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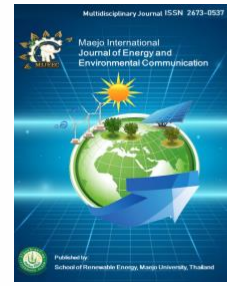

ARTICLE

Revolutionizing biogas generation: Polyethylene tubular digesters for household pig farms

Vannasinh Souvannasouk[1,*], Oudtakhone Singthong[1], Phoukhanh Sayavongsa[2], Saneth Meas[3], Thanousinh Phaxaisithidet[1], Salongxay Fongsamouth[1]

[1]Faculty of Economics and Management, Champasack University, 16000, Laos
[2]Faculty of Natural Science, Champasack University, Laos, 16000, Laos
[3]Oxfam Mekong Water Governance Program, Phnom Penh, Cambodia

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ABSTRACT

Manure decomposition from animal waste, including farm sludge, is a significant source of methane (CH_4) and carbon dioxide (CO_2) emissions, aggravating global warming. Addressing this issue is vital for the environment and pivotal in achieving sustainable development goals by combating pollution from agricultural activities. One promising solution is biogas production, which offers threefold benefits including mitigation of global warming, assurance of energy security, and efficient waste management. This can be achieved by optimizing the process using substrates that yield high biogas output while ensuring low water usage and retention. This study focuses on pig farms' biogas potential of liquid and solid manure fractions performed with laboratory-scale batch digesters and enhanced polyethylene tubular digesters for evaluation. From the screening system, the biogas output from pig slurry resulted in CH_4 and CO_2 in 45 days, achieving 61.44 and 36.35%, respectively. After the initial screening experiment, polyethylene tubular digesters were implemented for biogas production at household pig farms and produced through fermentation in polyethylene tubular digesters under anaerobic conditions and are mainly composed of CH_4 (60–64%) and CO_2 (29–38%). This study suggested that the pig slurry could be a reliable biomass energy source for biogas and applicable to householders.

1. Introduction

The global population stands at approximately 7.3 billion individuals, with a worrying 10.9% facing food scarcity. Projections suggest an exponential rise in the population, expected to reach 8.5 billion by 2030 and further to 11.2 billion by 2100 (Duarah et al., 2020). The burgeoning population increases resource consumption, which subsequently fuels socio-economic development. However, the limitless growth has generated significant environmental repercussions, chief among them being global warming (Gotore et al., 2021). Human activities, particularly in sectors like agriculture, industry, and logging, are major contributors to the global warming problem (Bhuyar et al., 2021). Deforestation and burning forests, alongside waste composting, are detrimental to environmental health—more resource management between developed and developing nations. Developed countries display excessive resource consumption, while the less developed ones grapple with effective resource

* Corresponding author.
E-mail address: vannasinhnoummin@gmail.com ; vannasinh@cu.edu.la (Souvannasouk. V)

management (Agus et al. 2021). An integrated approach that combines technological advancements with production processes is crucial to tackle these environmental challenges. Embracing sustainable solutions can help pave the way for future development (Van Tran et al., 2022). One such significant alternative is renewable energy, which can help offset the growing energy demands stemming from the population explosion and technological progress (Ramaraj et al., 2022). The rapid depletion of fossil fuel reserves and their adverse environmental impacts necessitate transitioning towards sustainable energy sources (Al-Shetwi, 2022). One promising renewable energy source is biogas, which has seen wide adoption across many countries due to its compatibility with various technological advancements and economic capacities.

Biogas primarily consists of methane and carbon dioxide, and it is produced by bacteria that decompose organic matter in oxygen-deprived (anaerobic) conditions (Sittisom et al., 2019). Various organic materials such as animal, human, and plant wastes can be biodegraded under specific oxygen-free conditions and converted into biogas (Junluthin et al., 2021). Wet organic matter, including livestock wastes (manure and fodder wastes), plant wastes (straw and forage), and household wastes (human waste, household garbage, and sewage) can all be used in the fermentation or anaerobic digestion process for biogas production. The conversion of organic waste, like livestock manure and rural wastes, into biogas is important for multiple reasons (Dussadee et al., 2022). The high energy output from biogas can be a viable alternative to fossil fuels. Additionally, biogas technology's implementation can positively impact the environment and human health through hygienic waste disposal. It also facilitates the production of nutrient-rich fertilizer from sludge and biogas plant output, thereby enhancing agricultural efficiency (Unpaprom et al., 2021). The optimal location for a biogas reactor would be near the biomass source.

