International Journal of Sustainability and Multidisciplinary Research (IJSMR) Vol. 1, No. 3 (2025), December 2025 e-ISSN: 3079-0808
DOI: https://doi.org/10.71214/ijsmr.01.03.03

Scaling Multi Substrate Biogas Systems for National Energy Security and Circular Economy Transition in Sri Lanka: A Case Study

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Abstract: The use of slaughterhouse waste management poses serious environmental and economic problems in the developing countries. The research questions explored in this study are how well can multi-substrate co-digestion systems be used to produce biogas and treat waste in the Sri Lankan emerging circular economy. Mesophilic conditions were used to test five batch reactors to compare various substrate mixtures: ternary poultry-fish-chicken blend, binary poultry-fish mixture, quaternary multi-waste mixture, beef-dominant mixture, and plant-animal hybrid system. The reactors had a 21-day hydraulic retention time to maximize on microbial activity and conversion of organic matter. Detailed characterization via physicochemical standards was done through analysis with standard procedures such as chemical oxygen demand, biogas composition by gas chromatography, and volumetric methodology. Findings revealed that the combination of ternary substrates had better methanogenic activity. The biogas obtained had desirable methane to carbon dioxide ratios with little inhibitory substances. Extrapolation on nationwide scale indicates that there is a massive potential of renewable energy with annual biogas generation predicted to sustain the 70% renewable energy goal of Sri Lanka by the year 2030. Economic modelling reveals that it is profitable based on the return on investment with competitive operational costs and environmental impact assessment reveals that it has significant benefits in terms of pollution abatement and greenhouse gas mitigation. The byproduct derived is the digestate, which has an extra value in picking up the nutrients that can be used in the farms. It is also a technology that combines the objectives related to environmental pollution and renewable energy, as well as resource recovery, which coincides with the goals of sustainable development and helps to shift to a circular bioeconomy.

***Keywords**: Anaerobic Digestion, Biogas, Waste Management, Chemical Oxygen Demand, Digestate.*

Introduction

The biogas production from the anaerobic digestion of waste in the slaughterhouse proves to be a very viable way of not only solving environmental issue but also the economic one. The digestion process yields two valuable outputs: biogas consisting mainly of methane and carbon dioxide and digestate, which can be applied in form of an organic fertiliser. The importance of this research can be expressed in the possible ability to control troublesome by-products like the blood, fat and proteins which are usually hard to dispose with regular methods. By use of the biogas of these materials, the quantity of waste that is disposed in the landfills is reduced extensively lowering the level of pollution of the environment. Also, anaerobic digestion traps methane to which it would be a powerful risk, since it has a Global Warming Potential of at least 25 times higher than carbon dioxide. Production of biogas has the positive effect of emitting reduced greenhouse gases, since it transforms the methane in the form of renewable energy, it also provides energy security and a low carbon footprint through its role in offering a solution to fossil fuel replacement (Adedeji & Olayanju, 2021).

Biogas is discovered to possess numerous applications including a source of electricity, heating and fuel source to drive vehicles among others. With the further development of independent facilities for processing meat, such as sausage factories, the enterprises can reduce their reliance on the external sources of energy and secure themselves from the price fluctuations for energy by using the biogas they produce. The setting up of biogas plants also enhances economic activities at the local level as they provoke employment outings associated with the plant construction, operation, management and system maintenance. Study of biogas generated from abattoir waste forms part of the rational optimization of the anaerobic digestion conditions and thus increase in the yield of gas and process efficiency (Ahmad, 2023). Further all improvements of pre-treatment technologies and co-digestion strategies can also be applied as a contribution to the economic performance and overall productivity of the systems of biogas. Use of biogas technology in the meat processing industry especially in Alatotiers is environmentally friendly and that its use helps in conservation of the natural resources and also the overall aspects of sustainable industrial development.

The increase in a renewable source of electricity production cannot be even but its pace is changing rapidly, primarily due to technological advancement. Such production growth is, for example, renewable energy sources like the wind and solar energy. Unlike the fossil fuels which take millions of years to be formed, renewable energy resources can be renewed much quicker. In Southern Africa, key economic sectors dependent on energy include Energy (33%), Transportation (14%), Agricultural production (14%), and Water supply (13%). Exhaustive use of fossil fuels during energy generation releases carbon dioxide and other green gases that are dangerous in regard to change of climatic conditions (Akhtar, Li, & Zhang, 2022). Carbon dioxide emission during combustion of fossil fuel is far off compared with that released by power generated using renewable energy sources. To cope with the effects of climatic change, there is a need to switch to alternative sources of energy particularly in renewables, which will help to reduce the emission of the greenhouse gas into the atmosphere. In the world, the renewable energy is expanding and is developing three times as many jobs as energy based on fossil fuels. With the rise in the share of sustainable sources of energy in the world energy consumption, the inclusion of variable renewable sources into the grid becomes crucial. As such, sustained investments and favourable policies must be sustained to ensure sustainable development of renewable energy. The nations all over the world are building regulatory systems, incentives, and rewards to stimulate the use of renewable energy (Al-Baldawi et al., 2022). Performance increasing technologies, cost-cutting ones, and those that are aimed at solving practical challenges, should remain at the centre of development and improvement. This refers to addressing such challenges as grid integration, environmental impact, and land

use issues. A narrative review discusses the current studies on management of the waste and energy production through anaerobic digestion in Abattoir. The review integrates available assessments on the environmental, economic, and social impacts of mismanaged waste, highlighting how anaerobic digestion may offer a promising solution.
In order to start this document, it will study the environmental, as well as the economic and social issues concerning handling waste at the abattoirs. The paper goes on to explore how an anaerobic digestion is exactly carried out when it comes to the creation of a biogas out of the generating of waste at slaughterhouses (Ali et al., 2023). Abattoir waste chemical composition is assessed in the paper as well as positive factors and technical barriers to apply the anaerobic digestion in the given sector. At the end of the paper's analysis, some existing biogas production implementations in Sri Lanka and the foreseeable future development prospects for this sector are also examined (Ali, Rashid, & Kim, 2021).

