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ORIGINAL ARTICLE

Evaluation of biogas yield and kinetics from the anaerobic co-digestion of cow dung and horse dung: a strategy for sustainable management of livestock manure

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Abstract In this study, investigation was done to determine the optimum combination of cow dung (CD) and horse dung (HD) for enhanced biogas production and plant stability. Anaerobic co-digestion of CD and HD at varying percentage combination was carried out in five (5) identical 25 L cylindrical digesters (A–E) for a retention period of 37 days, at an average ambient temperature of 33 °C. Using the Microsoft excel solver function, 2010 version, the modified Gompertz model was applied to predict the relevant kinetic variables of the digestion process. Result obtained shows that digester D with 25% CD and 75% HD produced the highest daily biogas, followed by C (50% CD and 50% HD), B (75% CD–25% HD), A (100% CD) and E (100% HD). Digester D also had maximum biogas production potential (A) of 13.8 L/gVS, maximum biogas production rate (μ) of 0.69 L/gVS/day and shortest lag phase (λ) of 5.20 days. Digester E with 100% HD, though had a short lag phase of 5.72 days, had the least total biogas yield of 5.1 L/gVS. The closeness of the coefficients of determination (R^2) to 1 reflects a good fit, between experimental and simulated data. The study found that increase in the amount of cow dung beyond 25% led to decrease in biogas yield. It has also shown that biogas production from CD and HD is feasible and can serve as way of removing CD and HD from the environment while serving as a source of bioenergy. Further study on best ways of pre-treating the substrates for greater biogas yield is recommended.

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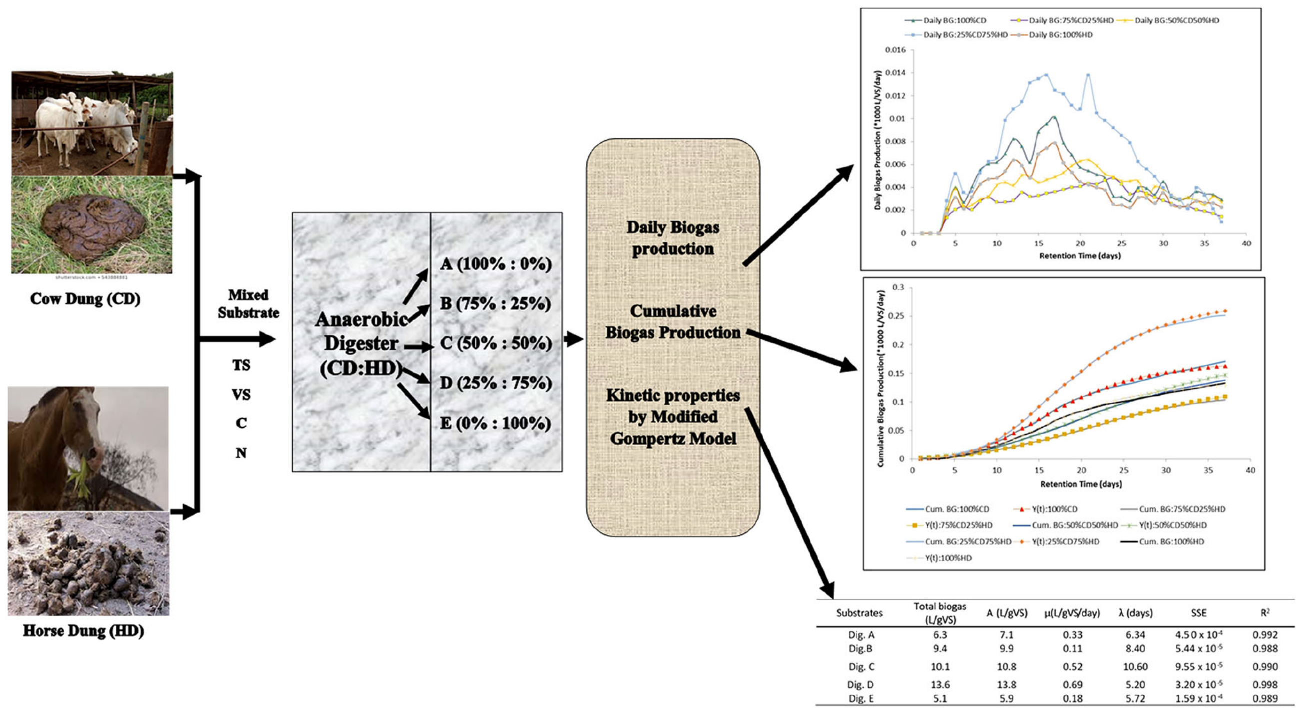
Graphic abstract