Livestock wastes have traditionally been energy sources and valuable additions to livestock production in many countries (Ersoy and Ugurlu, 2020). After purification, the biogas produced can be utilized for electricity and/or heat generation and incorporated into the gas network (Ardebili, 2020). This research demonstrates how waste from swine feeding activity, such as swine manure, can be leveraged to develop a pilot model for biogas production in Sanasomboun district, Champasack province, Lao PDR. This model could identify suitable locations for biogas production plants, thus presenting a viable solution for sustainable development.

2. Material and methods

2.1 Assessing biogas production from pig farm sludge: a screening experiment

Experiments for screening were carried out in groups using new sludge sourced from pig farms. This study utilized 1000 mL lab bottles, with a working capacity of 700 mL, as our reactor for the batch anaerobic digestion (AD) tests, assessing biogas composition. Over 45 days, the reactors were consistently maintained at ambient temperature within a water bath. Biogas production and its components were collected and evaluated using water displacement techniques and a gas analyzer. The experimental setup and analysis procedure were based on the methodologies presented by Souvannasouk et al. (2021a,b). According to Standard Methods APHA (2012) were determined total solids (TS), volatile solids (VS), total Kjeldahl nitrogen (TKN), chemical oxidation demand, ammonium nitrogen (NH_4^+-N), and total phosphorus (TP) NH4+-N. After the initial screening experiment, we implemented polyethylene tubular digesters for biogas production at household pig farms.

Figure 1. Tradianl pig farm

Figure 2. Balloon-type digester system

2.2 Implementation approach for the experimental project

This study methodology thoroughly analyzed multiple critical elements for the anaerobic digestion project. Initially, we embarked on a detailed inventory of the types and quantities of organic waste available, ensuring a consistent supply for the digestion process (Kwietniewska and Tys, 2014). We then assessed the region's capacity for constructing and operating such digesters and simultaneously gauged the local biogas demand relative to other energy sources. Fiscal considerations and understanding the prospective applications for digestate were meticulously reviewed, a valuable by-product of the process. Considering all these factors and evaluating different digester designs, the balloon-type model was the most fitting choice due to its cost-effectiveness and alignment with our project's objectives (Fatimah et al., 2022).

2.3 Experimental setup of the balloon-type anaerobic digestion project

The project was carried out on traditional pig farms in

Sanasomboun District, Champasack Province, Lao PDR, which supplied fresh pig slurry (pig farm slurry), including manure (Figure 1). We established drainage channels to direct the pig slurry into the pilot model of the balloon plastic digester, which the farmer cleans daily (Figure 2). The digester system construction necessitated a trough-shaped trench lined with a 0.3 mm * 2 m * 6 m PVC tarpaulin. Also needed were 100 mm PVC pipes of 1.20 m length for both the inlet and outlet, a gas stove head, a gas transmission line, an on-off valve, 18 mm wide eve glue along with a brush, a hoe, a shovel, an old motorcycle tire, hard rubber, copper wire, and other materials.

Table 1. Demonstrate the balloon biogas plants pilot model

No	Item	Units of measure	Quantity
Building material			
1	Bricks	Number	500
2	Red cement	Bag	4
3	Blue cement	Bag	5
4	Gravel + Sand	m^3	1
Installation material			
1	PVC tarpaulin*width*length 0.3 mm *2 m*6 m	Once	1
2	PVC pipe Ø 100 mm, length 4 m	Once	1
3	Eve glue with a brush	Can	2
4	Outer joints - in PVC 18-20 mm	Once	2
5	Motorcycle tires	Once	10
6	Hard plastic sheet, size 8-10 cm	Once	1
7	Joints 3 PVC size 18 mm	Once	1
8	Rubber bottle for steam	Bottle	1
9	Valve open-close, 18 mm wide	Once	2
10	Gas stove head	Once	1
11	Gas transmission line	M	50
Labor			
1	Earth excavation	man-days	1
2	Main construction works	man-days	2
3	Balloon biogas plants Installation	man-days	2