Literature

Prospective potential of Sri Lankan abattoir

Table 1: Slaughter house static-Cattle (2010 -2023) (Only the number of animals slaughtered at licensed slaughter houses-For only top rankings)

District	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023*
COLOMBO	333	-	363	-	-	-	-	-	-	-	-	-	2	-
GAMPAHA	9,890	5,809	9,342	6,439	5,052	7,739	9,865	8,723	8,128	10,859	4,518	6,010	5,696	4,455
KALUTARA	4,251	2,772	3,608	3,339	2,290	2,516	3,502	2,691	2,590	2,521	1,891	2,269	2,354	3,234
KANDY	8,399	4,550	8,671	7,835	7,746	7,153	7,650	6,679	6,615	6,445	5,517	4,858	7,748	5,813
MATALE	6,633	5,087	4,925	5,272	4,206	4,085	4,115	3,726	6,615	3,931	4,258	2,987	3,752	4,148
NUWARA ELIYA	4,900	5,156	5,253	3,196	2,129	2,972	2,790	2,934	3,118	2,047	1,408	1,268	1,801	2,321
GALLE	728	728	745	622	790	1,775	1,460	1,557	1,609	1,192	1,074	549	536	636

Source: *Department of Census and Statistics (DCS) of Sri Lanka*

Table 2: Goat and sheep -The number of animal slaughtered

District	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
COLOMBO	33,669	35,835	49,067	44,089	35,940	30,728	34,015	27,480	31,342	31,880	18,437	21,825
GAMPAHA	3,651	341	287	685	443	112	220	441	126	300	-	102
KALUTARA	276	338	179	124	151	-	-	-	-	54	3	4
KANDY	3,596	3,837	4,309	2,014	2,605	2,014	1,310	1,242	1,169	1,452	952	1,005
MATALE	141	302	195	219	207	229	195	227	203	605	340	293
NUWARA ELIYA	424	225	673	497	394	767	503	655	922	391	406	561
GALLE	-	-	-	-	-	343	330	329	306	313	357	259

MATARA	-	189	201	349	220	221	185	223	367	71	37	174

Source: *Department of Census and Statistics (DCS) of Sri Lanka*

Several interrelated factors including enhanced market stability, technological advancements in livestock development, and reduced costs of raw materials indicate substantial growth potential within Sri Lanka's meat industry, encompassing poultry, swine, cattle, sheep, and goats. In the case of technical leadership using large platforms of operation such as research, extension services, animal health management and genetic improvement; there is a collaborative manner in which both government and privately owned institutions work in Sri Lanka as there is functional cooperation. Furthermore, the market infrastructure and the pricing mechanism in Sri Lanka for meat; specifically, poultry is advanced enough to foster industry expansion. The country has established networks for exports in the regions such as the Middle East, Asia, and Europe, therefore improving its potential of receiving reliable access to world markets. Nine Provincial Departments of Animal Production and Health provide institutional support, as well as provincial veterinary offices which help in the implementation of livestock development programmes (Al-Masri & Khalil, 2024).

The National Livestock Development Board (NLDB) plays a critical role in maintaining core breeding herds of various livestock species and supplying farmers with genetically improved animals. At the same time, the private sector is also involved by availing necessary equipment and machinery especially in the poultry industry and veterinary pharmaceuticals and vaccines. Multinational corporations are actively engaged in integrated operations within Sri Lanka’s poultry industry, contributing to its modernization and expansion. The Provincial Departments of Animal Production and Health (PDAPH) have consistently supported the growth of the swine population through artificial breeding programs (Amin & Kumar, 2022). Due to health issues relating to the consumption of pork, the dietary guidelines have grown to encourage the replacement of red meat with poultry. This global change of consumer preferences by people to lean meats opens a potential opportunity for the Sri Lankan poultry products’ market expansion. According to international projections, such conditions as urbanisation, growing income levels, and expanding populations are to continue to increase demand for livestock products over the decades to come. In Sri Lanka, per capita meat consumption particularly of poultry is anticipated to grow in parallel with income growth (Azman & Angelidaki, 2021).

Impact of Slaughterhouse Waste

Environmental Pollution

The impact of the waste water from animal processing industries to the environment is severe. There is extensive use of water in proceedings on dairies, tanneries and in slaughter houses and this leads to mass production of waste water including the one used in general cleaning. The processing activities of a significant nature determine the number and composition of pollutants in the wastewater very much. The liberation of the biodegradable organic compounds (BOCs) has the potential to deplete the dissolved oxygen (DO) concentration in the receiving water bodies which might cause a decline in the biological activity or even the death of aquatic life in the water bodies (Baek & Kim, 2021). In addition, nutrients like nitrogen (N) and phosphorus (P) may lead to eutrophication that is excessive algal growth. The subsequent diet and mineralization of algae also causes depletion of oxygen, which is a further threat to the aquatic ecosystems. Some of the components that are normally present in agro-industrial effluents like un-ionized ammonia, tannins and chromium (chromium, especially in tannery effluents) may be very toxic to aquatic life. It can also be classified as to correspond with the parameters normally employed in determining the pollution load of such waste water such as suspended solids (SS), chemical oxygen demand (COD), and biochemical oxygen demand (BOD), COD and BOD are considered as primary indicators to determine the amount of organic pollutants content (Bai, Zhou, & Xu, 2022).

Economical Conflicts

The effective waste management facilities are capital intensive to implement. Apart from the initial set up costs, these facilities are extremely costly to operate having high amounts in labour costs, energy use, use of chemicals, and normal maintenance. Compliance with strict environmental regulations drives the waste processing and disposal costs up most of the time. More so, the logistics of gathering and transporting the wastes from the slaughterhouses to the treatment plants can be quite expensive. Especially for situations where the plants are distant away from the sources of the wastes. Some byproducts obtained from dealing with the abattoir waste may have poor commercial viability which may cause financial losses. Storage and management of unwanted or immediately non serviceable byproducts add to the operations overhead. The process of waste treatment in slaughterhouse may be energy intensive and the price changes in energy may influence overall cost of maintaining the facility substantially (Cao & Angelidaki, 2022).

Social Concerns

Improperly handled abattoir waste is a high threat to the environment and human health. It attracts pests and becomes suitable for various pathogenic microorganisms and viruses breeding, also possible spreading of the infectious diseases. This poses direct danger to the public health, especially for the community located within the proximity of abattoir facilities. The breakdown of organic waste produces foul smells that can significantly affect the standard of living of the local residents. Also, the ugly nature of waste disposal sites causes psychological problems and detracts the beauty of the environment and the value of the same. Sub efficient practises of waste disposal also led to the loss of recoverable resources. As a case in point, most of the essential nutrients present in wastes from abattoirs are wasted instead of being used in composting and production of biogas, thus placing increased reliance on artificial fertilisers and other outsourced inputs. Some of the financial consequences include regulatory fines, remediation costs, and lost reputation to corporations. Moreover, the economies of the region that rely on agriculture or tourism could also be impacted in the wrong way. Disparities are common where vulnerable and marginalized communities take the burden more than they can, because in many cases they have no capacity or political leverage to insist on better waste management systems (Chen, Liu, & Zhang, 2023).