Keywords Anaerobic digestion · Modified Gompertz model · Biogas · Cow dung · Horse dung

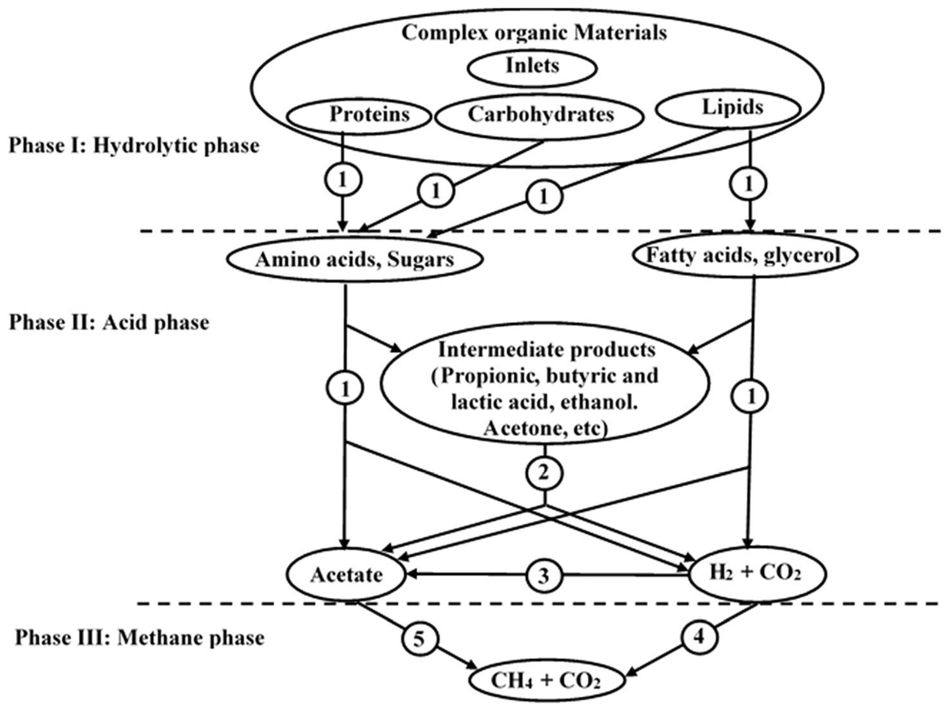
1 Introduction

The continuous increase in global population, has led to excessive demand for water, energy, and high rate of solid waste generation (Owamah et al. 2020; Owamah 2020a, b; Owamah et al. 2017). This excessive demand for energy has in turn put great pressure on conventional energy resources such as fossil fuels (Onokwai et al. 2020; Jaro et al. 2020; Reza et al. 2020; Pratiwi and Juerges 2020). Dairy production has also become an important industry in Nigeria and world-over and contributes about 7% of the aggregate agricultural production worth (Coppolecchia et al. 2015). The expansion in livestock production has resulted in the generation of huge quantity of livestock manure, which is of great environmental concern in areas such as release of greenhouse gas (GHG), contamination of surface water, etc. (Esteves et al. 2019; Veroneze et al. 2019; Valenti et al. 2017). Furthermore, much of this livestock manure comes from cattle. The demand to decrease the carbon footprint of ruminants, as they contribute the hugest amount (61%) to livestock-related GHG emissions has become commonplace (Dinuccio et al. 2013). During anaerobic digestion, while biogas for heat and power generation is produced, biofertilizer for agriculture is also obtained as the digestate (McLeod et al., 2015; Menardo and Balsari 2012). Generation of biogas takes place as microorganisms degrade organic matters into methane and carbon (IV) oxide (de Azevedo et al. 2020).