The biogas balloon pilot model was designed to accommodate waste from at least five pigs, though the capacity for more exists. The trench had a level floor, sturdy sides, and a gentle 5% incline to drain spent slurry. The pipeline is linked to a biogas safety valve when the gas storage is filled. If biogas overflows and evaporates into the air, the balloon plant operates similarly to a fixed-dome plant. To ensure optimal performance, avoiding underfeeding or overfeeding the digester is crucial as it may reduce gas production. The system is set up by positioning the digester horizontally in the trench, with the inlet, outlet, and gas tube facing upwards. A mixture of animal waste and water in a 3:1 ratio is fed into the digester until it reaches about 75% capacity. The system is then allowed approximately a week for activation before the gas produced can be used.

2.4 Operational condition of the biogas system

Maintenance is integral for the operation of the biogas system. Regular checks for leaks (via pressure testing), unblocking pipes when necessary, emptying water traps, monitoring the slurry level in the outlet chamber, and ensuring the digester is not overloaded are essential. Every 5-10 years, the digester should be dislodged. Water vapor condensing in pipes can lead to accumulation at the lowest points, and water traps are employed to eliminate this water.

2.5 Operational condition of the biogas system

The higher calorific values (HCV) and lower calorific values (LCV) of pure methane were 39.82 and 35.87 MJ/m^3. HCV and LCV of produced biogas were determined according to the following formula:

HCV_{biogas}=0.3989 x MC = 0.0213 (R^2 =1) Eq. (1).

LCV_{biogas} =0.3593 x MC = 0.0192 (R^2 =1) Eq. (2).

2.4. Statistical Analysis

Every analytical result underwent rigorous verification, being cross-checked at least three times. Subsequently, we computed the mean and standard deviation for each parameter. The analysis of standard deviations was conducted using Microsoft Excel 2003 for Windows.

3. Results and discussion

3.1 Pig slurry composition and assessing biogas production: a screening experiment

Pig slurry is a complex mixture with two primary fractions. The liquid fraction comprises mainly nitrogen compounds such as ammonia (NH_3), nitrate (NO_3^-), and nitrite (NO_2^-). Additionally, it contains potassium, other trace minerals, and high water content—mainly if sourced from flush systems, which aids in slurry transport and application (Chelme-Ayala et al. 2011). This liquid segment also consists of soluble organic matter, encompassing sugars, amino acids, and other soluble compounds. On the other hand, the solid fraction is rich in phosphorus, primarily organic phosphates. Pig slurry compositions before and after fermentation results were presented in Table 2. This solid matter also includes fibrous materials, proteins, fats, and remnants of undigested feed (Angelidaki et al., 2003). Furthermore, it might contain pathogens like bacteria, viruses, and parasites, with their presence determined by the health and management of the pigs.

Some trace heavy metals, such as zinc and copper, often originating from pig feed additives, might also be part of this composition (Holman and Chénier, 2015). However, several factors influence the exact composition of pig slurry. The pig's diet, especially its protein and mineral constituents, largely dictate the slurry's nitrogen, phosphorus, and heavy metal content. The water consumption habits and usage at the farm can dilute the slurry, while varied farm management practices, spanning collection to treatment, can modify its chemical and biological attributes (Lautrou et al. 2021). Though the general composition might have a consistent pattern, precise concentrations can fluctuate for multiple reasons. Hence, it is pivotal for farmers to periodically analyze their pig slurry, ensuring its efficacious and eco-friendly utilization in agriculture.

Table 2. Pig slurry composition

Composition	Before fermentation	After fermentation
TS g/L	29.11 ± 1.4	21.07 ± 2.3
VS g/L	17.06 ± 2.7	10.46 ± 3.1
COD g/L	33.12 ± 1.9	24.33 ± 2.5
TKN g/L	4.25 ± 1.1	6.02 ± 1.4
NH_4^+-N g/L	2.77 ± 0.3	5.15 ± 0.5
TP g/L	0.89 ± 0.4	2.73 ± 0.8

Fresh sludge sourced from pig farms was systematically tested during the screening experiments. As a result, biogas production was observed, and its constituents were successfully extracted and assessed. Water displacement methods proved efficient for collecting the biogas, while a gas analyzer provided detailed insights into the components of the biogas. The findings from this experiment hold significant promise for future applications, particularly in optimizing biogas production from pig farm sludge. The consistent production observed over the 45 days suggests the robustness of the methodology, with potential implications for scalable and sustainable biogas solutions. Table 3 showcases biomethane concentrations derived from various feedstocks.