Table: Quantitative evidence of impacts of slaughterhouse waste

Impact Category	Parameter	Typical Value / Range	Implication
Environmental	Biochemical Oxygen Demand (BOD)	1,500 – 6,000 mg/L	Depletes dissolved oxygen, harms aquatic life.
	Chemical Oxygen Demand (COD)	2,000 – 10,000 mg/L	Indicates high organic pollutant load.
	Total Suspended Solids (TSS)	800 – 2,500 mg/L	Causes turbidity and disrupts aquatic ecosystems.

	Ammonia (NH_3)	50 – 150 mg/L	Toxic to fish and aquatic organisms.
	Total Nitrogen (TN)	100 – 300 mg/L	Leads to eutrophication and algal blooms.
	Total Phosphorus (TP)	10 – 50 mg/L	Promotes excessive algal growth and oxygen depletion.
Economic	Waste treatment cost per m³	USD 0.70 – 2.50	High operational costs limit adoption.
	Energy consumption per ton of waste	200 – 400 kWh	Increases ongoing operational expenses.
	Revenue from by-products	< 30% of treatment cost	Often not financially sustainable.
Social	Odor impact radius	Up to 1 km	Reduces residential quality of life near slaughterhouses.
	Potential for disease outbreaks	High	Increases public health risks from pathogens.
	Annual community complaints per facility	50 – 200	Reflects social dissatisfaction and potential for unrest.

Source: Efficacy of biogas production from different types of livestock manures.

Energy Recovery from Abattoir Waste

The main product at the end of this study is biomethane, an upgraded and purified biogas of increased energy content and application. The basic principles of production of biogas are shown herein, such as the biological techniques, technological ways, and apparatus. It also combines both the main systems including; digesters, gas collectors among others with the secondary systems that are used in gas upgrading and purification. Biomass energy is a form of energy storage, being a fixed form of solar energy and the majority of the green plants are trapping the solar energy to take in the carbonic dioxide (CO_2) in the air and change it into the form of organic compounds whenever there is the process of photosynthesis. This basic biochemical process takes place behind biomass production and it can be defined with the help of the next equation (Chowdhury & Ghosh, 2023).

$$\mathbf{CO_2+H_2O+Light+Chlorophyll–C_6H1_2O_6 +O_2}$$

The green plants have chlorophyll as their primary photosynthetic pigment and play an important role in the overall absorption of light and transformation of carbon dioxide (CO_2) and water (H_2O) to carbohydrates (Zhou & Huang, 2022). These major organic products of the photosynthesis are typically represented by the empirical formula (CH_2O) n and highly used example is glucose $C_6H_{12}O_6$. The transformation of one gram mole of carbon into a carbohydrate requires approximately 470 kJ (112 kcal) of energy, supplied by sunlight. The range for biomass's theoretical ability to handle solar energy is from 8% to 15%, yet it is commonly less than 2% in practise. Fruits and vegetables previously relied on by early herbivorous species are stores of the carbohydrates that plants manufacture. As solar energy moves toward higher levels in the food system, a decreasing share survives through normal metabolic and ecological processes (Dey, Saha, & Bhattacharya, 2023).

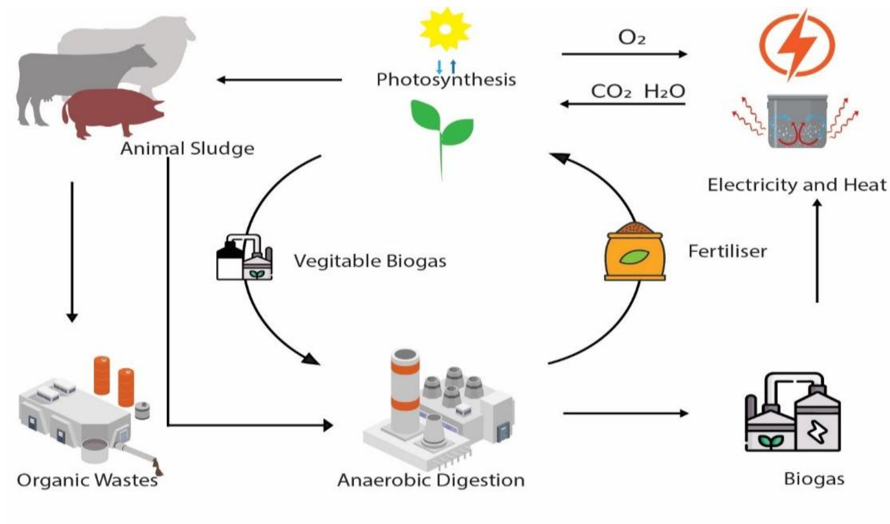


Figure 1: cycle of anaerobic digestion

It is an open secret that, the process of biogas production is defined as a microbial degradation of the organic material in the absence of Oxygen. The process produces a blend of gases mainly composed of methane CH_4 and carbon dioxide CO_2 and can be considered as one of the sustainability methods of recovering energy on biomass. The biogas constitutes mostly of methane CH_4 and carbon dioxide CO_2 with lesser amounts of various gaseous (Dong & Liu, 2021).

The use of biogas offers a potential method for mitigating greenhouse gas emissions, including carbon dioxide (CO_2). In the scope of the whole life cycle assessment of biogas production, net emissions of carbon to the environment are lower, and they are just close to zero (Dong, Zhang, & Wang, 2021).

Table 3: Composition of Biogas: A Detailed percentages

Component	Composition (%)
Methane	55-65
Carbon dioxide	35-45
Hydrogen sulfide	0-1
Nitrogen	0-3
Hydrogen	0-1
Oxygen	0-2
Ammonia	0-1

Anaerobic digestion (AD) offers economic benefits by generating income through the sale of heat and electricity, as well as from biogas production. Additionally, the AD process can be used to make agriculture sustainable since crops will be supplied nutrients, thus, lowering the use of synthetic fertilizers. Nevertheless, this aspect of AD has certain drawbacks such as initial capital costs, difficulty in optimizing the system and variability in performance. Nevertheless, AD can be an excellent technology in two functions of renewable energy generation and handling garbage. Technological developments and current research aim at increasing the cost recovery and efficiency of AD systems, as part of the low carbon circular economy development (Yadav et al., 2024).

