Life Cycle Assessment of Anaerobic Digestion of Food Waste in the Presence of Manure Concerned Global Warming Potential

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ABSTRACT

This study focused on residential biogas production using semi-continuous anaerobic digestion (AD) of food waste with a C/N ratio of 22.7% and a 2,000 kg inoculum framework. The four steps of the inventory plan—assortment, characterisation, normalization, and weighting consideration—were used to evaluate the life cycle of this inquiry using the life cycle assessment (LCA) method. 1.35 liters of useable biogas (CH4) were generated daily and were adequate to replace the commercial LPG used for cooking in homes. A whopping 4.37 and 3.15 liters of biogas and CO2 were produced daily, respectively. The rate constants and half-lives for the kinetic models of total biogas and methane, respectively, were 0.9102 and 0.1779 day-1 and 3.6443 and 3.8963 days. These models were specified in pseudo-first order. On the other hand, because of the challenging degradation of organic compounds in food waste, the CO2 kinetics model was decreased to pseudo-zero order with a rate constant and half-life duration of 309.32 and 10.4619 mL/day, respectively. The final GWP of food waste was 759.00 kg CO2, whereas the GWP of HBP was 792.92 kg CO2. The intriguing facts were that using LPG increased GWP by 0.56 kg CO2e/day, which evolved CH4 was able to minimize. In order to avoid using synthetic fertilizer N-P-K, the return of biofertilizer residues from the biogas storage pond's outflow residues was able to improve soil fertility and lower GWP by about 1.8552 kg CO2e/day. Because synthetic materials produced only 0.0245 kg CO2e per day for a period of five years, their total supply were insignificant.

1. INTRODUCTION

The rates of expansion of the economy, the population, and the urban areas are comparable to those of the demand for energy. As a consequence of this, it is absolutely necessary to supply various forms of energy to the right resources. When future expansion is taken into account, energy prices should be reasonable and should not, in the long run, pose a barrier to the social and economic development that is taking place across the nation [1]. Expanding domestic production of renewable energy utilizing high-performance technology is a high priority issue that needs to be solved as soon as possible for the next generation. This will help to decrease the impact that the production has on the environment and the community. Both overpopulation and excessive consumption have wreaked havoc on the globe and driven the energy resource closer and closer to an unavoidable dead end, where it is anticipated that it will be depleted in fewer than 80 years [2]. As a result of the rise in the price of fossil fuels, the effects of greenhouse gases (GHGs) released during burning, and the effects of pollutants on human health [3]-[4], the current focus may turn to alternative energy sources such as biogas produced by anaerobic digestion (AD) of biomass. This shift in attention could be attributed to the fact that biogas is produced by AD of biomass. The Thai fixed-dome digester method, which consists of a semi-continuous anaerobic digestion of an 8 m^3 polyethylene (PE) balloon, is commonly used for the removal of organic waste from animal dung and agricultural residue. This is one of the technology's common applications [5]. In anaerobic digestion (AD), suitable microscopic organisms use four distinct processes - hydrolysis, acidogenesis, acetogenesis, and methanogenesis - to transform biodegradable organic materials into biogas in the absence of oxygen [6]-[7]. As a consequence of this, AD is regarded as an effective strategy for dealing with food waste and for facilitating the fulfillment of Thailand's growing demand for energy in a manner that minimizes the adverse effects on the surrounding environment [8]-[9]. Additionally, by-products, such as processed digestate, have a number of beneficial applications when used as a biofertilizer on arable land. These applications include the

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replacement of some chemical fertilizer and the restoration of soil fertility [10]-[11]. Additionally, these applications help reduce chemical pollution [12]-[13] and encourage the recycling of nutrients [3], [12]. However, in order to implement this technique, a substantial financial investment and a complex technological procedure are necessary. In the meantime, the absence of a checking system for the expansion of biogas plants is consistently the cause of bad operational handling and low beneficial proficiency [14]-[15].

