Proceedings of 14th IOE Graduate Conference
Peer Reviewed
Year: 2023 Month: December Volume: 14
ISSN: 2350-8914 (Online), 2350-8906 (Print)

Environmental Impact Assessment of Biogas Plant: A Case Study of Rastriya Gai Anusandhan Kendra Biogas Plant, Rampur Chitwan

Binit Kaphle [a], Nabin Kumar Jha [b]

[a] *Department of Mechanical and Aerospace Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
kaphlebinit@gmail.com [a], navin.jha@pcampus.edu.np [b]

Abstract
Anaerobic Digestion (AD) is considered as an environmentally friendly technology to manage biodegradable waste like cattle dung. However, systematic environmental impact associated with different phases of life cycle of AD at digester is necessary to qualify the technology as environmentally friendly. Several such studies have been carried out in different parts of the world. However, such quantification may not be applicable under Nepalese conditions as the inventory and management of digestate and other technical parameters may be different. Very limited environmental impact studies have been conducted under Nepalese scenario and so the main aim of our study is to conduct environmental impact assessment of production of biogas from cow dung at typical fixed-dome digester operating in Rastriya Gai Anusandhan Kendra, Rampur, Chitwan. ISO 14040 based life cycle assessment (LCA) approach was employed as a methodological framework for the study and the study is concentrated to the only one environmental impact category i.e., global warming potential (GWP) due to greenhouse gas emissions. Primary inventory data were collected through field visits based on pre structured questionnaire and wherever necessary, secondary data were collected from the official data providing center of the country as well from the published scientific literatures. The operational phase was found the major contributor of GHGs emission (89%) whereas such emission is significantly lower in the construction phase (11%). Emission during storage of manure and digestate emission were identified as the major hotspots from GHGs emission perspective. Sensitivity analysis was conducted to observe the impact of leakage emission and digestate emission on the overall GHGs emission associated with the production of biogas which clearly suggests that the overall GHGs emission can be mitigated by 77% through digestate management. Our findings may be proved effective policy recommendation to the biogas plants developers in Nepal.

Keywords
Anaerobic Digestion, Life Cycle Assessment, Cowdung, Digestate

1. Introduction

Anaerobic digestion is a natural biological process that breaks down organic matter by microorganisms in an oxygen-free environment. It is commonly used for the treatment and management of various organic wastes and offers several benefits [1, 2]. The primary output of anaerobic digestion is biogas, which mainly consists of methane (CH4) and carbon dioxide (CO_2) which can be captured and utilized as a renewable energy source for electricity generation, heating, or vehicle fuel [3]. Anaerobic digestion reduces the volume of organic waste while converting it into valuable resources, such as biogas and nutrient-rich digestate [4]. By capturing methane, a potent greenhouse gas, during anaerobic digestion, the process helps mitigate the release of methane into the atmosphere, contributing to climate change mitigation. Anaerobic digestion can effectively treat organic waste streams, making them safer for disposal or reuse. It can also reduce odors and pathogens in the treated material. The digestate left behind after biogas production is a nutrient-rich material which can be utilized as a fertilizer, returning valuable nutrients to the soil [5, 6]. The use of anaerobic digestion can decrease the environmental impact of organic waste disposal, reduce the need for landfilling, and minimize water pollution from untreated organic waste. Biogas from anaerobic digestion is considered a renewable energy source since it is derived from organic matter that can be continuously replenished. It contributes to sustainable waste management practices and the reduction of greenhouse gas emissions while simultaneously producing valuable resources for various applications [7, 8].

Converting manure into biogas and compressed gas can be an effective strategy to mitigate greenhouse gas (GHG) emissions associated with manure management. Manure is a source of methane (CH4) emissions, a potent GHG, when it decomposes anaerobically in storage systems or lagoons. By converting manure into biogas and compressed gas, we can achieve several mitigation benefits [9]. Biogas can be further processed into compressed natural gas (CNG) or renewable natural gas (RNG). CNG can be used as a vehicle fuel, reducing GHG emissions in the transportation sector when substituted for conventional fossil fuels. To effectively mitigate GHG emissions associated with manure management, it is crucial to implement proper anaerobic digestion systems, manage biogas production and utilization efficiently, and ensure the safe handling and application of the resulting digestate as a fertilizer. The success of such projects depends on factors like the scale of operation, feedstock composition, and regional regulations and incentives.