Potential of Anaerobic Digestion for Waste from Slaughter Houses

The composition of the waste arising at the slaughterhouses can vary with various factors such as age, breed of the animals, type and quality of feedstocks exploited and their features. According to a basic understanding, the slaughterhouse wastewater is complex and very demanding, whereby about 45% of it is in the form of suspended organic solids, and the rest, which is 55%, is in the soluble form. It is known from previous studies that the amount of nitrogen in blood is normally up to 3.500 mg/L in form of ammonia and it influences composition of blood as a whole (Eze & Agboola, 2022). With a chemical oxygen demand (COD) averaging 375,000 mg/L, blood is a significant source of dissolved organic pollutants in abattoir wastewater. Plant-based materials in slaughterhouse waste degrade faster under both, aerobic and anaerobic conditions. Although the protein, fat, and carbohydrate content in this waste are the determinate of the methane yield potential, the concentrations of these ingredients can be manipulated. Due to the high lipid and protein content, certain components of abattoir waste exhibit substantial theoretical methane potential, with an average yield of 980 mL CH_4/gVS (Fang et al., 2022). Despite its potential, anaerobic digestion (AD) is often hindered by the slow biodegradation of lipids. High level of proteins and lipids may interfere with the microorganism activities and functions that undertake the degradation process. During lipid and glycerol hydrolysis, extracellular lipases break down lipids into long-chain fatty acids (LCFAs), which consist of long carbon chains (Xu, Chen, & Guo, 2022). Wastes of high lipid content are of low alkalinity, but it makes the process of anaerobic digestion problematic. This low alkalinity may hinder the process, and stifle methanogen activity stall digestion process (Farooq & Kim, 2023). These blockages are usually associated with microbial cell death and total exhaustion of essential nutrients. However, the system is capable of recovering from stagnation. After the microbial communities are in line with their habitat, it is possible to continue with the degradation of LCFAs efficiently. However, in anaerobic conditions, proteins, which are large macromolecules being long chains of amino acids through peptide bonds, also go through hydrolysis. The Clostridia genus of microorganisms plays a dominant role in the hydrolysis of protein-rich feedstocks in anaerobic environments (Gao et al., 2022).

The Clostridia genus is also essential in subsequent amino acids degradation. Anaerobic digestion (AD) raises important questions regarding the metabolism of abattoir waste. Still, using rumen contents in AD is preferable because they contain a much lower protein concentration. Rumen contents contribute to about 60% of the solid waste at slaughterhouses and this large amount can be used alongside cactus in the treatment of waste. Rumen, that is extracted from the rumen of the ruminant animals has microbiological fermentation similar to those used in biogas digesters. Therefore, microorganisms in rumen can play a significant role in the process of bio methanation as a result of enhancing fermentation of organic matter through breakdown of substrate. However, the high degree of pH decrease brought about by the rumen degradation may kill most of the microorganisms in the digester (Wang & Zhao, 2021). Blood is rich in protein and nitrogen, but an illustrious organic composition that can be high in methane production potential but at the same time may result in ammonia inhibition by the elevated amounts of nitrogen. At the other end, paunch contents have a moderate level of nitrogen spiked with high fibre and food that have not been digested, thereby offering a superior C/N ratio for AD (Gómez & Silva, 2024). Paunch contents can produce considerable amounts of methane potential if pre-treated so as to disintegrate fibrous substance. Manure and stomach lining, of moderately high to high nitrogen and high fibre, returns a mild methane potential. In order to achieve optimal C/N ratio, they have to be co-digested with other wastes. The biochemical nature of meat and offal that has high concentrations of fats, protein, and nitrogen also highlights promising methane yield from them. Ammonia inhibition in such cases can be mitigated through co-digestion with food waste, which helps balance the C/N ratio (González-Martínez et al., 2021).

Table: Methane Potential of slaughterhouse waste components

Waste Component	Key Composition	C/N Ratio	Methane Yield (mL CH_4/g VS)	Remarks
Blood	High protein, high nitrogen, high COD (375,000 mg/L)	3–5 (very low)	980	High methane potential, but prone to ammonia inhibition due to excess N.
Rumen Content	Microbes, moderate nitrogen, digested plant matter	15–20	450–550	Good inoculum source; pH drop risk if not buffered.
Paunch Content	High fiber, moderate nitrogen, undigested feed	20–30	400–500	Requires pre-treatment to improve degradability.
Meat/Offal	High protein, fat, nitrogen	6–8	800–950	High methane yield; risk of ammonia inhibition; best for co-digestion.
Fat Trimmings	High lipid content	Very low alkalinity	1000–1200	High energy content; can inhibit digestion if not balanced.
Manure	Moderate protein, high fiber	15–25	300–450	Stabilizing co-substrate; balances high-N wastes.
Stomach Lining	Protein, moderate fiber	10–15	400–600	Medium methane potential; useful in mixed digestion systems.
Slaughterhouse Wastewater	Dissolved solids, blood residues, fats	Low	250–400	High pollutant load; needs treatment before discharge or AD.

Source: Bioresource Technology

Type of Waste Management Plants can be Introduced for Sri Lanka

Fixed Dome Digester

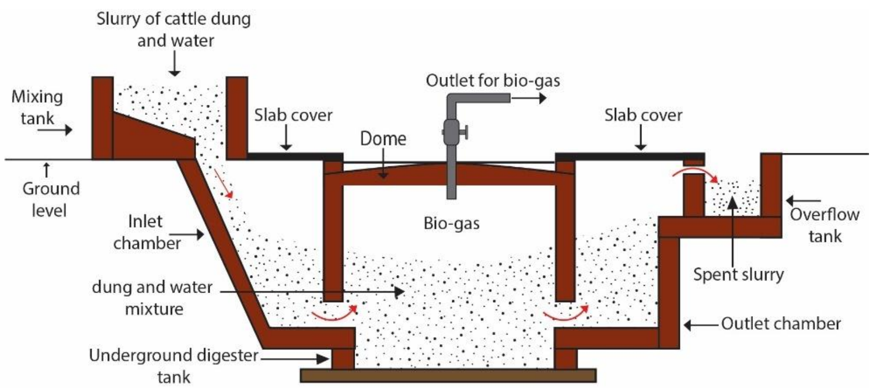


Figure 2: Fixed dome Anaerobic digester

In 1936, the first recorded Chinese fixed-dome biogas plant was developed underground with bricks. The structure of the feeding inlet and gas chamber has been preserved. It brings the gas storage tank and digestion container into one unit. Biogas is mostly made up of methane, carbon dioxide, and some other, smaller gases. Gas is sealed in the dome, and water from the compensation tank takes up the gas space, balancing the pressure. Slurry in the digester is pushed into the compensation tank during gas production and then returns, making the slurry in the digester a continuous mixture that is typical for a continuous stirred tank reactor. The construction of a fixed-dome digester is simple and cheap, it does not move, and this makes it trustworthy for use over 20 years (Han, Kim, & Lee, 2021).