Figure 1 shows the fundamental framework for the transformation of organic matter into biogas. Though the mono-digestion of cow dung has been proven to be reasonable due to its bacteria content, as well as its degradable matters such as carbohydrate, anaerobic digestion of cow dung alone usually has low biogas yield when compared with its theoretical biogas yield, majorly due to it high lignin content (Perazzolo et al. 2016). It is therefore important to co-digest cow dung with other manure especially those not as abundant in a region as CD to balance carbon–nitrogen ratio and make the AD process more efficient.

Studies on co-digestion of substrates for biogas yield optimization abound in literature. While Zhai et al. (2015) carried out a laboratory-scale digestion to investigate the effect of pH range of 6.0–8.0 for the anaerobic digestion of cow dung and kitchen waste, Riggio et al. (2015) performed a feasibility study on the co-digestion of apple pulp, olive pomace and cow slurry with result showing that biogas production was enhanced with a mixture of 5% apple pulp, 85% cow slurry and 15% olive pomace. Batch and high volume laboratory-scale digestion of pasteurized food waste and cow dung under thermophilic condition was investigated and reported to have biogas production enhanced by 86% (Zarkadas et al. 2015).

Fig. 1 Fundamental steps for the anaerobic digestion of organic matters into biogas. (Adapted from Achinas et al. 2018)



These studies notwithstanding, only a few like Kalia and Singh (1998) investigated the co-digestion of different animal dung for optimal biogas production. Hadin et al. (2016) reported that horse manure consists of urine, feces and bedding, and has a total solid of 20% or above. Horse dung is usually seen as a problem to the environment due to its large quantity, inadequate land for spreading and lack of storage facility (Hadin et al. 2016). Horse dung could be useful for anaerobic digestion because it has a high content of total solids. Parvage et al. (2015) and Garlipp et al. (2011) stated that nutrient leaching from paddocks, storage of horse dung, enrichment of soil nutrient, bedding material are among the harmful environmental impact beclouding managing horse manure. In the work of Fischer et al. (2013), it was revealed that biogas of about 328 L_{CH4}-$kg^{-1}{}_{VS}$ could be produced when horse dung substrate undergoes digestion for up to 100 days under mesophilic plug flow reactors. Alvarez et al. (2006) co-digested llama, CD and sheep manure and noted that co-digestion was better. Lo et al. (1983) had reported that removing the coarse solids from cow dung prior to anaerobic digestion, had a very low effect on biogas yield rate.

Indeed, literature information on the anaerobic co-digestion of cow dung and horse dung for biogas yield optimization is scanty. Furthermore, the consequences of anaerobic co-digestion of different animal dung requires appropriate evaluation for effective implementation on the large scale. This current paper is therefore aimed at investigating the biogas yield and yield kinetics of CD and HD and the behaviour of the digestion process. The study used a more abundant substrate (CD) and less abundant one (HD) in order to determine the correct mix ratio for biogas yield. The modified Gompertz model was utilized for the prediction of the relevant biogas yield kinetics.

2 Methodology

2.1 Collection and preparation of substrates

Cow dung (CD) and horse dung (HD) used as substrates in this study were collected fresh and free from impurities, from Zaria, Kaduna State, Nigeria and transported to the experimental ground of Water Resources and Environmental Engineering Laboratory of the Ahmadu Bello University, Zaria. The substrates were respectively screened through a sieve of 0.5 cm × 0.5 cm mesh size and stored prior to use. Physiochemical analyses were conducted by applying the standard protocol outlined in APHA (2012).

2.2 Experimental design and anaerobic digestion

The anaerobic digestion was carried out in five (5) experimental designs conducted simultaneously using five (5) identical 25 L digesters (with gas collection system; gasholder and water jacket) labeled A–E. The design involved the variation of the substrates combinations to give 100% CD, 75% CD and 25% HD, 50% CD and 50% HD, 25% CD and 75% HD and 100% HD for digesters A-E respectively. Six (6) kg of the respective substrates combinations were mixed with water in the ratio of 1/1 (weight/volume) and respectively fed into the digesters. The slurry in each digester was allowed to occupy 75% of the digester space, thereby leaving a good height for gas production. The batch anaerobic digestion was carried out for a retention period of 37 days, after which no noticeable biogas was produced. While the details of the design of the digester and gas collection system have been previously described in Alfa et al. (2012), details on methods of gas collection and scrubbing adopted can be found in Owamah et al. (2020). The gasholders were calibrated with a rule for ease of reading the daily biogas yield at 3 pm (Alfa et al. 2013).