Life Cycle Assessment (LCA) is a precious tool used to assess the environmental, social, and economic impacts related with various products, processes, or systems throughout their entire life cycle [10]. When applied to anaerobic digestion (AD), LCA can provide important insights into the sustainability of AD systems and help optimize their environmental performance. LCA helps identify environmental "hotspots" or areas within the AD system where the most significant environmental impacts occur. This information can guide decision-makers in making targeted improvements to reduce these impacts. LCA assesses resource use, including water consumption, land use, and energy inputs, helping optimize resource utilization in AD processes. This can lead to more efficient and sustainable system designs. Clear communication of the environmental benefits of AD can also facilitate public acceptance and support.

The implementation of biogas technology has played a pivotal role in creating a substantial number of green jobs in Nepal, estimated at around 13,000. Furthermore, the majority of villages, exceeding 2,800 out of a total of 3,915, spanning all 75 districts of Nepal, have successfully adopted biogas systems [11]. Studies indicate that alongside biogas adoption, there has been a gradual improvement in health and sanitation conditions, and a reduction in deforestation due to decreased reliance on firewood [12, 13]. Notably, efforts are being made to ensure inclusivity in the biogas sector, considering aspects such as caste, ethnicity, and gender, to create a more participative, decentralized, and balanced industry. Waste to Energy (W2E), as a variation of the biogas system, represents a relatively recent energy project adopted in Nepal [14]. Despite the fact that the biogas technology is suitable for environment, the systematic environmental impact is necessary to qualify the technology as an environmental friendly [15]. Several studies have been carried out in different parts of the world. But in case of Nepal, very limited studies have been carried out. Here we present report on to estimate the GHGs emission associated with the biogas production from cow dung in Rastriya Gai Anusandhan Kendra, Rampur, Chitwan.

2. Materials and Methods

ISO 14040 standard (ISO, 2006) based LCA framework was employed as a methodological framework in the study to estimate GHGs emission associated with each phase of life cycle during production of biogas [16, 17]. The framework recommends following four steps to assess the environmental impact: a) goal and scope definitions, b) life cycle inventory, c) life cycle impact assessment, and d) interpretation.

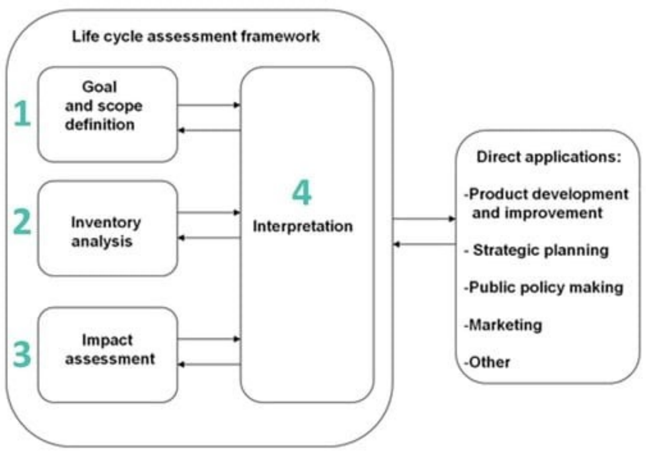

Figure 1: LCA framework adapted [18]

The steps followed for our current study are elaborated in the following subsections.

2.1 Goal and Scope

The goal of our study was to estimate the GHGs emission associated with the biogas production from cow dung and the study is specifically focused in Rastriya Gai Anusandhan Kendra, Rampur, Chitwan. The size of the digester in the plant is 200 m3 and fixed dome digester has been used in the plant for digestion of cattle dung from around 200 cows. Daily 3000 kg of cow dung is mixed with equal amount of water and continuous feeding is done on daily basis.

Figure 2: Figure Showing the digester at the site

Figure 3: Site Location at Rampur, Chitwan

2.2 Functional Unit and System Boundary

A functional unit is a key concept used to define the purpose and scope of the assessment. It serves as a reference quantity that represents the specific function or service provided by a product or system being analyzed. Here, the FU is production of 1 m3 biogas, which is typically utilized for the purpose for cooking. The generated biogas is supplied to the consumer through pipelines, and it is used as a cooking fuel purpose only. As recommended during field investigations, a useful lifetime of 40 years was considerd and it is expected 360 days as the operational every year and short stoppages from deficiencies or during maintenance slot has been considered which is as per suggested by [19].