Floating Drum Digester

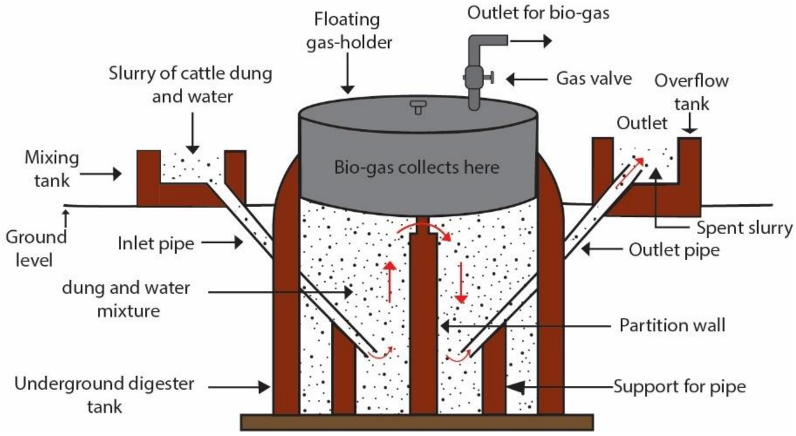


Figure 3: Floating drum digester: Created using illustrator

In 1956, building on India's standard, Jashu Bhai J. Patel invented the floating drum biogas plant. This design was standardized by India's Khadi and Village Industries Commission (KVIC) in 1962 and quickly gained acceptance both nationally and internationally (Tiwari & Sharma, 2023). It features a well made of concrete surrounding the digester tank, called T, which is organised into two segments. There is a part of the tank that acts as an inlet for feeding slurry. A stainless-steel dome, referred to as H, is placed on top of the tank and gathers the biogas coming from the reaction. The main difference between the two technologies is the floating dome. Through opening V, the main compartment releases biogas into the next compartment of tank T to make sure that the material being processed does not finish decomposing. Any excess solid and liquid waste from the compartment is transferred through a pipe and used as fertiliser in farms (Han, Liu, & Wang, 2022).

Table: Comparison of Fixed dome and floating drum digester

Parameter	Fixed Dome Digester	Floating Drum Digester	Remarks
Year of Invention	1936 (China)	1956 (India)	Historical origin of each design.
Gas Holder Type	Integrated, immovable dome	Steel drum (movable, floating)	Affects gas pressure and storage monitoring.
Gas Pressure	Variable (based on slurry level)	Constant	Floating drum allows steady supply to appliances.
Biogas Storage Volume	0.8–1.0 m^3 per m^3 of digester	0.6–0.8 m^3 per m^3 of digester	Fixed dome allows slightly more storage in dome space.
Typical Plant Size	2–50 m^3	2–25 m^3	Both suitable for small to medium rural setups.
Construction Material	Brick, concrete	Concrete tank + steel drum	Floating drum needs metalwork for the gas holder.
Average Lifespan	20–25 years	10–15 years	Fixed dome lasts longer with lower maintenance.
Maintenance Requirement	Low	Medium–High	Steel dome can corrode and needs cleaning.

Cost of Installation (per m³)	USD 100–150	USD 150–250	Fixed dome cheaper due to simpler construction.
Suitability	Rural, long-term use	Areas requiring visible gas storage	Floating drum preferred where gas level observation is important.
Gas Leakage Risk	Moderate (if dome cracks)	Low (easy to detect in steel drum)	Dome leakage harder to detect in underground systems.
Scum Removal	Difficult	Easy	Drum can be lifted; fixed dome requires manual effort.

Source: Second generation bioethanol production: A critical review.

Case Study

Waste Management Challenges in Sri Lanka

The state of Sri Lanka generates approximately 7000 tonnes of solid waste per day, of which 55-65 per cent waste component was organics of municipal solid waste stream. The livestock sector which has about 1.2 million cattle population, 380,000 buffaloes, and 34 million poultry (Department of Animal Production and Health, 2022), produces significant quantities of animal waste. Moreover, there is also the fish processing industry that processes some 530,000 metric tons of fish every year (Ministry of Fisheries, 2023), generates substantial organic waste. The conventional waste disposal practises in Sri Lanka (open dumping and unregulated landfill) help aggravate the environmental degradation through polluting the groundwater, emitting methane, and creating health threats for the general population. Indiscriminate deposition of animal waste aggravates these challenges especially in the rural areas where waste management infrastructure is lacking.

Energy Context in Sri Lanka

Sri Lanka has a serious energy security problem; the country currently imports 43% of energy via fossil fuels. (Sri Lanka Sustainable Energy Authority, 2023). The vast majority (77%) of the population which is found in the rural areas predominantly uses traditional biomass to cook hence causing indoor pollution among other health effects (World Health Organisation, 2022). The nation has developed goals to boost the contribution of renewable energy in the national grid to 70 % by 2030 (National Energy Policy and Strategies of Sri Lanka, 2019). Biogas technology offers an opportunity to realise these targets while solving issues of waste management, especially in rural areas where there is an overwhelming amount of animal wastes (Hassan & Lee, 2021).

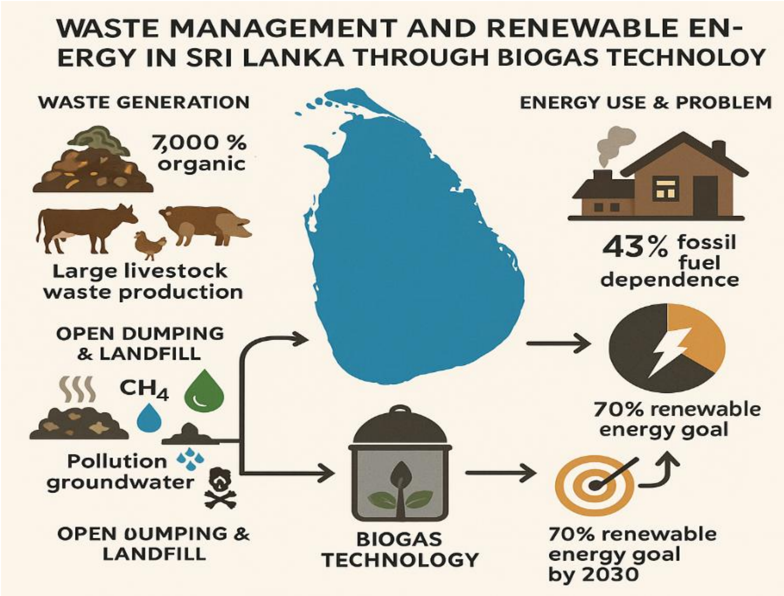


Figure 4: Waste management integrate with Bio energy

Methodology

Experimental Setup

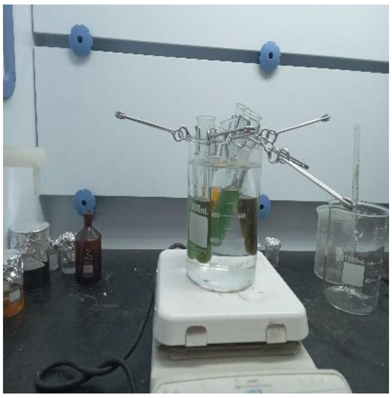
The study employed 5 batch anaerobic digesters, having a working volume of 1 litres each, and carried out the work under the mesophilic conditions (35±2°C). The inoculum used for the digesters comprised of anaerobic sludge from an active biogas plant in Kandy district of Sri Lanka. Five unique combinations of feedstock were tested to assess their potential for the production of biogas. These included: 1) a 50:20:30 blending of poultry manure, fish waste and chicken waste feedstock, 2) 50:50 blending of poultry waste manure and fish waste, 3) 25:25:25:25%, chicken waste, fish waste, poultry waste and beef, 4) 40:30:30, beef, fish waste and chicken waste and 5) 50:50 blend of poultry and cactus. This was done to determine the performance of the anaerobic digestion of the various blends of the organic wastes that would act as a pre-cursor towards the optimisation of the biogas quantity and quality (Jadhav & Khanna, 2021).