In the context of waste-to-energy initiatives and the bio-circular economy, the ability to harness methane from diverse feedstocks is a promising venture. Li et al. (2013) highlighted that Corn stover exhibits a potential methane yield of 51%. Maize is just a little behind, with a documented concentration of 50%, as found in a 2013 study by Rohstoffe eV (2013). Although clover grass does not have a specific citation, it offers a methane concentration of 42%. Research from Chuanchai et al. (2019) pinpointed Napier grass's methane production capacity at 48.45%. Without a cited source, duckweed and para grass produce 50.34% and 54.36% methane concentrations. As studied by Pereira and de Jesus (2011), water hyacinth stands at a yield of 40.3%.

Drawing attention to the transformative power of repurposing waste, food waste's methane yield is an impressive 59.0%, based on Li et al. (2017) findings, while fruit/vegetable waste emerges as a frontrunner with a 63.4% yield, according to Qiao et al. (2011). Methane concentrations from farm animals and agro-municipal wastes and residues hover around 60%, as Liu et al (2016) and Frühauf et al. (2015) reported. The current study shows that pig farm slurry can contribute a robust methane concentration of 61.44%. These data points underscore the vast potential and efficiency of various waste feedstocks in bioenergy production, reinforcing their pivotal role in driving a sustainable and circular energy economy.

Table 3. Biomethane concentrations from different feedstocks

Feeds stock	Methane (%)	References
Corn stover	51	Li et al., (2013)
Maize	50	Rohstoffe eV, (2013)
Clover grass	42	
Napier grass	48.45	Chuanchai et al., (2019)
Duck weed	50.34	
Para grass	54.36	
Water hyacinth	40.3	Pereira and de Jesus, (2011)
Food waste	59.0	Li et al., (2017)
Fruit/vegetable waste	63.4	Qiao et al. (2011)
Farm animal wastes	60	Liu et al. (2016)
Agro-municipal wastes and residues	60	Frühauf et al., (2015)
Pig farm slurry	61.44	This study

3.2 Discussion on the classification of AD technologies

Anaerobic digestion (AD) stands at the forefront of sustainable waste management and renewable energy production techniques (Dussadee et al., 2016). This biological process involves the breakdown of organic matter in an oxygen-deprived environment, ultimately producing biogas, a renewable energy source primarily composed of methane (Ramaraj et al., 2015). The diversity in design and functioning of AD systems has given rise to various technologies, each catering to different requirements and conditions. This paper delves into the classification of these technologies, spotlighting three predominant types:

- the Floating-drum,
- the Fixed-dome, and
- the Balloon-type.

Each type brings unique features, advantages, and challenges, making them apt for specific scenarios and operational needs. By understanding these three classifications' core characteristics and operational dynamics, stakeholders can make informed decisions tailored to their specific environmental and operational contexts. AD has increasingly been recognized as a pivotal technology in organic waste management and methane production (Pantawong et al., 2015). This review paper seeks to present an organized classification and elucidation of the diverse AD technologies, diving deep into their inherent advantages and disadvantages.

3.2.1 Wet-continuous-mesophilic fixed-dome reactor

The wet-continuous-mesophilic fixed-dome reactor offers several compelling advantages, making it a notable choice in anaerobic digestion. From an economic standpoint, its most prominent benefit is apparent during its construction phase. This design is cost-effective, especially when one factor in the long-term benefits (Aggarwal et al., 2021). Its robust and durable design is a testament to its longevity, ensuring stakeholders get value for extended periods. Notably, the absence of moving or metal components prone to corrosion means the reactor requires minimal maintenance (Kwietniewska and Tys, 2014). Furthermore, the reactor's underground design serves dual purposes: it optimizes space by staying out of sight and simultaneously acts as a natural insulation barrier against fluctuations in external temperatures. This subterranean aspect not only conserves space but also offers stability. A significant emphasis on promoting local construction is also evident. This approach ensures that the reactor is adaptable to the specificities of local conditions and acts as a catalyst for community development by creating skilled job opportunities.