2.3 Feedstock characterization

Nitrate, Phosphate, Sulphate and Carbon/Nitrogen ratio of the feedstock and digestate were measured using the standard methods described in APHA (2012) and Owamah et al. (2021). Ambient and slurry temperatures were measured using 2/1 °C thermometers put in the temperature probe of each digester. The pH of the digester content was measured with a pH meter, model pHS-2S, (Shanghai Jinyke Rex, China). This was done to ascertain the influence of the feedstock on acidity/alkalinity and consequently, the metabolism of the bacteria consortium.

2.4 Modeling of the cumulative biogas production

The modified Gompertz model described by Eq. 1 was used to determine the relevant biogas production kinetics useful for scaling up to large scale production. The model had been used by many contemporary researchers to study the kinetics of biogas production (Owamah 2020a).

$$y(t) = A\exp\left\{-\exp\left[\frac{\mu_m e}{A}(\lambda - t) + 1\right]\right\} \quad (1)$$

where $y(t)$ = cumulative biogas produced (m^3) at any time (t), A = maximum biogas production potential (m^3), λ = lag phase (days), which is the minimum time taken to produce biogas, t = cumulative time for biogas production (days) and e = mathematical constant (2.718282) while μ_m = maximum specific biogas production or rate. Constants A, μ_m and λ were determined using the nonlinear regression optimization technique, through the aid the solver function of Microsoft excel tool pack, version 2010. This method has been extensively used by researchers to study cumulative biogas production as well as bacteria growth in anaerobic digestion processes (Matheri et al. 2015).

3 Results and discussions

3.1 Daily biogas production

Table 1 shows the physicochemical characteristics of the substrates and reveals that the substrates are potentially biodegradable (Hagos et al. 2017). From Table 2, there was a general increase in nitrates, sulphates and phosphates which could be attributed to a high rate of microbial activity in the system. The daily biogas production from the respective substrates combinations presented in Fig. 2 shows that the average time needed to yield biogas, increased rapidly in digester D with 25% CD and 75% HD, when compared to other digesters. It could have been as result of higher volatile and suspended solid in dig. D (Xia et al. 2012).

At the end of the 37-day retention period, it was observed that digester D with (25% CD and 75%HD) produced the highest daily biogas, followed B (75%CD and 25%HD) and by C (50% CD and 50%HD), B (75%CD and 25%HD), A (100%CD) and E (100%HD) as shown in Fig. 2. The good performance of digester D could be due to the adequate carbon to nitrogen ratio of 20:1–30:1 obtained after the substrates were mixed (Ojolo et al. 2007). The poor biogas production recorded in digester E could be attributed to higher lignin content, which could have made hydrolysis, a limiting pathway (Owamah 2020a; Owamah et al. 2020) and the C/N ratio outside the normal (Hagos et al. 2017; Ozturk 2013; Ghasimi et al. 2009). Furthermore, the time taken for the bacteria to acclimatize, though took a short time in digester E, the biogas yield was not well sustained, possibly due to acidification (Alfa et al. 2014).

3.2 Anaerobic digestion pH

The result of the slurry pH observed for the retention period is presented in Table 3. Digester D had a digestion pH range 6.30–7.01, which is within the range recommended by Wang et al. (2014) and Wellinger et al. (2013) for optimal production of biogas. It was also observed that

Table 1 Physico-chemical characteristics of the horse dung and cow dung

Type of analysis	Horse dung	Cow dung
(%) Total Solids	20.97	18.74
(%) Volatile Solids	78.34	82.65
(%) Carbon	51.45	53.43
(%) Nitrogen	1.56	1.31