a. Set-up **b. pH test** **c. SEM analysis**

Figure 5: Experimental Set up and Lab Testing

Analytical Methods

Samples were analysed for Chemical Oxygen Demand (COD) by the closed reflux colorimetric method in Standard methods for the examination of water and wastewater. The composition of biogas was determined using the gas analyser, with the Aspen plus. Syringe displacement method was used to measure the production of Biogas (Karki et al., 2023).



a. COD test **b. Gas composition checking**

Figure 6: Analytical Methods

Efficiency of reduction of COD was determined from the given equation (Li & Chen, 2022)

COD Reduction (%) = ((Initial COD – Final COD) / initial COD) × 100

Results and Discussions

COD reduction efficiency

All five experimental configurations demonstrated remarkably consistent COD reduction efficiencies, ranging from 59.94% to 60.05% (Table 4). The consistency implies that regardless of the diversity of feedstocks, it was equal all mixtures attaining a similar treatment efficiency in terms of biomatter disintegration.

Table 4: COD reduction of different feedstock combinations

Batch no	**Reactor composition**	**Initial COD (g/Liter)**	**Final COD (g/Liter)**	**COD Reduction (%)**
1	Poultry Manure: Fish Waste: Chicken Waste (50%:20%:30%)	8.72	3.49	59.94%

2	Poultry Manure: Fish Waste (50%:50%)	10.98	4.39	60.02%
3	Chicken Waste: Fish Waste: Poultry Manure: Beef (25%:25%:25%:25%)	9.89	3.96	59.96%
4	Beef: Fish Waste: Chicken Waste (40%:30%:30%)	7.97	3.19	59.97%
5	Poultry Manure + Cactus (50%:50%)	4.38	1.75	60.05%

The notably lower initial COD concentration in Batch 5 (Poultry Manure + Cactus) at 4.38 g/L compared to the animal waste mixtures (ranging from 7.97 to 10.98 g/L) indicates lower organic content available for biological degradation. Research bears witness to this fact as plant feedstocks that have more lignocellulosic molecules are more difficult to biodegrade and produce less gas as compared to animal-sourced wastes.

Biogas Composition and Quality

The generated biogas through the different combinations of the feed stock assists in different parts of the methane. Methane concentration was between 48-55% with Batch 1 Poultry Manure: Fish Waste: Chicken Waste, 50 % :20 %:30 % recording the highest yield of the methane and Batch 5 Poultry Manure + Cactus, 50 percent:50 percent recording the lowest yield of the methane.

Table 5: Biogas Composition from different feedstock compositions

Batch	CH_4 %	CO_2 %	H_2S %	NH_3 %	N_2 %	Other Trace gaseous %	Biogas 100 %
(Poultry Manure: Fish Waste: Chicken Waste, 50%: 20%: 30%)	55	40	2	1	2	0	100
(Poultry Manure: Fish Waste, 50%: 50%)	52	42	1.5	0.5	2	2	100
(Chicken Waste: Fish Waste: Poultry Manure: Beef, 25%: 25%: 25%: 25%)	53	41	1.5	0.5	2	2	100
(Beef: Fish Waste: Chicken Waste, 40%: 30%: 30%)	50	44	1.5	0.5	2	2	100
(Poultry Manure + Cactus, 50%: 50%)	48	45	1	0.5	2	3.5	100

The superior methane content in Batch 1 (55%) can be attributed to the synergistic effects of the three animal waste components. Poultry manure is contained in this mix as it has numerous nutrients other than ensuring that compost is more absorbable because of buffering. The mixture of the fish waste 20% and chicken waste 30 % seems to offer an adequate balance in the ratio of carbon-and nitrogen C/N ratio that is essential in optimal methanogenic activity. The batch 5 that was prepared with 50% of the cactus showed the least percentage of methane 48, indicating that the plant addition of the animal waste might not improve the production of methane. The plant material has substantial quantities of lignocellulose hence takes longer time to hydrolyse it and there is a likelihood that not much of methane may be produced at the end.