Households in rural areas that have between 5 and 10 pigs are increasingly putting in place systems for household biogas production (HBP) as a result of technological advancements in anaerobic digestion and biogas fermentation. The volume of biogas that is typically fermented ranges between 8 and 10 cubic meters. HBP ferments agricultural waste at room temperature while being confined by environmental conditions by using a shared fermentation chain and a typical classical biogas fermentation technique [3]. In addition, HBP systems have come to the realization that a better yield of AD can be achieved through a combination of energy balancing, complex systems, and the utilization of co-product assistance when the conditions are appropriate [16]. There have been several attempts [15], [17]-[18] made to investigate the history of HBP as well as the environmental management of the substance. It is possible that the 8-m^3 hydraulic biogas fermentation that is part of the household biogas project will be able to reduce the effects of environmental pollutants on eutrophication potential (EP), acidification potential (AP), energy consumption (EC), global warming potential (GWP), human toxicity potential (ETP), and photochemical oxidation (POP), which accounted for 84.84%, 54.37%, 39.16%, 27.67%, 19.35%, and 5.55%, respectively [18].

The life cycle assessment (LCA) approach is one that may be used to investigate the effects that a certain product, process, or activity has on the surrounding environment [19]. This method is both adaptable and comprehensive. An inventory analysis of the most recent HBP scenario was carried out using LCA on an organic farm located in the Nong Ya Plong District of the Phetchaburi Province in Thailand. The primary objectives of this research were to: 1) use the AD process to produce biogas in the HBP system; 2) investigate how the HBP system affects the environment or how it may contribute to global warming in the life cycle of fermented biogas; and 3) determine whether or not the HBP system may one day be utilized to assist in the expansion of ecological agriculture and to improve the fermentation process.

2. EXPERIMENTAL

2.1 Semi-continuous AD Experiment

On the organic farm in Nong Ya Plong District, Phetchaburi Province, around 2,000 kg of fresh cow dung was collected from the livestock (cattle) framework (western Thailand). Fresh cow dung was placed in a plastic bag, sealed tightly, and left at room temperature for an entire night so as not to kill off any of the necessary organisms (methanogens) for AD that are found in the surrounding environment. The air pressure booster completely inflated the 8-m^3 PE balloon until it reached 90% of its resistance to compressive pressure in order to join the inlet (food waste) and the outflow (digestate) (approximately 7,200 L). In order to remove a significant amount of oxygen from the inflated PE balloon, it was transported to a pond used for the storage of biogas and then filled with water (to the point when the balloon's resistive capacity was at 50%). In order to cultivate methanogens and collect a suitable amount for AD, the inoculum of freshly created cow manure was put into the PE balloon for 2,000 kg. This process took place at room temperature for 20 days. On day 21 of the experiment, food scraps obtained from the organic farm were added to the polyethylene balloon's intake. The volume of total biogas that was sampled was measured once every day for a period of seventy days using a pressure gauge that was attached to the PE balloon. The volatile fatty acids (VFAs), carbon dioxide (CO_2), and methane (CH_4) found in various biogas products were investigated with the use of the GC analyzer and alkali titration, which will be described in the next session.

2.2 Analysis of biogas compositions

In order to calculate the C/N ratio, we employed an element analyzer (a CHNS/O analyzer from Perkin Elmer PE2400 located at Suranaree University of Technology in Nakhon Ratchasima, Thailand) to measure the amounts of total carbon and total nitrogen. The entire volume of biogas was measured on a daily basis for a period ranging from 21 to 70 days using a pressure gauge that was attached to the PE balloon. This allowed the researchers to convert the measured pressure into the volume of biogas. In order to carry out a quantitative analysis of biogas, an Agilent Technologies 7820A gas chromatograph was furnished with two Porapak molecular sieve columns, flame ionization detection (FID), and thermal conductivity detection. The instrument was utilized to analyze the gas (TCD). When performing the quantitative calibration with the help of standard gas combinations, helium was used as the carrier gas. The sample of ten microliters of biogas was injected into the gas chromatography apparatus that was operating at a detection temperature of three hundred degrees Celsius and an oven temperature of two hundred and seventy degrees Celsius. The flow rate of helium was 26 mL/min, and the pressure was 80 psi. The flow rate of hydrogen was 30 mL/min, and the pressure was 40 psi. The flow rate of air was 300 mL/min, and the pressure was 60 psi [20]. A range of 10 to 100 mL of distillation water was subjected to an alkali titration in order to determine the content of the volatile fatty acids (VFAs). In the presence of a three-drop methyl orange indicator, a quantity of the diluted solution that was 20 mL in volume was pipetted into an Erlenmeyer flask. The solution was then titrated with 0.1 M KOH until the color of the solution changed to a light pink and then faded. Stoichiometric calculations led to an estimate that the volume of KOH that corresponds to the existing concentration of VFAs in grams per liter.