Measurements were done on dry weight basis

Table 2 Physicochemical characteristics of feedstock and substrates

Substrates	Nitrates (mg/l)		Sulphates (mg/l)		Phosphates (mg/l)	
	Before digestion	After digestion	Before digestion	After digestion	Before digestion	After digestion
100%CD	2.7	3.2	7	9.2	4.8	6.6
100%HD	0.6	0.9	6.2	7.4	5.7	6.2
25%HD 75%CD	1.4	2.7	3.4	3.6	9.2	10.1
50%HD 50%CD	1.5	3.2	2.5	3.2	8.7	9.3
75%HD 25%CD	1.8	1.4	3.1	3.4	8.1	8.3

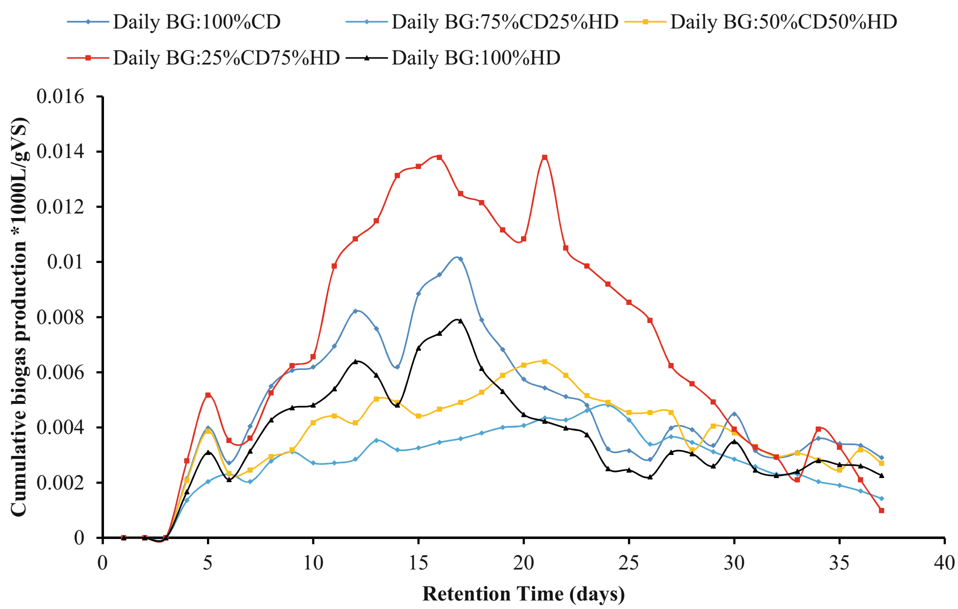


Fig. 2 Daily biogas yield from respective substrate combinations

Table 3 Slurry pH from the respective digesters

Retention Time	Dig. A	Dig. B	Dig. C	Dig. D	Dig. E
1	5.74	6.61	6.40	6.30	5.86
5	6.20	6.71	6.53	6.50	6.27
10	6.40	6.83	6.73	6.58	6.49
15	6.70	6.98	6.92	6.76	6.57
20	6.97	7.01	7.20	6.83	6.76
25	7.15	7.13	7.30	6.91	6.83
30	7.20	7.20	7.41	7.01	6.84
35	6.62	6.92	6.93	6.68	6.51

there was a general increase in pH towards alkalinity with minimal fluctuation in all the digesters. This progressive increase in pH could be the reason for the steady gas production as posited by previous studies Ahmadu et al. (2009) and Igboro et al. (2011). Ojolo et al. (2007) and Alfa et al. (2014) suggested that low pH could be a limiting factor for biogas production. Furthermore, Karki et al. (2005) opined that methanogenic bacteria are very sensitive to pH and do not thrive below a value of 6.0. Also, operating conditions such as pH value and feeding rate strongly influence methanogens (Alfa et al. 2014).

3.3 Cumulative biogas production

The result of the cumulative biogas production modelled using the modified Gompertz equation is presented in Fig. 3 and shows that digester D has the highest cumulative biogas production. This could be attributed to increase in the spectrum of microorganisms available in the digester, thus, enhancing the degradation of total organic matter during the co-digestion process (Sebastien 2014). The low biogas production recorded in digester E as reflected by Fig. 3 may be as a result of excessive accumulation of organic acids during the anaerobic digestion process (Veeken et al. 2000). Higher level of, and different type of cellulose content arising from the nature of feeds consumed by horses might also be the reason for the poor biogas yield noticed in digester E.