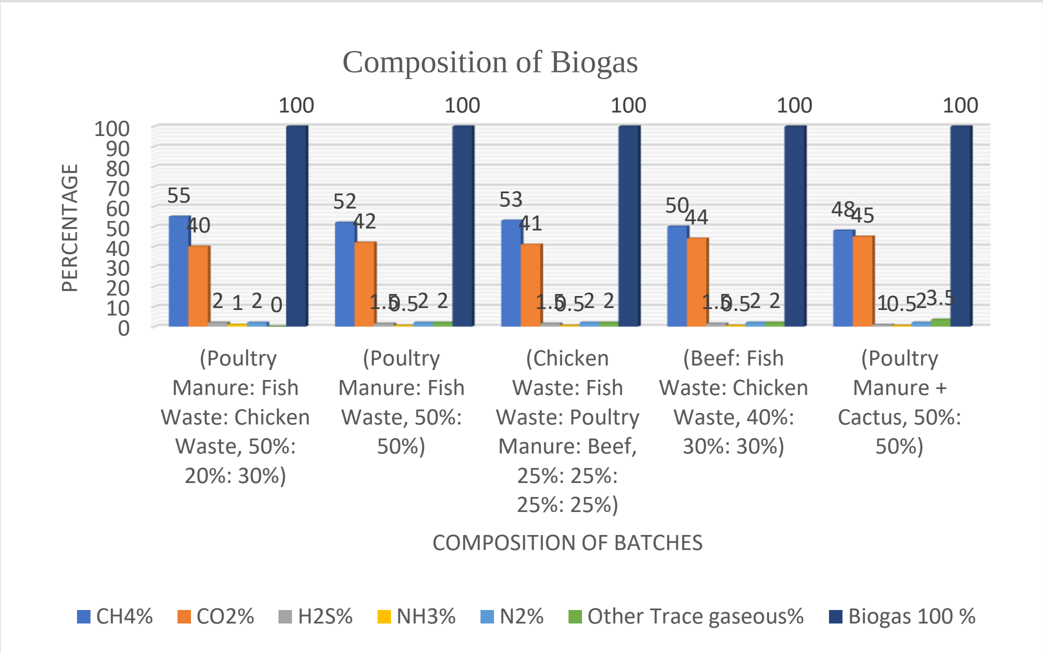


Figure 7: Composition of Bio gas

Relationship between Initial COD and Biogas Quality

With the initial concentration of COD (chemical oxygen demand) as the independent variable variable, the result was that, the more the COD, the lesser the methane in the experimental batches. Batch number 2 showed highest COD 10.98 g/L at the beginning but yielded a biogas that had a moderate level of methane 52%. Conversely, Batch 1, with an intermediate initial COD (8.72 g/L), generated the highest methane content (55%). It contradicts a commonly held notion that the greater the organic loading the more the biogas. The study indicates that the manner in which organic matter is generated makes a greater contribution towards the formation of methane emission. Consequently, the batch contained improved performance of methanogens because of the addition of; poultry manure, fish waste and chicken waste.

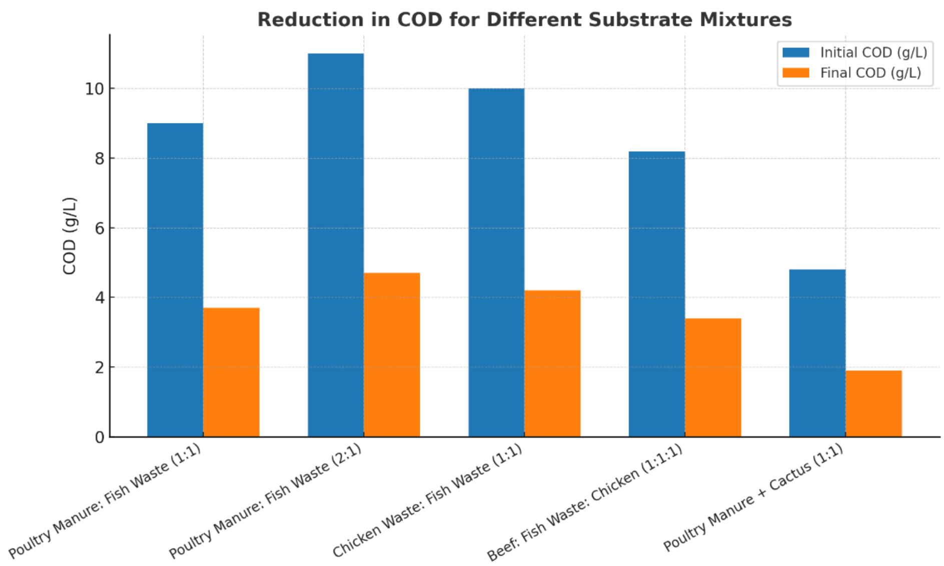


Figure 8: Initial COD VS final COD Reduction

Implication for Sri Lankan context

The consistent COD reduction efficiency (approximately 60%) across all feedstock combinations demonstrates the potential of anaerobic digestion as an effective treatment method for animal waste in Sri Lanka. Use of these systems would eliminate significantly the destructive effect of animal waste in the environment, which is mostly in the regions that animal farms and fish factories are concentrated. In the Sri Lankan context, where approximately 7,000 metric tons of manure are generated daily from livestock operations (Ministry of Agriculture, 2023), anaerobic digestion could potentially treat a substantial portion of this waste. The outcomes of Batch 1 indicated that the selection of similar systems could result in a reduction of organic contamination by approximately 60 %, and the environment would become safe and minimize the risks of people (Liang et al., 2024).

The superior methane content (55%) observed in Batch 1 indicates promising energy recovery potential from animal waste mixtures in Sri Lanka. According to the outcomes of the experiments and statistics of the waste results in the whole country, anaerobic digestion of animal waste might supply up to 245 million cubic metres of biogas a year which would generate the equivalent of 1,348 GWh of electricity. This energy potential could contribute significantly to Sri Lanka's renewable energy targets while addressing energy poverty in rural areas. When a person adhered to the implications stated by the study and conducted the use of recommended feedstock-based digesters at their houses, about 1.2 million families in India could have an opportunity to obtain superior alternatives to using biomass in cooking and using light sources (Lu et al., 2023).

How likely animal waste-to-energy plants are in Sri Lanka will depend on their construction cost, operation cost and the earning potential from selling electricity and fertilisers. Based on case studies from similar developing countries, the payback period for household-scale biogas digesters utilizing optimal feedstock combinations (similar to Batch 1) is estimated at 2-3 years. Widespread use of biogas is not popular in Sri Lanka, making it a big challenge. Many people may adopt biogas if they think positively about animal waste and cooking with biogas. Programmes showing the benefits of biogas to nature, health and the economy are vital for encouraging more people to use it (Luo & Wu, 2023).

Recommendations for Implementation

According to the experiments, it is suggested to make several changes to have better animal waste-to-energy systems in Sri Lanka. An optimal feedstock composition consisting of poultry manure (50%), fish waste (20%), and chicken waste (30%) has been identified as the most effective combination for maximizing methane yield (Ma, Xu, & Zhang, 2021). With respect to co-digestion, the incorporation of a mix of animal waste materials gives a preference, since this may result in improved nutrient management, increased processing stability, and an increase in overall methane production. In the event of its use, an additive based on plants will require additional preparation to increase the ability to break down and produce methane. With the increase of the initial level of chemical oxygen demand COD, the volume of methane in the experimental batches decreased. The initial COD was highest in batch 2 The digester systems have to be designed according to what is available in terms of feedstock mixture. What this means is that it maximised the key operational parameters, i.e. optimising organic loading rates (10.98 g/L) and hydraulic retention times and also achieved efficient mixing and temperature control (required to enable stable and efficient anaerobic digestion) and led to moderate methane content biogas production (52%) (Patel & Singh, 2024).

It is suggested that a series of policy interventions are necessary to render the animal waste to energy systems effective and sustainable in the Sri Lanka. Firstly, an integrated waste management framework should be established to align animal waste management with the country's renewable energy objectives, enabling coordinated action across relevant sectors. Remarkably, there should also be an inculcation of investment in the bio-gas technology through provision of subsidies, tax exemptions and loans at low-interest rates, something that should primarily be done to small and medium-scale farmers, who are not readily able to get large sums of money at hand. It is, also, required to establish technical support systems to enable these communication systems to be supported in the long term. The support provided includes providing specially designed courses, easy-to-use maintenance services, and expert advice for correct use and management of biogas digesters. Research and development efforts should be sustained by giving them ongoing funds and support from the organisation. Such projects ought to optimise the production of biogas from local livestock wastes and update these technologies to fit Sri Lanka’s setting. All things considered, these points can result in a more sustainable, decentralised, and inclusive animal waste-to-energy sector (Qamar & Khalid, 2022).

