1/1000 × 365)).

Activity 4.3. Data analysis and further suggestions

4.3.1. Health Survey

A field survey was conducted to investigate household energy use patterns and associated health impacts in Tanzania. The survey was divided into two phases, each involving 20 participants. In the first phase, ten households were randomly selected from the local community in Jiro village and an additional ten from urban areas of Arusha city to represent both rural and urban energy usage. The second phase of the survey used a revised questionnaire to gather more detailed responses and was conducted primarily within the Arusha urban area. Survey questions focused on household fuel types used for cooking, accessibility to alternative energy sources such as biogas and natural gas, and self-reported respiratory health conditions. All participants voluntarily completed the questionnaire as presented in Fig. 17, and responses were collected and analyzed to assess correlations between biomass fuel usage and the prevalence of respiratory diseases such as chronic coughing, bronchitis, and severe lung complications.

4.3.2. Health Survey results

The second survey was conducted in Arusha, Tanzania, to investigate additional health issues associated with the use of biomass in household kitchens. For this survey, 20 households were randomly selected around Arusha city.


DONGGUK UNIVERSITY

Tanzania Biogas Utilization Survey

Full Name ____________ Age ______ Gender ○ Male ○ Female

Address ____________

What energy sources are used at home for cooking in your household?

○ Natural Gas ○ Biogas ○ Wood

○ Coal ○ Other (Please specify) ____________

How many times do you use kitchen for cooking in a day

○ 5 ○ 4 ○ 3 ○ 2 ○ 1

Did you ever experienced repiratory(Lung) disease, sickness or pain defore?

○ Strongly agree ○ Agree ○ Neutral ○ Disagree ○ Strongly Disagree

If you have experienced lunge sickness before, how severe was it?

○ 5 ○ 4 ○ 3 ○ 2 ○ 1

Have you ever heard of Biogas for energy source for cooking?

○ Strongly agree ○ Agree ○ Neutral ○ Disagree ○ Strongly Disagree

What is your opinion on current cooking environment in Tanzania?

____

Are there any comment, suggestion or question reguarding our Tanzania biogas utilization survey and research?

____

Thank you for taking the time to complete our Tanzania biogas utilization survey.
Your feedback will help us improve our research.

Fig. 17. 2nd survey questions for health issue in Tanzania community

The findings revealed that out of 20 households, 13 households still rely on biomass or coal for cooking as shown in Fig. 18. Additionally, 7 households reported using natural gas, which appeared to be more commonly used in Arusha city. Most notably, 82% of individuals using biomass or coal reported suffering from lung disease. Also, an additional survey question focused on severity of the lung disease, and 40% of people with biomass as energy source suffered from severe lung disease. These additional findings indicate that a shift to biogas as a clean energy source is an urgent matter in Tanzania.

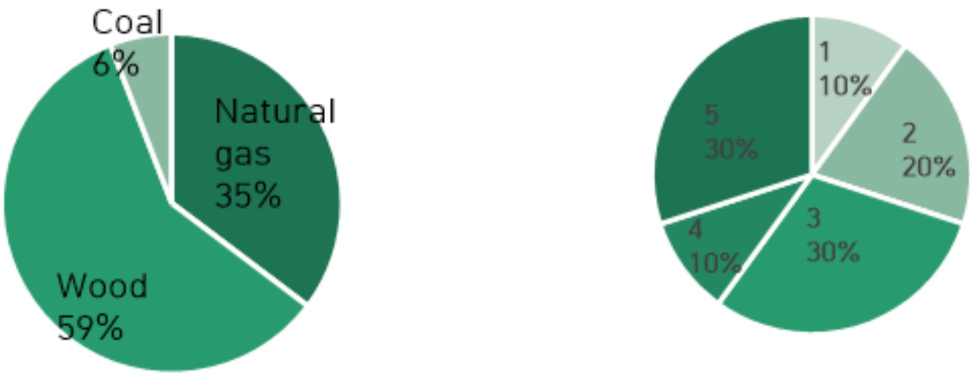

Fig. 18. Survey results Left) Survey result for energy source Tanzania household Right) Survey result for severalty of lung disease with biomass household