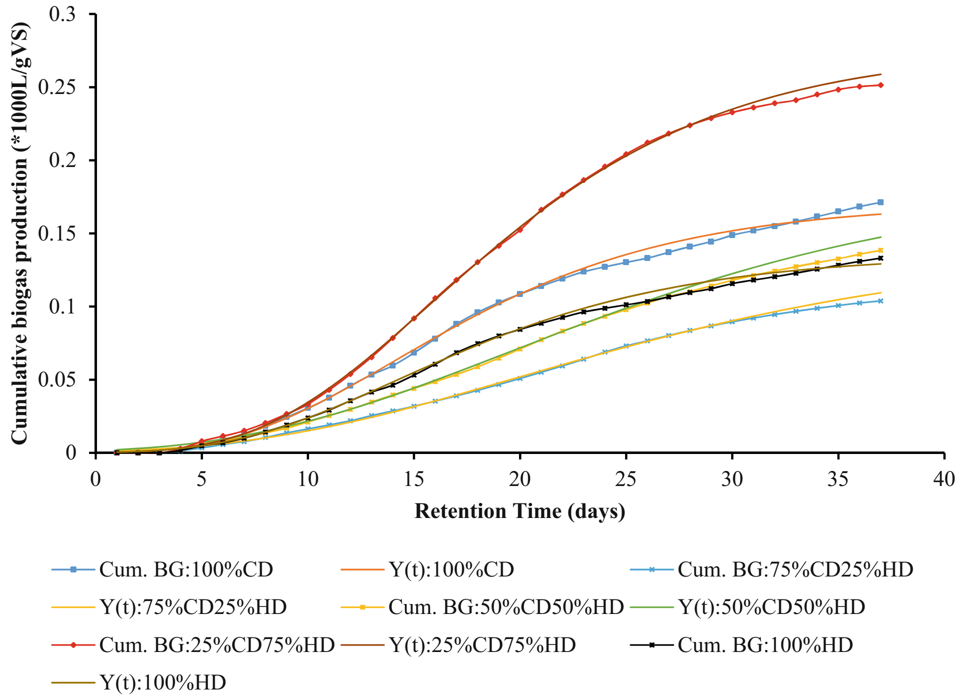


Fig. 3 Modified Gompertz model fitting of the biogas production

Table 4 Kinetic parameters obtained from the Gompertz model

Substrates	Total biogas (L/gVS)	*A* (L/gVS)	*M* (L/gVS/day)	λ (days)	SSE	R^2
Dig. A	6.3	7.1	0.33	6.34	4.50×10^{-4}	0.992
Dig.B	9.4	9.9	0.11	8.40	5.44×10^{-5}	0.988
Dig. C	10.1	10.8	0.52	10.60	9.55×10^{-5}	0.990
Dig. D	13.6	13.8	0.69	5.20	3.20×10^{-5}	0.998
Dig. E	5.1	5.9	0.18	5.72	1.59×10^{-4}	0.989

Table 4 shows that Dig. D had the highest total biogas production of 13.6 L/gVS at a maximum biogas production rate (μ) of 0.69 L/gVS/day and shortest lag phase (λ) of 5.20 days. Table 4 equally reveals that while Dig. E with 100% HD, had a short lag phase of 5.72 days, its least total biogas yield of 5.1 L/gVS shows that horse dung may be reasonably degradable but suffers easily from acidification.

Dig. C containing 50% HD and 50% CD had the longest lag phase of 10.6 days. This could be a reflection of low microbe population or inability of the microbes to quickly acclimatize to the slurry environment. It could also mean that there was an initial antagonism among the microbes in the CD and HD. Dig. B, despite producing the highest amount of biogas, had a low maximum biogas production rate (μ) of 0.11 L/gVS/day showing that the higher the CD content in digesters with mixed substrates, the slower the hydrolysis of substrate to forms, easily consumed by microbes. It could also be reflective of the lower rate of metabolism of the microbial population in Dig. B due to the high lignin content of cow dung and its fibrous nature.