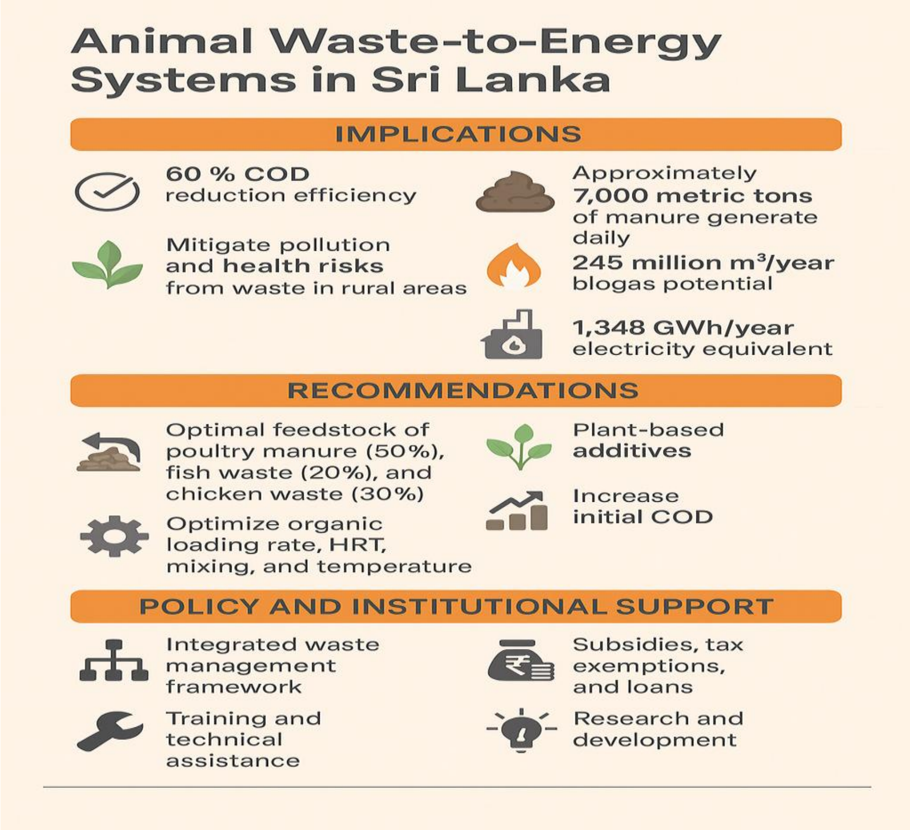


Figure 9: Animal waste to energy systems

Conclusion

This detailed research on the biogas technology of animal waste shows that a lot can be done to tackle all the issues that are interconnected in Sri Lanka; which are waste management, energy security as well as the environmental sustainability. The three key dimensions that arise out of this research are as follows: The experimental research indicates the technical feasibility of anaerobic digestion technology in the conditions in Sri Lanka. The combination of poultry manure (50 %), fish wastes (20 %) and chicken wastes (30 %) was the best feedstock which produced 55 % methane with a COD reduction efficiency of 59.94%, compared to all the other combinations that had been tested. In each experimental set up, the COD values reduced between starting elevations of 4.3810.98 g/L down to 1.75-4.39 g/L, representing an average performance of 60 percent. The constant biogas ratio (48-55% methane, 40-45% CO_2, 0.5-2% impurities) and the size of resources in Sri Lanka (7,000 tonnes/day solid waste- 55-65% organic) and livestock populations (1.2 million cattle, 380,000 buffaloes, 34 million poultry) confirm the scalability of the technology. This national potential of 245 million cubic meters of biogas every year equating to 1,348 GWh of electricity can be directly measured in terms of contributing to the 70 % renewable energy goal by 2030, and the capacity to supply 1.2 million households with clean cooking fuel directly relates to the 77% of rural households currently reliant on traditional biomass. It is necessary to have strategic policy measures that can facilitate technical feasibility to national levels. The policymakers need to focus on financial tools in order to deal with the huge initial capital expenditure, such as subsidies, special low-interest financing systems, and public-private alliances that will shorten the payback period (2-3 years) of household digesters. The regulatory frameworks should put in place quality requirements on biogas production, regulations on installation and safety of the biogas, and grid integration of electricity produced by bigger facilities. It should be integrated with the current waste management systems, especially the livestock industry and municipal arable organic wastes. The two-fold advantage of the technology, which includes capturing methane (25 times more potent than CO_2) and reducing fossil fuel importation (43% at the moment) justify its presence in both climate action agendas and energy security plans as one of the priorities. There should be capacity-building programs that are made to train technicians, extension workers and rural people on how to operate and maintain the digester to ensure they adopt the technology in a sustainable way. Also, policies ought to be used to encourage the best feedstock usage approach to follow because it has been shown that using animal waste mixtures is 7% more efficient than using plant-animal mixtures.

There are a number of research gaps that need to be filled in order to be able to transition between laboratory validation and commercial deployment. The next step is pilot-scale testing, which will entail scaling up of the existing 10-liter laboratory digesters into pilot-scale facilities (at least 100-1,000 litter) in different geographic and climatic locales within Sri Lanka to confirm the consistency of performance in different in operational conditions (temperature variations, feedstock supplies, seasonal differences). Economic models should no longer be restricted to payback but techno-economic assessments where they include: lifecycle cost analysis, sensitivity analysis of feedstock prices and energy market conditions, comparative analysis with other renewable technologies and socio-economic impact assessment determining health benefits due to indoor air pollution reduction and savings in time savings due to more fuel collection methods. The optimization of pre-treatment technologies needs to research cost-effective ways of lignocellulosic enhancement, which might boost the yield of methane above the current mark of 55%. Studies in the long-term monitoring involving timeframes that go beyond the batch-scale are required to evaluate the performance decline of digesters, stability of microbial community, and maintenance needs in the operation period in the multi-year range. Moreover, the maximization of co-digestion with other organic waste streams (agricultural residues, food waste, industrial organic effluents) should be investigated to ensure that the resource is used to its maximum potential and the potential of digestate valorisation should be investigated based on the agronomic value and marketability of nutrient-rich effluents as biofertilizers. Lastly, the policy research must simulate the implementation pathways, the best intervention points, the strategy of stakeholder engagement, and how the biogas systems can be inbuilt in the developing energy infrastructure in Sri Lanka to achieve potential of the 1,348 GWh of potential electricity production each year by using the current waste materials.

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