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Improving Biogas Production from Chicken Droppings Using *Prosopis Juliflora* (Sw.) DC Biochar and Crushed Pods as Additives: Quantity, Composition and Kinetic Modelling

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ABSTRACT

Low biogas quantity from the mono-digestion of chicken droppings limits their use as a renewable energy feedstock. This study evaluated the effects of biochar and crushed pods of the invasive *Prosopis juliflora*, added separately at 10%, 15%, and 20% of a fixed 1,000 g chicken-droppings mass, on substrate properties, biogas production and composition, and anaerobic digestion kinetics. A completely randomized design of seven substrate groups (an unamended control and each additive at three proportions), each replicated three times, was run in twenty-one laboratory-scale batch digesters for fifty-six days. Biogas volume was measured weekly by water displacement; pH, solids and chemical oxygen demand were determined before and after digestion; and biogas composition was analysed with a Gasera One analyser. Data were analysed by two-way analysis of variance with Tukey's test, and cumulative production was fitted with First Order and Modified Gompertz models. Amended substrates produced more biogas and showed greater reductions in solids and organic load than the control, and the 15% and 20% amended treatments shifted pH towards alkaline conditions. Biochar at 15% gave the highest cumulative yield (37.2 L), followed by crushed pods at 15% (33.4 L), and compared with 14.8 L for the control. Crushed pods at 20% gave the highest methane concentration (191,870 ppm, about 19.2% by volume), and ammonia appeared only in the 15% and 20% crushed pod treatments. The Modified Gompertz model fitted better than the First Order model ($R^2 \geq 0.9987$ versus ≤ 0.9733). Both additives improved the digestion of chicken droppings while valorising an invasive species.

INTRODUCTION

Biogas is a renewable gas generated when microorganisms degrade organic matter under anaerobic conditions in closed reactors (Jameel *et al.*, 2024; Kunatsa & Xia, 2022). It consists mainly of methane and carbon dioxide, with traces of hydrogen sulphide, hydrogen, ammonia, nitrogen and water vapour, and methane usually makes up 45% to 75% of the gas depending on the substrate (Aworanti *et al.*, 2023; Kabeyi & Olanrewaju, 2022; Uddin & Wright, 2023). Rising energy demand, climate change and shortages of fossil fuels have increased interest in biogas as a renewable energy source that also manages organic waste (Ahmed & Elfaki, 2024) and reduces methane emissions from agricultural waste by 70 to 90 percent (Akingba & Agbetoye, 2025).

Despite this potential, global biogas, production is estimated at only about six percent of the world's potential (Calero *et al.*, 2023; Radosits *et al.*, 2024). In Kenya, biomass supplies roughly 68 percent of total energy demand (Ang'u *et al.*, 2023), yet biogas contributed just 0.215 GWh, or 0.00316 percent, of electricity generation in 2023 (Mudany, 2025), despite substantial unexploited potential across farm, agro-processing and municipal waste streams (Gbadeyan *et al.*, 2024; Mutahi *et al.*, 2025; Schuett, 2024).

Poultry manure is an attractive biogas feedstock because of its high organic matter content and availability

(Frankowski & Czekala, 2023), but the mono-digestion of chicken droppings gives low and slow biogas production, creating a need for suitable additives (Adams, 2024; Song *et al.*, 2023). *Prosopis juliflora* is an invasive woody species in Kenya that generates abundant, largely unutilised biomass while posing serious environmental and livelihood challenges (Eschen *et al.*, 2024; Mungoche *et al.*, 2025). Its branches can be converted to biochar and its pods offer a carbohydrate-rich lignocellulosic material, yet to the authors' knowledge, their use as additives for chicken droppings to improve biogas quantity, composition and digestion kinetics has not been adequately investigated.

This study therefore evaluated the effects of *P. juliflora* biochar and crushed pods, each added at 10%, 15% and 20% of substrate mass, on the anaerobic digestion of chicken droppings. The specific objectives were to (i) characterise the substrate mixtures before and after digestion; (ii) determine the effect of additive type and proportion on cumulative biogas production and fit First Order and Modified Gompertz kinetic models to the data; and (iii) determine the effect of additive type and proportion on biogas composition in terms of methane, carbon dioxide, nitrous oxide, ammonia and water vapour. The study asked whether either additive improves biogas yield over unamended droppings, whether the response is proportional to the amount added, and whether the

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additive that maximises gas volume also maximises methane concentration.

LITERATURE REVIEW

Anaerobic Digestion of Chicken Droppings and Its Constraints

Anaerobic digestion proceeds through four stages: hydrolysis, in which complex polymers are split into soluble monomers; acidogenesis, which yields volatile fatty acids, alcohols, hydrogen and carbon dioxide; acetogenesis, which produces acetate, hydrogen and carbon dioxide; and methanogenesis, in which methanogenic archaea form methane (Harirchi *et al.*, 2022; Kunatsa & Xia, 2022). Because these microbial groups differ in growth rate and tolerance, performance is sensitive to pH, temperature, the carbon-to-nitrogen ratio of the feed, organic loading and inhibitors such as free ammonia and hydrogen sulphide (Chen *et al.*, 2008; Ibro *et al.*, 2024). Batch tests, in which a fixed quantity of substrate is digested without further feeding, remain the standard laboratory means of comparing substrates and additives, although the source of inoculum strongly influences their outcome (Angelidaki *et al.*, 2009).