Furthermore, maximum biogas production potential (A) was highest (13.8 L/gVS) in Dig. D containing 25% CD and 75% HD and lowest (5.9 L/gVS) in Dig. E containing 100% HD. The closeness of the coefficients of determination (R^2) to 1 reflects a good fit, indicating a strong relationship between the experimental and simulated data by the modified Gompertz model. Also, the latency (λ), which is the minimum expected time needed for active methanogenesis to take place, increased as the amount of cow dung increased (Iqbal et al. 2011), indicating that the presence of cow dung above the optimal level could lead to inhibition. Though it was difficult to make comparison of previous findings with those of this study, due to the lack of literature information on co-digestion of HD and CD, improved biogas yield was obtained from the mono-digestion of CD with 104.3 NmL biogas g^{-1} VS as against the co-digestion of CD and sheep manure that yielded a less biogas of 89.0 NmL biogas g^{-1} VS (Achinas et al. 2018). Also, digestion of sewage sludge with swine and poultry dung yielded 400 dm^3/kgVS of biogas with a 30%

addition of swine manure (Borowski et al. 2014). Comparison of findings from previous studies and those of this study is shown in Table 5 and reveals that values obtained are similar to those in the literature.

Table 5 Anaerobic co-digestion using various substrates: previous study versus this study

S/N	Authors/Year	Results
1	Veerappan et al. (2019)	The study looked at the co-digestion of cotton seed hull (CSH) and cow dung (CD) without pretreatment, for biogas production. The feedstock was thoroughly mixed at different proportions and digestion was carried out for 45 days at mesophilic temperature of about 35 ± 2 °C at 90 rpm. Results obtained showed that mono-digestion of CSH and CD yielded 193 ml/g VS and 33 ml/g VS, respectively. Also, the optimum biogas generation of 186 ml/g VS was obtained from the co-digestion of CSH and CD at ratio of 75:25, respectively
2	Dima et al. (2020)	A mathematical model to predict the rate of biogas generation from co-digestion of sugar beet root waste (BRW), cow dung (CD), and poultry manure (PM) was developed by the authors. The effect of process factors (C/N ratio, pH, and time of digestion) on methane yield was investigated and optimized using response surface methodology (RSM). The optimum cumulative biogas production as process response ranged 105.32–356.10 mL/g VS. Also, the optimum value 347.48 mL/g VS was estimated for CD fraction of 0.323 at C/N ratio of 26.24
3	Owamah et al. (2020)	The authors carried out a preliminary study on co-digestion of horse dung (HD) and chicken feather (CF). CF was found to have a negative effect on biogas yield as HD alone produced the maximum biogas yield of 0.36 L/gVS
4	Oladejo et al. (2020)	The research looked at co-digestion of food waste (FW), piggery dung (PD) and cow dung (CD) at equal mixing percentages, at mesophilic temperature range of 26–32 °C. Results obtained showed that maximum cumulative biogas yield of 0.0488L was got from the co-digestion of FW + PD + CD while the least biogas yield was recorded when FW was singly digested
5	Noonari et al. (2019)	The study assessed the influence of magnetite nanoparticles (Fe_3O_4NPs) on co-digestion of canola straw with dung of buffalo. Optimum biogas yield of 256.0mLCH4/gVS was obtained when 0.81 mg of Fe_3O_4NPs was added to the mixture CS and BD prior to the co-digestion
6	Pan-in et al. (2017)	In the study, experimental investigation on the generation of methane gas from various animal manure and seed corn residuals was conducted. The study showed that the rate of daily biogas production for the mixture of goat dung/husk (GH), pig dung/seed (PS), pig dung/cob (PC), goat dung/cob (GC), pig dung/husk (PH), goat dung/seed (GS), cow dung/cob (CC), cow dung/seed (CS) and cow dung/husk (CH) were 168.19, 15.65, 3.55, 2.85, 2.65, 2.50, 2.29 1.61 and 0.88 CH_4ml/gVSday, respectively
7	Awosusi et al. (2020)	The influence of anaerobic co-digestion of South African food waste (FW) with cattle manure (CM) was carried out. It was deduced that at a ratio of 3:1 for FW;CM, the peak daily biomethane generated was 4.41 kgVS/L/day after 30 days of hydraulic retention time, while no biogas was obtained from the mono-digestion of FW due to acidification
8	Wadjeam et al. (2019)	The authors used the RSM to design and optimize the production of bio-hydrogen from the co-digestion of cassava starch wastewater with buffalo dung. Results showed that peak hydrogen generation was 1787 mL H^2/L under optimal conditions
9	Khayum et al. (2018)	Investigated the co-digestion of spent tea waste (STW) with cow manure (CM). The mixture of STW and CM were 50:50, 40:60, 30:70, 20:80, and 0:100% on a mass basis for five identical digesters. The digester with 40% STW and 60% CM gave the highest cumulative methane production of 1500 ml/kg
10	Paranhos et al. (2020)	Evaluated the quantity of biogas generated from the co-digestion of rice straw (RS), coffee husk (CH), corn cob (CC), sugarcane bagasse (SB) peanut shell (PS) and sawdust. After the co-digestion, the optimum biogas production of 126.02 Nm^3 CH_4. ton $residue^{-1}$ was generated
11	Feng et al. (2020)	The authors did a feasibility study on anaerobic digestion of various substrates such as cover crop, barley straw and cattle manure. It was observed that methane gas could be generated from mono-digestion of barley straw, cover crop and cattle dung but enhanced by the co-digestion of cover crops with manure and less straw due to volatile solid reduction and nutrient balance
12	Li et al. (2018)	The paper carried out anaerobic co-digestion of apple pulp (AP) and corn stover (CS) to enhance the performance of pig manure (PM) and chicken manure (CM) in a ratio of 2:1, 4:1, 4:1 and 4:1 for CM/AP, CM/CS, PM/AP and PM/CS respectively. The result revealed that the maximum specific biogas production of 0.34 L g^{-1} VS_{added} was obtained in the co-digestion of CM/AP due to increase in buffer capacity and nutrient balance
13	This study	Investigation was done to determine the optimum combination of cow dung (CD) and horse dung (HD) for enhanced biogas yield and plant stability. Result obtained show that digester D with 25% CD and 75% HD produced the highest daily biogas, followed by C (50% CD and 50% HD), B (75% CD-25% HD), A (100% CD) and E (100% HD). Dig. D had maximum biogas production potential (A) of 13.8 L/gVS, maximum biogas production rate (μ) of 0.69 L/gVS/day and shortest lag phase (λ) of 5.20 days