Also, this reactor type has its challenges. One significant obstacle during construction is the need for specialized technical skills. Such expertise is paramount to ensure the reactor's efficiency and safety (Manser et al., 2015). While mostly efficient, the design sometimes needs consistent gas pressure, especially if stale gas accumulates. Achieving a gas-tight interior demands a specific type of sealant for the inner plastering, which can be an added complication. The system's integrity is highly dependent on craftsmanship; if not constructed by skilled masons, there is a heightened risk of gas leaks. Furthermore, its design could be more relaxed regarding specific terrains. For instance, regions with predominant bedrock make constructing this reactor challenging. Additionally, should there be a need for any post-construction modifications or repairs, the task becomes notably more challenging, given the reactor's buried positioning.

3.2.2 Wet-continuous-mesophilic floating-drum reactor

The wet-continuous-mesophilic Floating-Drum Reactor is marked by certain distinct advantages that position it as a feasible choice in anaerobic digestion. Its principal strength lies in its operational simplicity and intuitiveness. Users can effortlessly maneuver the system without needing intricate knowledge or training. Additionally, one of the intuitive design elements is the ability to visually ascertain the volume of gas stored in the system, allowing for efficient management and utilization. Beyond the ease of use, the system is engineered to consistently maintain stable gas pressure, ensuring a steady output over time (Sathish and Vivekanandan, 2016). Despite its seemingly simple design, the reactor boasts commendable reliability, ensuring the processes inside work as intended. Moreover, a significant feature of this design is its resilience. Minor construction inaccuracies or deviations only substantially affect the system's performance and ability to produce gas efficiently.

However, like all systems, it presents certain disadvantages. The cost implications associated with the steel drums stand out as a significant concern. These drums escalate the initial investment and have associated longevity concerns. Since steel is susceptible to corrosion, this reactor type might have a reduced operational lifespan, particularly compared to alternatives like the fixed-dome variant. Maintenance routines add to the operational costs, with tasks like repainting the drum being a recurrent expenditure. A notable operational challenge presents itself when fibrous substrates are utilized. In such scenarios, there's an elevated risk of the gasholder getting trapped in the scum layer, potentially hindering the system's efficiency.

3.2.3 Wet-Continuous-Mesophilic Tubular Reactor (Balloon-Type)

The wet-continuous-mesophilic tubular reactor, commonly called the balloon-type reactor, carries several inherent advantages. Financially speaking, this reactor is a boon, especially during its initial construction phase, due to its cost-efficient nature. Moreover, practicality is embedded in its design: the reactor can be transported, deployed, and maintained, simplifying operational procedures (Ardebili, 2020). A significant benefit is its thermal adaptability; in warmer geographical regions, the reactor can consistently maintain optimal digester temperatures. Its design, characterized by a shallow installation depth, also becomes a strategic advantage in areas plagued by high groundwater tables or where the bedrock is particularly resistant to excavation.

Every silver lining has a cloud, and the balloon-type reactor is no exception. The primary concern with this design is its abbreviated lifespan, which could lead to more frequent replacements or overhauls. Further, the reactor's physical structure could be more resilient to mechanical damage, making it somewhat fragile in rough operational conditions (Fatimah et al., 2022). The logistics associated with this reactor type can also pose challenges; materials for its construction are often sourced from distant locations, potentially elevating costs or causing supply chain delays. Operational nuances, like maintaining the desired pressure levels, can be intricate and may demand additional equipment like weights. A unique challenge to this reactor is the difficulty in scum removal, further compounded by the fact that local artisans often lack the expertise to repair or restore a damaged balloon.

In the decision, the world of anaerobic digestion offers multiple reactor types, each with its strengths and weaknesses. While the balloon-type reactor shines in many aspects, the decision to deploy it should be grounded in a comprehensive understanding of local factors, resource constraints, and specific operational needs. The goal should always be to harness maximum efficiency and reliability from the chosen system.

3.3 Project implementation using the balloon model

For the anaerobic digestion route, several factors come into play. These include: securing a steady and accessible supply of organic waste; local expertise in construction and operation; the demand and need for gas; the potential to compete with other energy sources; budgetary constraints; and the demand and use for the digestate byproduct (Kwietniewska and Tys, 2014). Given the considerations of cost and construction, the balloon type was selected for this project. Traditional swine farming in the Sanasomboun District of Champasack Province, Lao PDR, was the source of fresh swine slurry, depicted in Figure 1. The setup involved directing the swine slurry through drainage channels leading into the balloon plastic digester pilot model, which the farmer cleans daily.