Chicken droppings are a particularly demanding substrate. They are rich in nitrogen, much of it as uric acid and protein, and have a low carbon-to-nitrogen ratio, so that microbial degradation releases substantial ammonia (Song *et al.*, 2023; Tawfik *et al.*, 2023). Free ammonia is toxic to methanogens, particularly acetoclastic species, and can cause volatile fatty acids to accumulate, methane yield to decline and, in severe cases, the process to fail (Adams, 2024; Chen *et al.*, 2008; Rajagopal *et al.*, 2013). Proposed remedies include dilution, co-digestion with carbon-rich materials and additives that buffer pH, adsorb inhibitors or stimulate microbial activity (Hakimi *et al.*, 2023; Haque *et al.*, 2024; Zhao *et al.*, 2021). Mono-digestion has been reported to yield less biomethane than co-digestion with cardboard waste (Zhao *et al.*, 2021), and co-digesting nitrogen-poor lignocellulosic wastes with manure has likewise raised biogas yield relative to mono-digestion (Al Mamun *et al.*, 2025).

Biochar and Unpyrolysed Lignocellulosic Additives

Biochar, the carbon-rich solid produced by heating biomass under limited oxygen, is among the most widely studied additives. It is porous, has a large specific surface area and is typically alkaline, properties that provide attachment sites for microbial biofilms, buffer against acidification, adsorb inhibitors such as ammonia and, in some cases, facilitate electron exchange between syntrophic bacteria and methanogens (Ambaye *et al.*, 2021; Lehmann & Joseph, 2015). Positive effects on methane production have been reported for food waste, sewage sludge and chicken manure (Ambaye *et al.*, 2021; Chaher *et al.*, 2021; Ngo *et al.*, 2024; Zhang *et al.*, 2019). The response, however, is not uniform. In a comparison of nine biochars from three feedstocks, all enhanced

methane production from sewage sludge, but the highest yield came from corn-straw biochar pyrolysed at 600°C, which also had the largest specific surface area, and excessive dosing inhibited digestion (Zhang *et al.*, 2019). The magnitude, and even the direction, of the response therefore depends on the feedstock and pyrolysis conditions of the biochar and on the dose applied.

Lignocellulosic materials added in unpyrolysed form act differently. They serve as supplementary carbon sources that raise the carbon-to-nitrogen ratio of nitrogen-rich manure and supply additional degradable organic matter (Gayathri & Uppuluri, 2022; Hakimi *et al.*, 2023), but their usefulness depends on how accessible their cellulose and hemicellulose are to microbial attack. In the studies reviewed here, pyrolysed and unpyrolysed forms of the same biomass were seldom compared within a single experiment, although such a comparison would help to separate additive-surface effects from substrate-supply effects.

Prosopis juliflora as a Source of Additives

Prosopis juliflora was introduced into East Africa for dryland rehabilitation and fuelwood but has since spread aggressively, displacing native vegetation and pasture and affecting the livelihoods of pastoral and agropastoral communities (Eschen *et al.*, 2024; Mungoche *et al.*, 2025). Its pods are produced in large quantities and, on a dry basis, contain about 26.6% cellulose, 30.9% hemicellulose, 4.7% lignin and 11.6% protein, with about 87.7% volatile matter, which qualifies them as a promising bioenergy feedstock (Gayathri & Uppuluri, 2022). Its woody branches and twigs are suitable raw material for biochar. Using the same invasive species as the source of both additives is attractive because it links invasive-species management, organic-waste treatment and renewable-energy production in a single value chain.

Kinetic Modelling of Batch Biogas Production

Kinetic modelling condenses the shape of a cumulative production curve into a few interpretable parameters. The First Order model assumes that the rate of gas production is proportional to the remaining degradable substrate and yields an ultimate production potential and a rate constant. The Modified Gompertz model, adapted from the description of bacterial growth (Zwietering *et al.*, 1990), additionally estimates a lag phase and a maximum production rate, which suits the sigmoidal cumulative curves typical of batch experiments (Kunatsa & Xia, 2022; Ulukardesler, 2023). Kinetic analysis of this kind has been applied to the co-digestion of chicken manure and sawdust (Hakimi *et al.*, 2023), to cow dung at different organic loadings (Hamzah *et al.*, 2023) and to grass and cow manure (Ulukardesler, 2023). Comparing parameters across treatments identifies which combinations shorten start-up, raise attainable yield or do both, information that is needed for digester design and operation (Galal *et al.*, 2025; Kegl *et al.*, 2025).