2.3 Data

The compilation of the data took place over the course of three months. The data for HBP's operations came from the biogas storage pond located on the organic farm in the Nong Ya Plong District of Phetchaburi Province in Thailand. Through field study, we were able to validate the AD processes that the PE balloon was using. During the time period in question, a number of samples of digestates (VFAs) and mineralized biogas (mostly CH_4 and CO_2) were obtained. At the laboratory center of Roi Et Rajabhat University, experimental elucidation of volatile fatty acids, total biogas volume, particular products of and mineralized biogas evolution, and the evolution of mineralized biogas was carried out (Selaphum, Roi-ET Province, 45120, Thailand). The Research Laboratory Equipment Center at Maha Sarakham University has more information available for you to peruse (Maha Sarakham Province, 44000, Thailand). Additional information on ecological emissions (also known as pollutant emissions), energy consumption rate, and other parameters utilized in this investigation were gathered through the use of a literature review [3].

2.4 Life cycle assessment

The framework and guiding principles developed by the International Organization for Standardization were used to direct the life cycle assessment [21]. In order to investigate the ecological problem that AD poses for the HBP, the following fundamental processes were carried out: establishing a target and a boundary; conducting an inventory analysis; evaluating the impacts; and providing an explanation.

2.4 1.Target and boundary definition

The objective of the LCA was to determine the ecological impact of HBP in terms of kg CO_2-equivalent per unit of annual deforestation and the energy consumption (including input and output activities of fermentation). It is required to have a functional unit (FU) that describes the basic function carried out by a product framework in order to be able to correlate the various biogas fermentation frameworks [22]-[23]. This allows for varied frameworks to be treated as functionally equivalent. Because the primary goal of the biogas frameworks is to generate energy from the fermentation of 20 kg/day of food waste and 2,000 kg of manure throughout the experiment flowing into the biogas digester, the biogas storage pond was selected as the FU of HBP based on its ability to process manure and food waste. The entire life cycle that is required for biogas fermentation was practically theorized in this study. This cycle began with the disposal of food waste and manure on the organic farm and continued through the production of biogas and biofertilizer (digestate from fermented organic matter). It was decided to systematize the steps of the fermentation processes that dealt with grouping, processing, and mobilizing [24]. The practicalities of shipping biofertilizer were also something that was taken into consideration. Because of the intricacy of the building materials, this study did not take into account the impacts of constructing and disassembling the frames.

2.4.2 .Impact assessment and interpretation

The energy balance and ecological effects of the HBP frameworks were evaluated by using the information gathered in the inventory consideration in four processes (assortment, characterization, normalization, and weighting consideration)[22]. These processes were carried out using the information that was gathered in the inventory. With regard to the global warming potential (GWP), we chose a particular category of baseline potential effects that is typically employed in the first life cycle assessment (LCA) of the biogas storage pond [11], [13]. Ecological effects were quantitatively allocated to the category that was chosen and quantified in terms of a standard unit for that category using the equation (1), where x represents the impact category x and I represent the contributing factor *i*.

$$E_{D(x)} = \sum E_{D(x)i} = \sum\left[Q_{(x)i}E_{F(x)i}\right] \tag{1}$$

According to Table 1, $E_{F(x)i}$ is the characterization factor of equation (1) on the potential impacts of x, $E_{D(x)i}$ is the environmental impact factor of equation (1), and $E_{D(x)i}$ is the potential environmental impact of category x. Additionally, $E_{F(x)i}$ is the environmental impact factor of equation (1).

3. RESULTS AND DISCUSSION

3.1 Feedstock Characteristics

The composition of the food waste varied based on the various feeding patterns and included grains, vegetables, meat, pork, poultry, eggs, and other important items [25]. The makeup of the food waste varied depending on the various eating patterns. The ratio of total solids to volatile solids (TS/VS) for food waste was 94.5%, and the ratio of carbon to nitrogen (C/N) for food waste was 22.7%. According to the findings of the previous pieces of research [26]-[27], this particular type of precursor for AD could be identified by its suitable C/N ratio, which was typically in the range of 20–30%. As a direct consequence of this, these food scraps were routinely gathered and utilized only as a carbon source for the AD of methanogens.