The digester design entails a trough-like trench covered with a

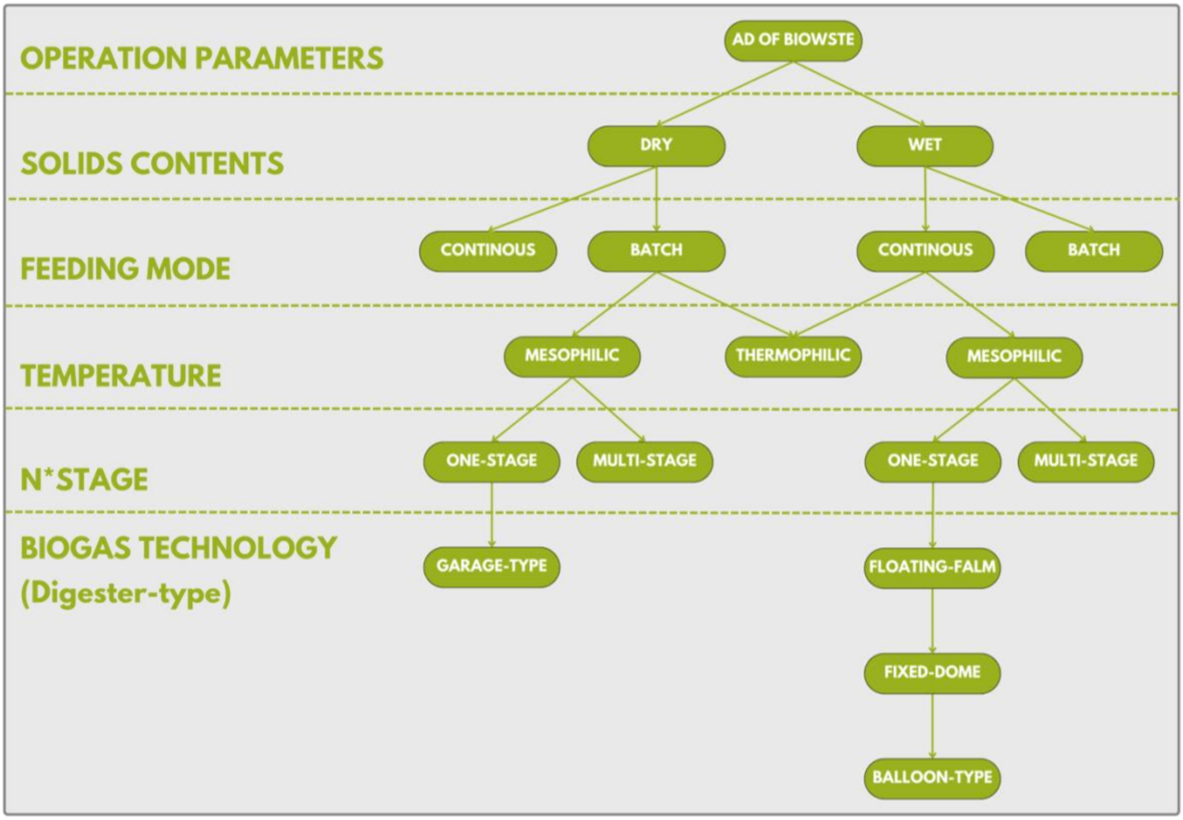

Figure 3. Anaerobic digestion technologies and operations

PVC tarpaulin (0.3 mm thick, 2 m wide, and 6 m long). Additional components include a PVC pipe (100 mm in diameter and 1.20 m long) for the inlet and outlet, a gas stove head, a gas transmission line, an on-off valve (18 mm wide), eve glue, brush, hoe, shovel, an old motorcycle tire, hard rubber, copper wire, and other materials. The model is designed to accommodate waste from at least five swine. The trench's design emphasizes a level base, sturdy sides, and a slight gradient (around 5%) to allow for the drained slurry. When the gas storage reaches capacity, a pipeline connects it to a biogas safety valve.