The system boundary sets the limits for what aspects of the product/system life cycle are considered in the analysis, specifying what's included and excluded. In this case, we're focusing on a fixed dome type digester unit, encompassing key inputs and outputs, land use, transportation, and emissions to soil, water, and air. Additionally, the analysis takes into account the demolition phase, waste processing, and recycling, all falling within the defined system boundary. In addition to biogas, digestate is also produced, and because it is nutrient-rich, it may either be disposed as trash or used as a system byproduct or coproduct (biofertilizer). Due to its high-water content, it is usually dumped to the environment (directly into the aquatic environment or via lagoons) in agricultural fields that are not near to the biogas unit since doing so is expensive and logistically challenging. In this case, digestate is considered as a residue and maintained outside the system boundary, but sensitivity analysis is used to investigate the impact of its usage as a biofertilizer [19, 20].

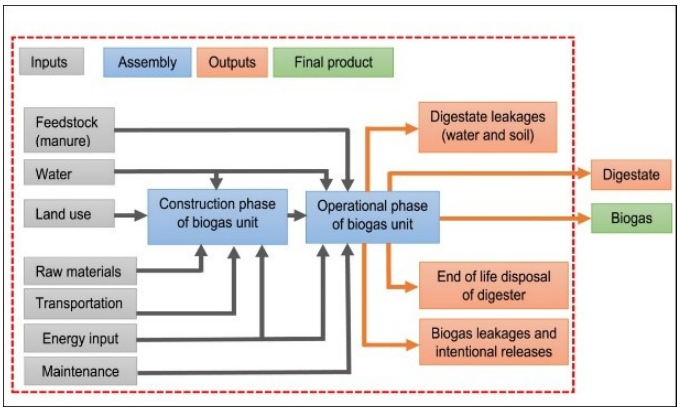

Figure 4: Showing the system boundary of the overall plant

2.3 Inventory Analysis

Inventory data of the biogas plant was collected from the Anusandhan Kendra, Rampur, Chitwan based on the pre-structured questionnaire and associated GHGs emission were estimated based on IPCC guidelines and other published scientific literatures [21].

3. Results and Discussions

3.1 Life Cycle Assessment

Time limitations and the intricate nature of each system (commercial biogas production, storage, distribution, utilization, and end-of-use waste, such as biogas digestate generation systems) limits the execution of a comprehensive cradle-to-grave analysis. Nevertheless, a thorough examination was conducted using all Life Cycle Assessment (LCA) components, primarily focusing on inventory analysis for each system.

To accommodate an easier analysis/discussion, the system was segmented into its two primary sub-systems: (a) the construction phase, inclusive of the unit's disposal/recycling at the end of its useful life, and (b) the operational phase, which also encompasses biogas/digestate leakages. The dominant contributor across categories is the operational phase, with the construction phase making a significantly smaller impact. This outcome aligns with expectations due to (i) the generally non-carcinogenic, non-mutagenic, and non-toxic nature of the raw materials used in biogas digester construction and (ii) the biogas unit's extended lifespan (40 years). It's worth noting that the recycling of plastics and metals post-unit lifespan was considered, but their minimal mass resulted in negligible contributions across midpoint impact categories. It is found that the GWP from the materials utilized in constructing the plant is 397128 kg CO_2 equivalent. As these plants operate in a sub-tropical region with elevated ambient temperatures, there's no necessity to heat them to maintain optimal conditions for anaerobic digestion reactions. Consequently, the influence of this operational aspect on the greenhouse gas emissions (GWP) can be ignored.

In terms of the construction phase, the primary contributions to impact categories stem from raw material mining and processing. Burnt solid bricks are the most impactful material, closely followed by cement, and to a lesser extent, sand and gravel mining. Clay extraction for brick production involves fossil fuel, typically diesel, for transportation, and the brick drying process is energy-intensive. The carbon emissions of the materials needed for the construction phase are detailed in the table.