4.3.3. Plants growth test using digestate fertilizer

Plant growth test was completed, and each plant in pot was measured for leaf width, length, and remaining leaf numbers. The control group without fertilizer exhibited the lowest average leaf survival rate, while both chemical and sludge fertilizers showed similar effects. Additionally, among mixed fertilizers, the 5:5 and 7:3 ratios delivered comparably positive results. Organic fertilizer demonstrated growth rates with a leaf width of 3.3 cm and a leaf length of 2.9 cm, whereas chemical fertilizer resulted in a leaf width of 2.0 cm and a leaf length of 2.42 cm. Further analysis of the growth differences in leaf width and length revealed that the organic fertilizer utilizing sludge had the highest growth rate. The mixed fertilizer, combining organic fertilizer in a 7:3 ratio with chemical fertilizer, exhibited the highest growth rate, measuring 1.7 cm in leaf width and 2.0 cm in leaf length. Overall, organic fertilizer has been validated as a viable substitute for chemical fertilizers, confirming it is non-toxic. It is concluded that the 7:3 ratio is the most appropriate for mixed fertilizer applications.

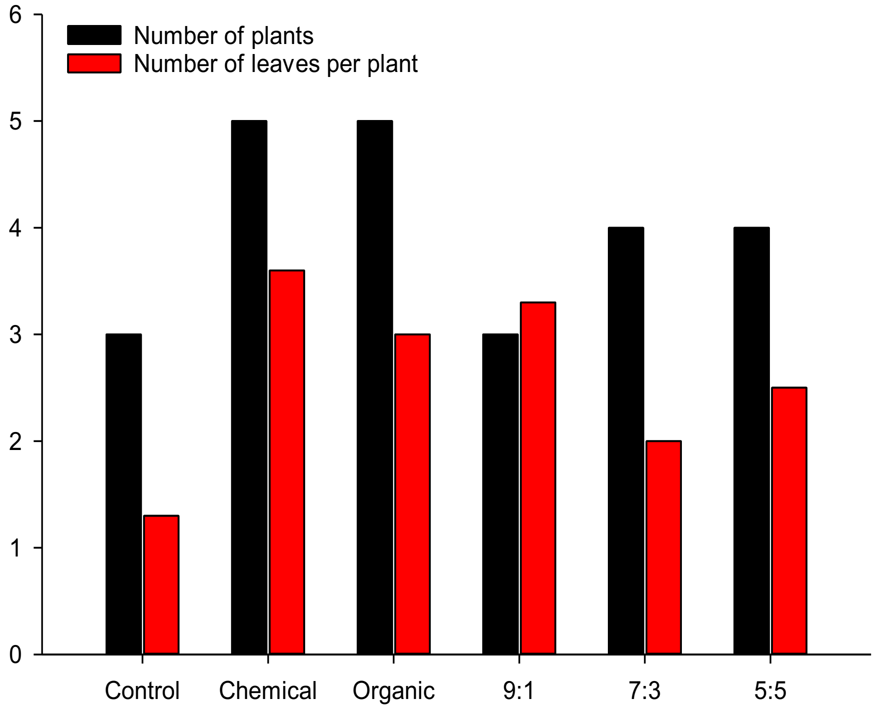

Fig. 19. Plant survival number and average leaf survived per plant by condition

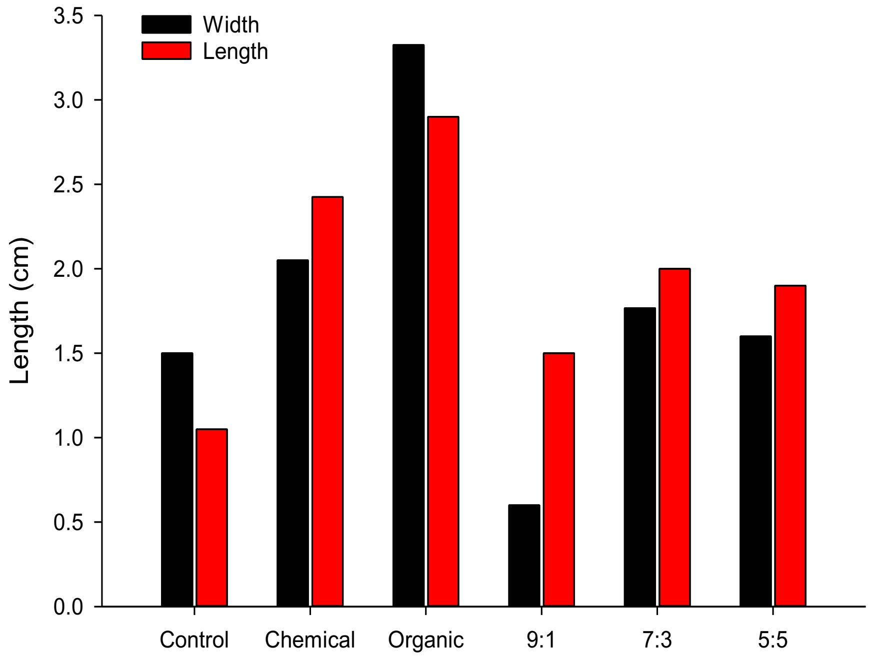

Fig. 20. Average leaf width and length growth rate by condition.

List of presentations and paper submission based on this work

Fig. 21. Domestic conference poster presentation at KSWM, 2024.