4 Conclusion

The study has revealed that the anaerobic co-digestion (ACD) of cow dung (CD) and horse dung (HD) could be a viable source of biogas production for renewable energy generation. The ACD of CD and HD in the ratio 1:3, respectively, produced the highest total volume of biogas (13.6 L/gVS). The study found that increase in the amount of CD beyond 25% led to decrease in biogas yield. Experimental results corroborated well with predicted results using the modified Gompertz model. ACD of CD and HD can serve as a means of safely removing both dung from the environment while serving as source of bioenergy. Further study on best ways of pre-treating the substrates for greater biogas yield is recommended.

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Author contributions Meshach Ileanwa Alfa initiated the study, generated the data and put the results in perspectives. Meshach Ileanwa Alfa, Hilary Ijeoma Owamah and Anthony Ogochukwu Onokwai prepared and edited the manuscript. Hilary Ijeoma Owamah and Anthony Ogochukwu Onokwai handled the submission and review processes. Sudalaimuthu Gopikumar, Solomon Olakunle Oyebisi, Smita Subodh Kumar,|Somvir Bajar, Olusegun David Samuel and Samuel Chukwujindu Ilabor assisted hugely in revising the manuscript after the first review especially in the area of graphical abstract preparation in conjunction with Meshach Ileanwa Alfa. Sudalaimuthu Gopikumar, Solomon Olakunle Oyebisi, Smita Subodh Kumar, Somvir Bajar, Olusegun David Samuel and Samuel Chukwujindu Ilabor also undertook the replotting of the graphs and enriching of the result and discussion section in line with reviewers' comments. Anthony Ogochukwu Onokwai prepared the tabular comparison of result obtained in the study with those of previous studies. Hilary Ijeoma Owamah handled the correspondences and general supervision.

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Compliance with ethical standards

Conflict of interest Authors have no competing interest whatsoever.

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