Table 1: Net amount and weight of the description according to survey

S.N	Description	No./Amount	Weight
1	Block	11000(162 m^3)	
2	Bricks	12000 (24 m^3)	
3	Cement		2000 kg
4	Sand		10000 kg
5	Labour	100 people	
6	Land	20000 m^2	
7	8 Inch Steel Pipe	26 m (340 kg)	340 kg
8	8 Inch PVC Pipe	12 m (28.5kg)	28.5 kg
9	28 Inch Steel Pipe	24 m (108 kg)	108 kg
10	3 Inch PVC Pipe	6 m (5.4 kg)	5.4 kg
11	17 Inch Steel Pipe	0.6 m (20 kg)	20 kg
12	Fencing Wire	70 m^2	
13	5 Inch Steel Pipe	128 m	1042 kg
14	Water (From Boring)		
15	Cow (Average weight 700 kg)	200	140000 kg
16	Transportation (Local For raw materials)	10 km (Distance between Narayangarh to Rampur)	
17	Square Pipe (Steel)	500 m	5070 kg
18	Other iron Materials		500 kg
19	Gravel (Stone)	800 m^3	
20	Corrugated Sheet	1500 m^2	30000 kg
21	Water (Per Day)	5100 l	
22	Feedstock (Per Day)		3000 kg
23	Manure Transportation	250 m	
24	Hydraulic Retention Time	45-50 days	
25	Tempreature	36°C	
26	Transportation (For Maintenence)	10 km	
27	Total Biogas		
28	Biogas after losses		
29	Electricity Consumption by machineries	1000 units	
30	Digestate (60% used as liquid fertilizer)		4860 kg
31	Digestate (40% used after drying)		3240 kg

Table 2: During the construction phase of biogas plant (Includes all the sheds, digester, mixer, exhaust, cows, Canals)

S.N	Description	Qty	Carbon Emission (Per Unit)	Total Carbon Emission	Unit	LCA Data Reference
1	Block	11000(22m3)	345 kg CO_2 eq	7590	kg CO_2 eq	[22]
2	Bricks	12000 (178 m^3)	635 kg CO_2 eq	113030	kg CO_2 eq	[22]
3	Cement	20000 kg	0.7 kg CO_2 eq	14000	kg CO_2 eq	[22]
4	Sand	80000 kg	6.59 kg CO_2 eq	527200	kg CO_2 eq	[22]
5	Labour	100 people				
6	Land	20000 m^2				
7	8 Inch Steel Pipe	26 m (340 kg)	1.77 kg CO_2 -eq	601.8	kg CO_2 eq	[23]
8	8 Inch PVC Pipe	12 m (28.5kg)	7.83kg CO_2-eq	223.155	kg CO_2 eq	[23]
9	28 Inch Steel Pipe	24 m (108 kg)	1.77 kg CO_2 -eq	42.48	kg CO_2 eq	[23]
10	3 Inch PVC Pipe	6 m (5.4 kg)	7.83kg CO_2-eq	42.282	kg CO_2 eq	[23]
12	17 Inch Steel Pipe	0.6 m (20 kg)	1.77 kg CO_2 -eq	35.4	kg CO_2 eq	[23]
13	Fencing Wire	70 m^2				
14	5 Inch Steel Pipe	1280 m (10426 kg)	1.77 kg CO_2 -eq	18454.02	kg CO_2 eq	[23]
15	Water (From Boring)					
16	Cow (Average weight 700 kg)	200*700	20 kg CO_2-Eq	2800000	kg CO_2 eq	[24]
17	Transportation (Local For raw materials)	10 km (Distance between Narayangarh to Rampur)				
18	Square Pipe (Steel)	500 m (5070 kg)	1.77 kg CO_2 -eq	8973.9		[25]
19	Other iron Materials	500 kg	1.45 Kg CO_2 - eq	725		[26]
20	Gravel (Stone)	800 m^3	237 kg CO_2 Eq	189600		[27]

3.2 Anaerobic digestion process

The AD feedstock, which consists of manure, is blended with water to create a slurry and introduced into the anaerobic digester [7]. The biochemical conversion process produces biogas as the primary output and a digestate as a secondary output. There are no further residues or emissions. The biogas is used as a fuel, mainly for cooking, and the digestate is returned to the land as a nutrient rich fertilizer [3, 12]. In order to promote bacterial degradation within the digester, a 1:1 mixture of manure and water is used. For this LCA study, and based on typical scale of 200 m3, an initial input of 10000 kg of cattle dung is required to start the plant. After that, a daily input 3000 kg of dung is used.

The biogas yield is 0.037m3 kg-1 for manure and the biogas composition is principally CH4 (60%) and CO_2 (39.90%). According to this, the total gas produced from the daily input (3000 kg of dung) is 105 kg by weight, where the methane content is 55 kg, the rest being mainly carbon dioxide. Given that the manure is considered a waste product, and water addition for manual mixing is taken from the nearby boring, there is no embodied energy attributed to this material.