3. 2 Cumulative volume of biogas, methane and carbon dioxide from AD of HBP

In this work, HBD was performed on food waste in anaerobic conditions when methanogenic and other essential microbes were present. The goal was to lower the cost of LPG production. In addition to that, it employed fermented biogas for the cooking of meals for the household. In order to allow the essential microorganisms to finish their maturation cycle and make them fully available for the AD of HBP [28], the inoculum media for a 2,000 kg livestock (cattle) system in an 8-m^3 PE balloon (biogas storage pond) were prepared at room temperature (mesophilic condition) for the first 20 days of the experiment. Because of this, 20 kg of food waste were introduced to the incubator framework each day. From day 21 until day 70, the framework also continuously collected part of the gases that were produced. The results showed that the total biogas evolved gases, CH_4 and CO_2, started to occur substantially on day 21 and reached saturation on day 30 with cumulative volumes of 4,368.27, 1,349.30, and 3,147.28 mL/day, respectively. In addition, the results showed that the volume of CO_2 reached saturation on day 30. (for examples, see Figures 1 and 2) Under the same conditions, the AD of cassava reached between 1,200 and 1,900 mL per day [6]. The amount of CH_4 that was used ranged from 0.5 to 3.14 liters, and the leftovers from the outlet were somewhere in the range of 15-20 kilograms of this semi-AD of the 8-m^3 PE balloon. These leftovers could be used as biofertilizer rather than chemical fertilizer for agricultural activities [29]-[30]. This was adequate for a daily cooking time of at least an hour [31]-[32].

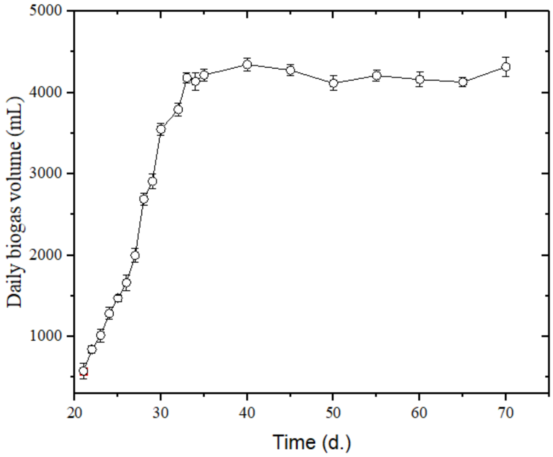


Fig. 1. Cumulative volumes of total biogas from HBP of food waste in the 8 m^3 biogas storage pond under mesophilic conditions for 70 days in the presence of 2,000 kg of cattle dung.

After day 33, the proportions of all gases were kept constant at variations of 5–10% of the maximum volumes, and they may continue to be used until the expiration date of the PE balloon, which is normally 5 years [5]. However, the leftovers for the outflow would be developed using a technique that is safe for the environment and sustainable, and the evolved gases would be evaluated for their potential to cause global warming (GW).

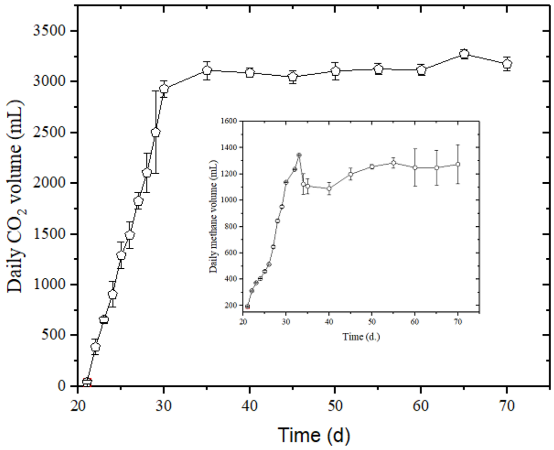


Fig. 2. Cumulative volumes of CH_4 and CO_2 from HBP of food waste in the presence of 2,000 kg of cattle manure in the 8-m^3 biogas storage pond under mesophilic conditions for 70 days.