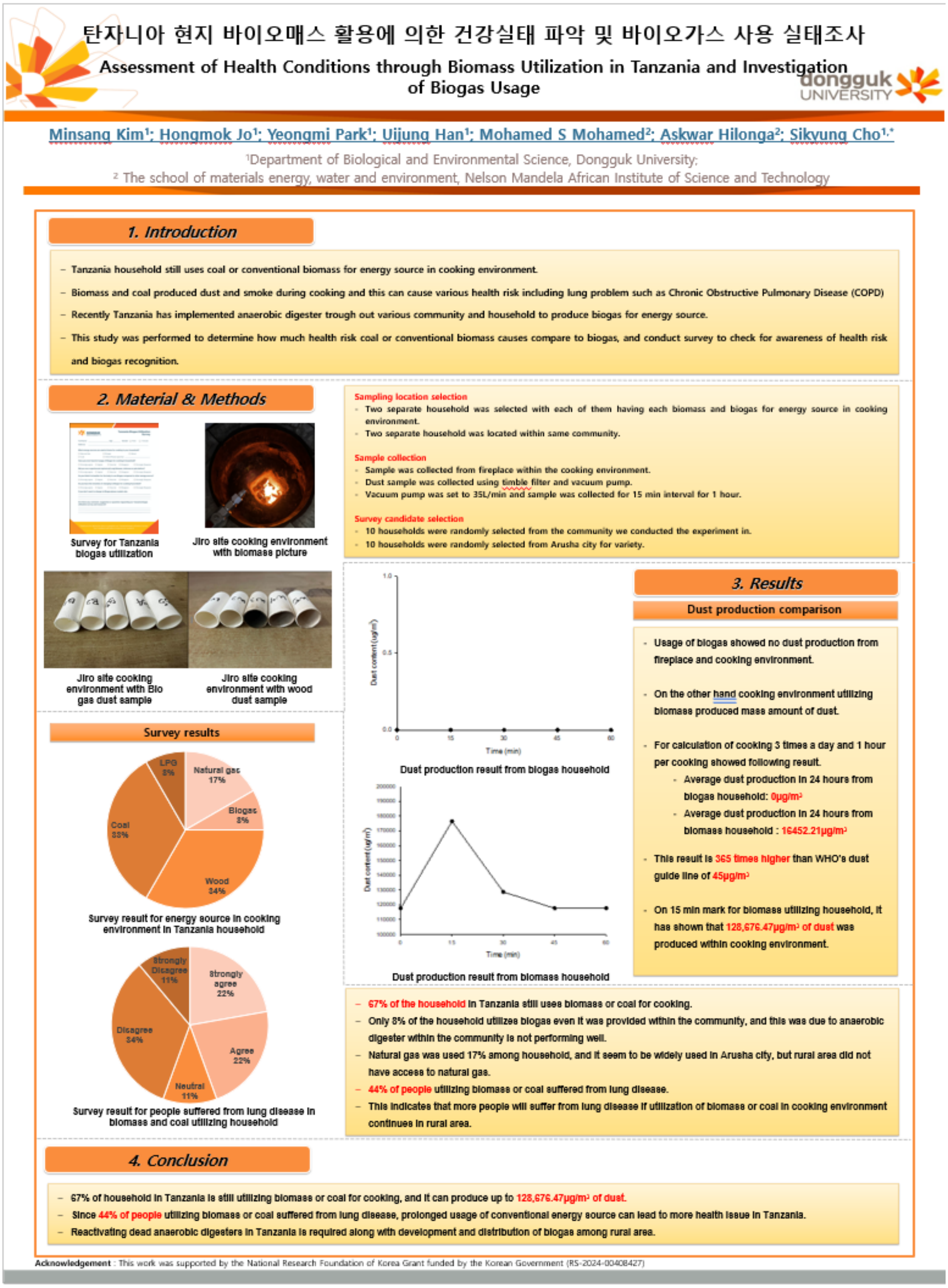

Fig. 22. Domestic conference poster presentation at KSEE, 2024.

탄자니아 농촌지역 소규모 바이오가스 시설 재가동 효과 평가: 실내 대기질 개선 및 소화액 비료 활용 가능성

김민상[a], 조홍목[b], 조시경[c]

Evaluating the effects of reactivating small-scale biogas plants in rural Tanzania: improvements in indoor air quality and utilization of digestate as fertilizer

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ABSTRACT: Access to clean energy remains a critical challenge in many developing countries, and in Africa, including Tanzania, biomass such as firewood continues to serve as the primary household fuel. In 2014, Tanzania installed approximately 12,000 biogas plants across rural areas. However, most of these facilities are currently non-operational, and the country continues to face significant health and resource-related challenges. This study was conducted in the Jiro site of the Arusha region to evaluate the health and agricultural benefits of reactivating small-scale biogas plants. Indoor air quality was assessed by comparing PM_{10} concentrations in households using biomass or biogas. The results showed that PM_{10} concentrations in biomass-using households averaged 16,452 μg/m³, approximately 365 times higher than the WHO recommended limit, while no PM_{10} emissions were detected in biogas utilizing households. In addition, a plant growth experiment was conducted to evaluate the potential use of digestate as an agricultural fertilizer with lettuce. Plant growth performance was assessed under six treatment conditions including digestate, chemical fertilizer, and mixtures of the two at varying ratios. The results showed that digestate treatment resulted in superior leaf growth compared to chemical fertilizer, with the 9:1 digestate to chemical fertilizer mixture producing the most balanced growth. These findings demonstrate that the application of small scale biogas plants can reduce indoor air pollution and associated health risks, while also serving as an effective alternative fertilizer source for rural farmers. Therefore, the reactivation of small scale biogas plants represents a practical and efficient solution to improve public health, energy access, and agricultural productivity in rural Tanzania.

Keywords: Tanzania, Biogas, air pollution, PM_{10}, digestate, fertilizer

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Fig. 23. Paper submission at Waste resource circulation society (KCI).