The GWP, owing to the initial charge, stands at 432,000 kg CO_2 equivalent. The daily input represents the quantity of raw material introduced daily to sustain the digester's functionality. In the case of a 200 m3 facility, the daily biogas output results in a GWP of 9,600 kg CO_2 equivalent. Assuming the operational lifespan of an AD plant spans 40 years, achieving a cumulative production over its lifetime supply of dung (= daily × 365 days/year × 40 years = 43800000 kg). This gives a GWP of 140,160,000 kg CO_2 equivalent. The overall impact is derived from both the initial input and the cumulative charge over the lifetime. The GWP impact, attributed to the biogas in a 200 m3 plant running for 40 years, amounts to 14,016 tons of CO_2 equivalent. (including impact of initial charge 43 t). The methane-rich biogas is used as fuel for cooking, thus converting methane to CO_2.

Hence, the operational phase contributes about 89% of GHG emissions whereas the constructional phase contributes about 11% of GHG emissions. This result is similar to the research (Mohammad et al, 2022) conducted in India, Tamil Nadu which

Table 3: Showing data of during Operational Phase (Including Machineries, Electricity Consumption, Biogas Production, Slurries)

S.N	Description	Qty	Carbon Emission (Per Unit)	Total Carbon Emission	Unit	LCA Data Reference
1	Water (Per Day)	5100 l				
2	Initial Feeding	135000 kg	3.2 kg CO_2 -eq	432000	kg CO_2 eq	[28]
3	Feedstock (Per Day)	3000 kg	3.2 kg CO_2 -eq	9600	kg CO_2 eq	[28]
4	Cow (Average weight 700 kg) 200 No.	140000 kg	20 kg CO_2-eq	2800000	kg CO_2 eq	[29]
5	Transportation (For Maintenance)	10 km				
6	Electricity Consumption by machineries	1000 units / month	0.02 kg CO_2 eq	20	kg CO_2 eq	[27]
7	Digestate (60% used as liquid fertilizer)	4860 kg	0.139 kg CO_2 eq	675.54	kg CO_2 eq	[30]
8	Digestate (40% used after drying)	3240 kg	0.060 kg CO_2-eq	194.4	kg CO_2 eq	[31]

concluded that the constructional phase contributed to about 13% and operational phase contributed to about 87% of overall GHG emissions. The results nearly compliances with the above study. This is due to the availability of the materials being same and the conditions present in those above mentioned areas.

3.3 Impact of Digestate

Digestate is a byproduct of the anaerobic digestion process, which is commonly used to break down organic materials like agricultural residues, food waste, and sewage sludge to produce biogas (a mixture of methane and carbon dioxide) [32]. It consists of the solid and liquid residues left behind after the biogas has been extracted. The impact of digestate and its potential to replace chemical fertilizers can vary depending on several factors, including its nutrient content, handling, and application methods.

The nutrient content of digestate can vary depending on the feedstock used for anaerobic digestion. It typically contains essential plant nutrients such as nitrogen (N), phosphorus (P), and potassium (K), along with micronutrients. The nutrient composition can make it a valuable source of plant nutrients for agriculture. It also contains organic matter, which can improve soil structure, water retention, and microbial activity. This can lead to improved soil health and fertility over time. Using digestate as a fertilizer can help reduce the environmental impact associated with chemical fertilizers. Chemical fertilizers can contribute to nutrient runoff and water pollution, while digestate can release nutrients more slowly, reducing the risk of nutrient leaching and pollution. To replace chemical fertilizers effectively, the nutrient content and composition of digestate must match the nutrient requirements of the crops being grown. This may require additional processing or blending of digestate to ensure it provides the right balance of nutrients. Proper application methods are crucial when using digestate as a fertilizer. It can be applied directly to fields, but it may need to be treated or processed to reduce pathogens and weed seeds. Appropriate application rates and timing should also be considered to maximize its effectiveness. It's important to conduct research and monitoring to assess the impact of digestate on soil quality, crop yield, and environmental factors. This helps optimize its use and ensure that it provides the desired benefits. Digestate from biogas production can have a positive impact on agriculture by providing nutrients and organic matter to improve soil health and reduce the reliance on chemical fertilizers. However, successful integration into agricultural practices requires careful consideration of nutrient content, handling, and application methods, as well as compliance with local regulations.

At present, only 60% of digestate from the dome is used as fertilizer in the agricultural land whereas 40% of digestate is left as usual and it has huge impact in the environment. This digestate can replace and hence it can help in mitigating the carbon emission due to the chemical fertilizers.