3.3 Effects of Inoculum on the AD of food waste in terms of pH and VFAs

The evaluation of the HBP's ability to spread depends on the pH solution, which is measured concurrently with VFAs and alkalinity. This measurement is performed simultaneously. The pH solution of the mixed-liquid biogas in the 8-m^3 biogas storage pond was initially only slightly acidic when it was first measured (pH 5.9). When the AD of HBP was spread out, volatile fatty acids (VFAs) were produced, which caused the pH of the solution to drop to a range that was between 5.7 and 5.3. (Figure 3). On the other hand, the AD of HBD continued to exist because the essential bacteria were able to survive in the pH solution, which was not lower than 4 [33].

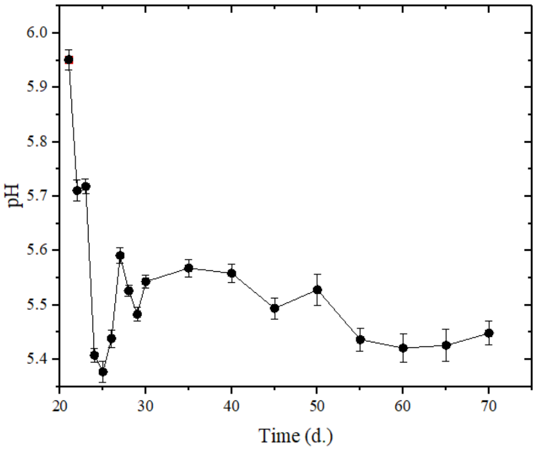


Fig. 3. pH solution of HBP from food waste in the presence of 2,000 kg of cattle manure in the 8-m^3 biogas storage pond under mesophilic conditions for 70 days.

Because the accumulation of VFAs causes a decrease in the pH solution of AD [34], monitoring the content of VFAs was done in order to determine the degree to which AD is stable. In the current investigation, the concentration of VFAs reached a maximum of 3.83 g/L on day 30, after having dramatically decreased between days 21 and 30. (Figure 4). The concentration remained stable until day 30 of the experiment, when it reached equilibrium. This may have something to do with the routine removal of residues and biogas liquid, as was noted earlier in the sentence. According to Siegert and Banks [35], the concentration of 4,000 mg/L for the VFAs was determined to be the lowest inhibitory concentration. This finding is in line with the findings of another investigation.

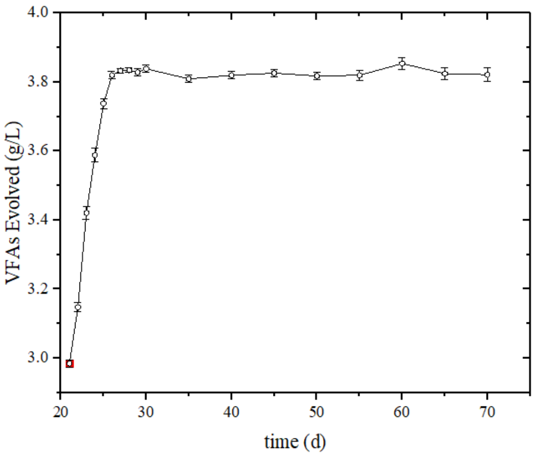
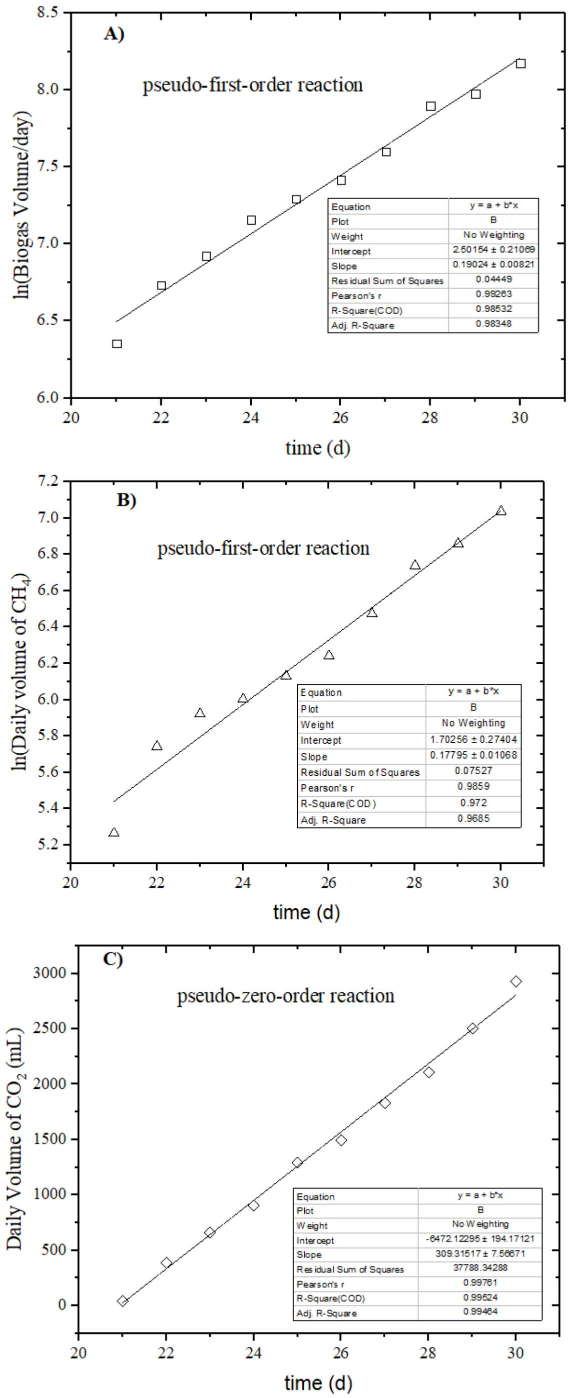