If there's an excess release of biogas, the balloon system functions similarly to a fixed-dome plant (Aggarwal et al., 2021). Underfeeding diminishes gas output while overfeeding causes incomplete digestion, reducing gas production. To commence operations, the digester is placed horizontally in the trench with its inlets, outlets, and gas tubes facing up. It's filled with a mixture of animal waste and water in a 3:1 ratio until it's about 75% full. The system is left for roughly a week to become active, after which the produced gas becomes available.

3.4 Impacts of the Balloon Biogas Pilot Model Installation

Completing the balloon biogas pilot model's system setup promises transformative advantages to the target household that rear swine. The primary yield is biogas derived from swine manure. This sustainable energy source offers a substantial quantity for household kitchen applications, generating approximately 90-120m3/month. With consistent usage spanning 4 hours daily, this biogas output can replace 108-144kg of firewood or charcoal, equivalent to roughly 10-14 sacks. In energy terms, this amounts to 108-144 kWh. It mirrors a fuel consumption of 41.4-55.2 liters, shaving approximately 15 minutes off each cooking session. Figure 4 demonstrates the balloon biogas pilot model installation with productive application.

Figure 4. Balloon biogas pilot model installation with productive application (a) burning test and (b) making hot water

Elevating the efficiency quotient of such a system necessitates two primary criteria: a bounteous biogas yield and a significantly high methane concentration. Notably, the calorific value of biogas derived from pig slurry surpasses that of conventional biogas plants. This augmented calorific value is not only superior to biogas yielded from orthodox AD systems, which possess a Lower Calorific Value (LCV) spanning 18.0-23.4 MJ/m^3 and a Higher Calorific Value (HCV) in the range of 20.0-25.9 MJ/m^3 as cited by Li et al. (2013) but also affirms the high-energy output of the system in focus. Furthermore, implementing polyethylene tubular digesters amplifies methane enrichment, especially at a micro-scale like household pig farms.

As a result, the biogas produced is of a higher calorific grade. This study unequivocally attests to the efficacy of such digesters in churning out high-calorific biogas, cementing their value in sustainable energy generation paradigms. A notable by-product is the bio-fertilizer residue known as slurry. With rich nutrient content, including Nitrogen (N), Phosphorus (P), Potassium (K), and trace elements, about $50m^3$ or approximately 70-80 sacks/month of this fertilizer can be produced. Households can incorporate this into their agricultural activities, replacing chemical fertilizers or capitalizing commercially at 10,000 kips per sack.

The system outputs around 1,500 liters/month of liquid fertilizer alongside solid bio-fertilizer. This high-grade fertilizer, sourced from the overflow during the biogas digestion process, can be diluted and utilized as a foliar spray for vegetables, offering an organic alternative to chemical fertilizers. Also, swine reared under this system exhibits improved health indicators. They are observed to be less stressed, consume more feed, and exhibit accelerated growth rates.

The installation addresses prevalent community concerns like unpleasant odors stemming from swine rearing, and curtailing complaints. Environmentally, it curtails emissions of potent greenhouse gases, namely CH_4 and CO_2, mitigating global warming contributions. The anaerobic digestion mechanism effectively neutralizes eggs of infectious vectors. This results in a notable decrease in pests such as flies, mosquitoes, and cockroaches, leading to a healthier, reduced-risk environment for the community. Introducing the balloon biogas model signifies a holistic improvement for the target household and the wider community, spanning energy, agriculture, environment, and health sectors.

4 Conclusion

The anaerobic digestion process offers a sustainable approach to managing the increasing organic waste by converting various waste types into biogas, a renewable energy source rich in methane and carbon dioxide. This biogas serves multiple purposes, from transportation to household cooking, and the residual by-product functions as a nutrient-rich organic fertilizer. Innovations like the balloon plastic biogas model expedite methane production, promising results within two weeks. Addressing the greenhouse gas emissions from manure decomposition is crucial for environmental and sustainable development goals. This study highlights the enhanced biogas potential of pig farms using polyethylene tubular digesters, emphasizing its higher calorific value compared to traditional methods. For households with pig farms, polyethylene tubular digesters provide an economical solution for biogas production. These digesters, designed to boost biogas yield, notably increase methane content, enhancing energy efficiency. The findings underscore the significance of biogas as a pivotal component in the shift toward sustainable energy solutions.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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