Nitrous oxide (N2O) has a GWP 265–298 times that of CO_2 for a 100-year timescale. The nitrogen content in the soils utilized by Nepalese farmers is likely insufficient. Therefore, supplementing nitrogen through biogas effluent might not result in the same adverse environmental effects. The nitrogen

Table 4: Showing Use of Digestate (Per Day) and its Carbon Emission

Percentage (%)	Digestate Amount	Carbon Emission
10	810	112.59
20	1620	225.18
30	2430	337.77
40	3240	450.36
50	4050	562.95
60	4860	675.54
70	5670	788.13
80	6480	900.72
90	7290	1013.31
100	8100	1125.9

percentage (by weight) of cow dung is 1.29, whereas synthetic (chemical) fertilizer (e.g., Urea – NH2-CO-NH2) contains 46% of nitrogen. Inorganic nitrogen has a GWP of 2.79 kg CO_2 equivalent and requires 44.94MJ of energy to produce 1 kg of it. The figures are 3.78MJ and 0.35 kg CO_2 equivalent for potassium and 6.95MJ and 0.74 kg CO_2 equivalent for phosphorus, respectively. As plant fertilizers, the effluent slurry from a biogas plant generally comprises 1.6% nitrogen, 1.5% phosphorus, and 1% potassium. These calculations indicate that applying 1 t of AD effluent to crops, in place of an equivalent amount of inorganic fertilizer, saves 0.06 t CO_2 equivalent. Further study is necessary to support these numbers, though, as they are not commonly acknowledged in the published literature [33].

Rural habitats and natural systems are deteriorating, which is a global problem. This is because to overuse of land and forests, overuse of chemical fertilizers and pesticides, and reckless animal waste discharge [34]. Research has shown that utilizing digestate from AD plants can effectively improve crop cultivation. [35, 36]. The nitrogen concentration in digestate is greater than that from fresh dung, as carbon, hydrogen and oxygen are lost as biogas. One kilogram of digestate contains an extra 0.5 kg of nitrogen compared with 1 kg of fresh manure [33]. Employing digestate as an organic fertilizer not only reduces reliance on chemical fertilizers but also enhances soil structure. This approach addresses soil degradation issues in regions where dung was previously used as a fuel source. The reduced use of synthetic fertilizers contributes to economic savings for households [37]. These aspects are not considered in the SimaPro software, which therefore underestimates the benefits of using AD [38]. The saving, as estimated above, is that 1 t of digestate, used as fertilizer, replaces 0.06 t CO_2 equivalent from chemical fertilizer. In the overall life of the plant, if we are able to use all the digestate which will be about 116800 t of digestate can replace 7008 t CO_2 equivalent from the chemical fertilizer [39].

4. Conclusion

The operational phase was found the major contributor of GHGs emission (89%) whereas such emission is significantly lower in the construction phase (11%). Sensitivity analysis was performed to examine the effects of digestate on the total amount of greenhouse gases (GHGs) released during the production of biogas. The results strongly suggest that digestate management can each GHG emissions by 77%. Our research may be proved a beneficial policy recommendation to Nepal's biogas plant developers and other stakeholders. Different types of materials which are locally available could be used such as building materials which could lead to less GHG emissions during the construction phase of Biogas plant. The digestate remained after the production of biogas could be used as the fertilizer and hence these fertilizers could be later processed as a vermicompost plant which will eventually have a higher nutrient content. So, the dependence on chemical fertilizers could eventually be minimized. Consumption of digestate may mitigate GHGs emission associated with the synthetic fertilizer. The grant provided by the government could be increased to manage digestate and minimize the leakage through maintenance.

Acknowledgments

The authors are grateful for the assistance provided by personnels from Rastriya Gai Anusandhan Kendra in terms of data throughout this research.

References

[1] Katheem Kiyasudeen S, Mahamad Hakimi Ibrahim, Shlrene Quaik, Sultan Ahmed Ismail, Mahamad Hakimi Ibrahim, Shlrene Quaik, and Sultan Ahmed Ismail. An introduction to anaerobic digestion of organic wastes. *Prospects of organic waste management and the significance of earthworms*, pages 23–44, 2016.

[2] Md Mosleh Uddin and Mark Mba Wright. Anaerobic digestion fundamentals, challenges, and technological advances. *Physical Sciences Reviews*, (0), 2022.

[3] B Bharathiraja, T Sudharsana, J Jayamuthunagai, R Praveenkumar, S Chozhavendhan, and J Iyyappan. Biogas production–a review on composition, fuel properties, feed stock and principles of anaerobic digestion. *Renewable and sustainable Energy reviews*, 90(April):570–582, 2018.