Fig. 4. Cumulative volumes of VFAs from HBP of food waste in the presence of 2,000 kg of cattle manure in the 8-m^3 biogas storage pond under mesophilic conditions for 70 days.

3.4 Kinetics models of biogas, methane and carbon dioxide from AD of HBP

The evolution of HBD is depicted using kinetic models for each of the generated gases in Figures 5A and 5B. Total biogas and CH_4 were found to have reaction orders that were determined to be a significant match for the pseudo-first order. Furthermore, their corresponding reaction constants and half-lives were reported to be 0.9102 and 0.1779 day^{-1} and 3.6443 and 3.8963 days, respectively. The value of R^2 for the linear regression was greater than 0.9853 and, correspondingly, 0.972. The production of biogas from food waste mixed with drinking water treatment sludge (DWTS) under mesophilic anaerobic digestion was demonstrated using data from the published literature [36]. This was accomplished by fitting the data using first-order kinetic models. (The value of R^2 is higher than 0.949). In spite of this, the CO_2 kinetics model was quite complicated, and the findings that Zhang et al. [37] came to were supported by the steep curve that represented the model's initial evolution. The reaction constant for the daily CO_2 volume's response to the pseudo-zero order was 309.32 mL/day, and the half-life period was 10.4619 mL/day.



Equation	y = a + b*x
Plot	B
Weight	No Weighting
Intercept	2.50154 ± 0.21069
Slope	0.19024 ± 0.00821
Residual Sum of Squares	0.04449
Pearson's r	0.99263
R-Square(COD)	0.98532
Adj. R-Square	0.98348

Equation	y = a + b*x
Plot	B
Weight	No Weighting
Intercept	1.70256 ± 0.27404
Slope	0.17795 ± 0.01068
Residual Sum of Squares	0.07527
Pearson's r	0.9859
R-Square(COD)	0.972
Adj. R-Square	0.9685

Equation	y = a + b*x
Plot	B
Weight	No Weighting
Intercept	-6472.12295 ± 194.17121
Slope	309.31517 ± 7.56671
Residual Sum of Squares	37788.34288
Pearson's r	0.99761
R-Square(COD)	0.99524
Adj. R-Square	0.99464

Fig. 5. Kinetics models of cumulative volumes of total biogas, CH_4, and CO_2 from HBP of food waste in the presence of 2,000 kg of cattle manure in the 8-m^3 biogas storage pond under mesophilic conditions for 70 days; A) total biogas, B) CH_4, and C) CO_2.

The coefficient of determination, R^2, was greater than expected at 0.9952. (See Figure 5C.) This may be supported by the findings of Vavilin et al. [38], who demonstrated that the first kinetics (FOK) model of complex organic materials was an exponential fall to zero over time (completely decaying) [39]. This model's behavior was shown to be dependent on the quantity of a non-biodegradable component. The reduction in FOK that was seen in this study may be due, in large part, to the presence of complex organic components in food waste.