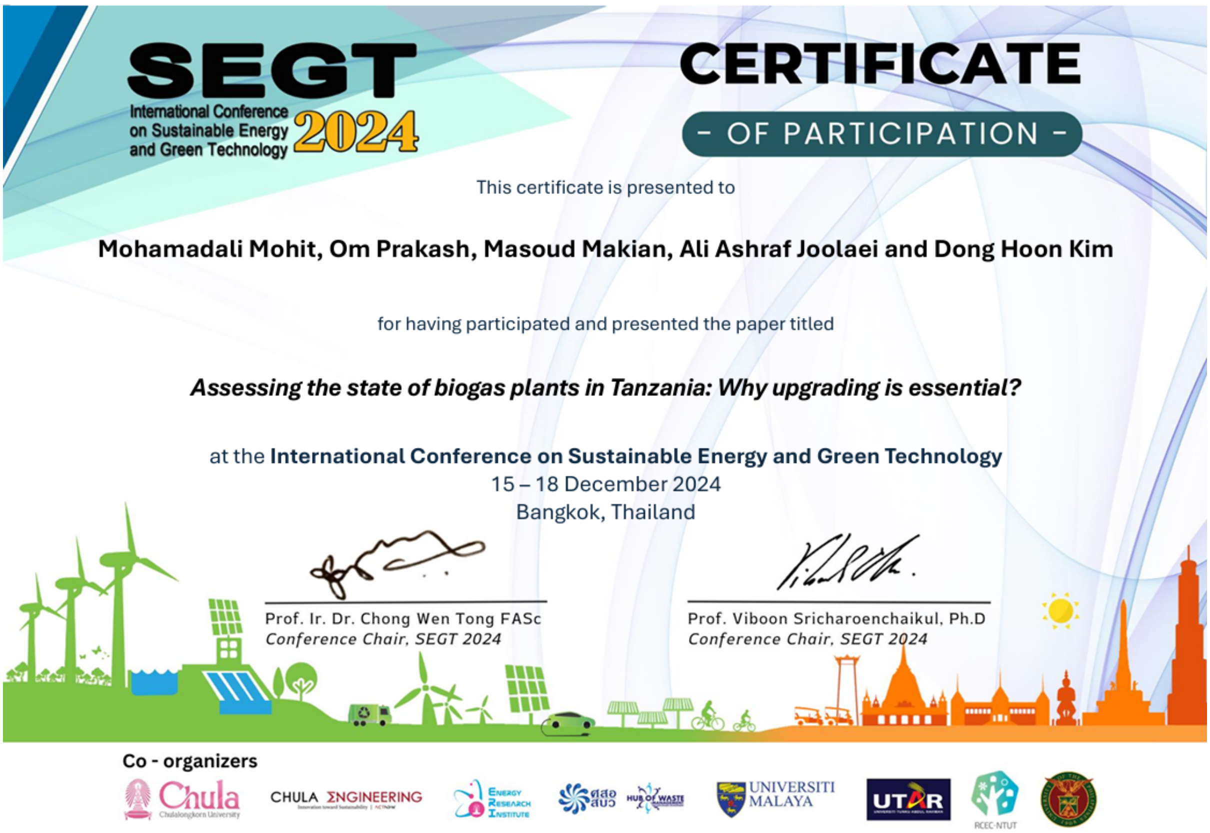

Fig. 24. Certificate of participation for poster presentations at SEGT, 2024 Bangkok, Thailand.

Fig. 25. Poster presentation at SEGT, 2024, Bangkok Thailand.

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Article

Retrofitting of Biogas Plant in Tanzania

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Abstract: Tanzania aims to meet 60% of its energy needs from renewable sources by 2026 to combat climate change and improve air quality. However, rural areas still depend heavily on biomass burning, leading to pollution and health issues. To address this, around 12,000 biogas plants were built over the past decade, but most are now non-functional or produce low biogas. This study examined a 10 m^3 operational biogas plant in Arusha, Tanzania, using cattle manure, to investigate its low biogas yield. On-site inspections revealed issues like sludge buildup and gas leakage. Retrofitting including sand and silt removal and sealing leaks boosted biogas production by 400%, achieving 2.6 m^3/day, matching theoretical estimates. Fresh digestate showed better biogas conversion efficiency (19%) and higher specific biogas activity (27%) than older sludge. Carbon reduction from using cow dung for biogas was estimated at 1.0 ton CO_2eq./year. Over a 30-year plant lifespan, this equals 30 tons of CO_2eq. reduced. These findings highlight the critical importance of retrofitting to restore and enhance the efficiency of biogas plants.

Keywords: biogas; retrofitting; carbon reduction; cattle manure

Fig. 26. Submission of Tanzania work into Energies (an international journal).