[4] Q Zhao, E Leonhardt, C MacConnell, C Frear, and S Chen. Purification technologies for biogas generated by anaerobic digestion. *Compressed Biomethane, CSANR, Ed*, 24, 2010.

[5] Veerasamy Sejian and Syed Mohammed Khursheed Naqvi. Livestock and climate change: mitigation strategies to reduce methane production. *Greenhouse Gases-Capturing, Utilization and Reduction*, pages 255–276, 2012.

[6] David PM Zaks, Niven Winchester, Christopher J Kucharik, Carol C Barford, Sergey Paltsev, and John M Reilly. Contribution of anaerobic digesters to emissions mitigation and electricity generation under us climate policy. *Environmental science & technology*, 45(16):6735–6742, 2011.

[7] Moses Jeremiah Barasa Kabeyi and Oludolapo Akanni Olanrewaju. Biogas production and applications in the sustainable energy transition. *Journal of Energy*, 2022:8750221, 2022.

[8] Zikhona Tshemese, Nirmala Deenadayalu, Linda Zikhona Linganiso, and Maggie Chetty. An overview of biogas production from anaerobic digestion and the possibility of using sugarcane wastewater and municipal solid waste in a south african context. *Applied System Innovation*, 6(1):13, 2023.

[9] Amanda Cuéllar and Michael Webber. Cow power: The energy and emissions benefits of converting manure to biogas. *Environ. Res. Lett*, 3, 2008.

[10] Johan Widheden and Emma Ringström. *2.2 - Life Cycle Assessment*, pages 695–720. Elsevier Science B.V., Amsterdam, 2007.

[11] Amrit Nakarmi, Amrit Karki, Ram Dhital, Isha Sharma, Pankaj Kumar, and ed. *Biogas as Renewable Source of Energy in Nepal. Theory and Development*. 2015.

[12] Ahmad R. S. Putra, Zhen Liu, and Mogens Lund. The impact of biogas technology adoption for farm households – empirical evidence from mixed crop and livestock farming systems in indonesia. *Renewable and Sustainable Energy Reviews*, 74, 2016.

[13] Nigussie Abadi, Kindeya Gebrehiwot, Ataklti Techane Teame, and Hailish Nerea. Links between biogas technology adoption and health status of households in rural tigray, northern ethiopia. *Energy Policy*, 101:284–292, 2017.

[14] Sunil Prasad Lohani, Martina Keitsch, Siddhartha Shakya, and David Fulford. Waste to energy in kathmandu nepal—a way toward achieving sustainable development goals. *Sustainable Development*, 29(5):906–914, 2021.

[15] Dipendra Bhattarai, E. Somanathan, and Mani Nepal. Are renewable energy subsidies in nepal reaching the poor? *Energy for Sustainable Development*, 43:114–122, 2018.

[16] Ioannis Arvanitoyannis. *ISO 14040: Life Cycle Assessment (LCA) – Principles and Guidelines*, pages 97–132. 2008.

[17] Ana Cláudia Dias and Luís Arroja. Comparison of methodologies for estimating the carbon footprint – case study of office paper. *Journal of Cleaner Production*, 24:30–35, 2012.

[18] Maria Apolónia and Teresa Simas. Life cycle assessment of an oscillating wave surge energy converter. *Journal of Marine Science and Engineering*, 9:206, 2021.

[19] Lida Ioannou-Ttofa, Spyros Foteinis, Amira Seifelnasr Moustafa, Essam Abdelsalam, Mohamed Samer, and Despo Fatta-Kassinos. Life cycle assessment of household biogas production in egypt: Influence of digester volume, biogas leakages, and digestate valorization as biofertilizer. *Journal of Cleaner Production*, 286:125468, 2021.

[20] Ahmed Alengebawy, Badr Mohamed, Keda Jin, Tingting Liu, Nirmal Ghimire, Mohamed Samer, and Ping Ai. A comparative life cycle assessment of biofertilizer production towards sustainable utilization of anaerobic digestate. *Sustainable Production and Consumption*, 33:875–889, 2022.

[21] Barbara Amon, Gültaç Çinar, Michael Anderl, Federico Dragoni, Magdalena Kleinberger-Pierer, and Stefan Hörtenhuber. Inventory reporting of livestock emissions: The impact of the ipcc 1996 and 2006 guidelines. *Environmental Research Letters*, 16(7):075001, 2021.

[22] T Rehl and J Müller. Life cycle assessment of biogas digestate processing technologies. *Resources, Conservation and Recycling*, 56(1):92–104, 2011.