3.5 LCA of biogas, methane and carbon dioxide from AD of HBP

Table 1 outlines the findings that were discovered as a result of our investigation of the inventory technique for the LCA of HBP. The global warming potential, also known as the carbon footprint, of HBP was determined to be 792.92 kg CO_2e. In this context, it is essential to keep in mind that all precursor wastes, such as food waste and manure, are invariably produced as a direct consequence of the consumption of food by humans and animals. If we do not place sufficient emphasis on the AD of HBP, the HBP will always naturally degrade and release GHGs into the atmosphere. According to the numbers presented above, using LPG would result in a daily reduction of 0.56 kg CO_2e to the global warming potential, while 759.00 kg CO_2e from food waste would result in the production of approximately 1.35 liters per day. In addition to this, it has been discovered that biofertilizer that is produced from the remains of biogas fermentation outlets is utilized [40]. 4.7-9.9-2.6 is the range of essential nutrients for nitrogen, phosphorus, and potassium, all of which are proportional to the liquid fraction of the digestate. It is recommended that a minimum of 15 kg of the liquid portion of the digestate be considered to include between 0.705 and 0.135 and 0.390 kg of N-P-K in order to improve soil fertility and reduce GWP (this can be accomplished by avoiding the use of synthetic N-P-K fertilizer). Because of this, the daily CO_2e emission will be around 1.8552 kilograms (see Table 1). The second category of materials utilized in the construction of the biogas storage pond at HBP resulted in a total GWP of approximately 44.8 kg CO_2e over the full AD of the facility. In order to divide the total dose of GWP into 8.956 kg CO_2e per year or 0.0245 kg CO_2e per day, it was assumed that the PE balloon would continue to function normally for a period of 5 years after the date on which it was supposed to expire. In this particular scenario, the AD of HBP was helpful in terms of preserving the environment and making responsible use of the energies available around the world.

Table 1: Global worming potential (GWP) from the list of HBP AD applications

No	List of Utilization for AD of HBD	Unit	Amount	EF ($kgCO_2e/unit$)	CF ($kgCO_2e$)	Ref.
1	Linear Density Polyethylene (LDPE)	kg	7.500	2.6922	20.19	[36]
2	Food waste	kg	300.000	2.5300	759.00	[36]
3	Butyl Tyre	kg	0.225	3.1300	0.70	[36]
4	Polyvinyl Chloride (PVC)	kg	1.440	2.4704	3.56	[36]
5	Manure (10 heards/yr)	kg	0.822	2.0000	1.64	[38]
6	Cement Pipe Tank Treatment Waste	kg	60.000	0.1300	7.80	[36]
7	Cement lime	kg	25.000	0.4900	12.25	[36]
8	Sand	kg	75.000	0.0037	0.28	[36]
	Total				**792.90**	

4. CONCLUSIONS

Food waste and a carbon to nitrogen ratio of 22.7% were used in the semi-continuous AD of HBP that was carried out with 2,000 kg of inoculum already present. In the end, the production of usable biogas (CH_4) reached a rate of 1.35 liters per day, which was sufficient to replace LPG as the primary fuel source for cooking in residential kitchens. Total biogas output was significant, coming in at around 4.37 liters per day, while CO_2 generation came in at about 3.15 liters per day. For the kinetic models of total biogas and methane, the rate constants and half-lives, respectively, were 0.9102 and 0.1779 day^{-1} and 3.6443 and 3.8963 days. Pseudo-first order was the notation used to specify these models. On the other hand, as a result of the difficult degradation of organic compounds in food waste, the CO_2 kinetics model was reduced to a pseudo-zero order, with a rate constant of 309.32 mL/day and a half-life duration of 10.4619 mL/day, respectively. This was done in order to account for these factors. The ultimate GWP for food waste was calculated to be 759.00 kilogram of CO_2, while the GWP for HBP was calculated to be 792.92 kg of CO_2. The fact that the use of LPG led to an increase in GWP of 0.56 kg CO_2e/day, which developed CH_4 was able to decrease, was a fascinating fact. The return of residues from the biogas storage pond's outflow residues was able to boost soil fertility while simultaneously reducing GWP by approximately 1.8552 kg CO_2e/day. This allowed for the avoidance of the need of synthetic fertilizer N-P-K. Due to the fact that synthetic materials only created 0.0245 kg CO_2e each day over the course of five years, their overall supply was minimal.

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