[23] Abdullah Yasar, Rizwan Rasheed, Amtul Bari Tabinda, Aleena Tahir, and Friha Sarwar. Life cycle assessment of a medium commercial scale biogas plant and nutritional assessment of effluent slurry. *Renewable and Sustainable Energy Reviews*, 67:364–371, 2017.

[24] Syed S Amjid, Muhammad Q Bilal, Muhammad S Nazir, and Altaf Hussain. Biogas, renewable energy resource for pakistan. *Renewable and Sustainable Energy Reviews*, 15(6):2833–2837, 2011.

[25] Muhammad Kamran. Current status and future success of renewable energy in pakistan. *Renewable and Sustainable Energy Reviews*, 82:609–617, 2018.

[26] Umar K Mirza, Nasir Ahmad, and Tariq Majeed. An overview of biomass energy utilization in pakistan. *Renewable and Sustainable Energy Reviews*, 12(7):1988–1996, 2008.

[27] Word Energy Council. Survey of energy resources 2007. *Retrieved January20*, 2009.

[28] E Akila, S Pugalendhi, and G Boopathi. Biogas purification using coconut shell based granular activated carbon by pressure swing adsorption. *Int. J. Curr. Microbiol. App. Sci*, 6(4):1178–1183, 2017.

[29] William G Mezzullo, Marcelle C McManus, and Geoff P Hammond. Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste. *Applied Energy*, 102:657–664, 2013.

[30] Aphichat Srichat, Ratchaphon Suntivarakorn, and Khanita Kamwilaisak. A development of biogas purification system using calcium hydroxide and amine solution. *Energy Procedia*, 138:441–445, 2017.

[31] Virendra K Vijay, Ram Chandra, Parchuri MV Subbarao, and Shyam S Kapdi. Biogas purification and bottling into cng cylinders: producing bio-cng from biomass for rural automotive applications. In *The 2nd Joint International Conference on "Sustainable Energy and Environment*, pages 1–6.

[32] Monjur Mourshed, Mostafa Kamal, Nahid I. Masuk, Sami A. Chowdhury, and Mahadi H. Masud. *Anaerobic Digestion Process of Biomass*. Elsevier, 2023.

[33] Khondokar M Rahman, Lynsey Melville, David Fulford, and SM Imamul Huq. Green-house gas mitigation capacity of a small scale rural biogas plant calculations for bangladesh through a general life cycle assessment. *Waste Management & Research*, 35(10):1023–1033, 2017.

[34] L. E. D. Smith and G. Siciliano. A comprehensive review of constraints to improved management of fertilizers in china and mitigation of diffuse water pollution from agriculture. *Agriculture, Ecosystems & Environment*, 209:15–25, 2015.

[35] Keda Jin, Yi Ran, Ahmed Alengebawy, Gaozhong Yang, Shijiang Jia, and Ping Ai. Agro-environmental sustainability of using digestate fertilizer for solanaceous and leafy vegetables cultivation: Insights on fertilizer efficiency and risk assessment. *Journal of Environmental Management*, 320:115895, 2022.

[36] Dawid Skrzypczak, Krzysztof Trzaska, Katarzyna Mikula, Filip Gil, Grzegorz Izydorczyk, Małgorzata Mironiuk, Xymena Polomska, Konstantinos Moustakas, Anna Witek-Krowiak, and Katarzyna Chojnacka. Conversion of anaerobic digestates from biogas plants: Laboratory fertilizer formulation, scale-up and demonstration of applicative properties on plants. *Renewable Energy*, 203:506–517, 2023.

[37] Adam M. Komarek, Sophie Drogue, Roza Chenoune, James Hawkins, Siwa Msangi, Hatem Belhouchette, and Guillermo Flichman. Agricultural household effects of fertilizer price changes for smallholder farmers in central malawi. *Agricultural Systems*, 154:168–178, 2017.

[38] Zhimin Li, Runsheng Tang, Chaofeng Xia, Huilong Luo, and Hao Zhong. Towards green rural energy in yunnan, china. *Renewable Energy*, 30:99–108, 2005.

[39] Vita Tilvikiene, Kestutis Venslauskas, Virmantas Povilaitis, Kestutis Navickas, Vidmantas Zuperka, and Zydre Kadziuliene. The effect of digestate and mineral fertilisation of cocksfoot grass on greenhouse gas emissions in a cocksfoot-based biogas production system. *Energy, Sustainability and Society*, 10(1):13, 2020.