Knowledge Gaps

The literature shows that chicken droppings are constrained by ammonia and a low carbon-to-nitrogen ratio, and that biochar and lignocellulosic additives can each improve digestion, although the response depends on the feedstock, preparation and dose. Evidence is lacking on additives derived from *P. juliflora* for the digestion of chicken droppings, and on direct comparison of pyrolysed and unpyrolysed material from the same biomass across graded doses. The studies reviewed here also seldom combine substrate characterisation, gas quantity, gas composition and kinetic parameters within one design. The present study addresses these gaps.

MATERIALS AND METHODS

Study Area and Sample Collection

The study was conducted at the University of Eldoret, Uasin Gishu County, Kenya, with biogas composition analysis carried out at the International Centre of Insect Physiology and Ecology (ICIPE), Nairobi. Chicken droppings were collected from a purposively selected poultry farm in Kimumu Ward, Moiben Sub-County, over three consecutive mornings before routine cleaning, combined and reduced to a representative composite sample by quartering (Rizzo *et al.*, 2022), then stored

at 4°C until use. *Prosopis juliflora* branches, twigs and pods were collected from ten randomly selected trees within a 10 km radius of Marigat town, Baringo County (Kyuma *et al.*, 2018), and transported to the laboratory for processing.

Sample Preparation and Experimental Design

Chicken droppings were manually screened of foreign material and thoroughly mixed. *P. juliflora* pods were cleaned, air-dried and ground (Gayathri & Uppuluri, 2022), while biochar was produced by heating cleaned, air-dried branches and twigs under limited-oxygen conditions, followed by cooling, grinding and sieving so that both additives could be mixed evenly into the slurry. The additives therefore differed in form (pyrolysed or raw) as well as in tissue of origin. A Completely Randomized Design, which is appropriate when experimental units are homogeneous and share the same environment (Salinas Ruiz *et al.*, 2024), was used with seven treatments: an unamended control (CT) and chicken droppings amended with *P. juliflora* biochar or crushed pods at 10% (BC10, PD10), 15% (BC15, PD15) and 20% (BC20, PD20) of substrate mass (Table 1), each replicated three times to give twenty-one batch digesters (Dujany *et al.*, 2025).

Table 1: Substrate composition of the experimental treatments

Substrate	Composition	Additive proportion
CT	Chicken droppings slurry (control)	0%
BC10 / PD10	Slurry + <i>P. juliflora</i> biochar / crushed pods	10%
BC15 / PD15	Slurry + <i>P. juliflora</i> biochar / crushed pods	15%
BC20 / PD20	Slurry + <i>P. juliflora</i> biochar / crushed pods	20%

Digesters were ten-litre airtight plastic jerricans fitted with a sealed lid and gas outlet. Each received 1,000 g of chicken droppings, 100, 150 or 200 g of additive (10%, 15% or 20%) and 1.5 L of distilled water; the control received droppings and water only. Digesters were sealed, headspace was retained for gas accumulation, and units were incubated at ambient laboratory temperature away from direct sunlight for fifty-six days in batch mode: substrate was loaded once, with no feeding and no withdrawal of digestate. Because the source of inoculum strongly influences batch assays (Angelidaki *et al.*, 2009), no external inoculum was added, so that the microbial community indigenous to the droppings was the only source of microorganisms in every treatment and differences among treatments can be attributed to the additives.

Substrate Characterisation

The pH was measured before and after digestion using a calibrated HANNA HI 8314 digital pH meter (Castellano *et al.*, 2023). Percent total solids (TS) were determined gravimetrically by oven-drying at 105°C for 24 hours (American Public Health Association [APHA], 1999; Wang *et al.*, 2023), and percent volatile solids (VS) by

loss on ignition at 550°C (APHA, 2023; Harirchi *et al.*, 2022), both expressed on a fresh mass basis. Chemical oxygen demand (COD) was determined by the closed reflux titrimetric method, in which organic matter is oxidised by hot acidified potassium dichromate and the excess dichromate is titrated with ferrous ammonium sulphate (APHA, 2023). Initial values were determined before digestion and final values after the fifty-six-day incubation. Solids conversion was calculated as the difference between initial and final percentages, and COD reduction as (initial COD – final COD) / initial COD × 100.

Biogas Measurement and Composition Analysis

Biogas volume was measured every seven days by downward water displacement (Amo-Duodu *et al.*, 2023; Mkhize *et al.*, 2023), in which gas leaving the digester displaces water from a graduated vessel and the volume of water displaced is taken as the volume of gas produced. Readings were summed to obtain cumulative production over fifty-six days, and production rates were derived from the increments between successive readings. Biogas composition, comprising methane, carbon dioxide, nitrous oxide, ammonia and water vapour, was

analysed at seven-day intervals on gas from parallel five-litre digesters, which allowed compositional sampling to proceed independently of the volume measurements. A Gasera One greenhouse gas analyser at ICIPE was used; it is a photoacoustic infrared spectroscopy instrument that quantifies several gases simultaneously at parts-per-million levels (Kauppinen, 2021). Concentrations are reported in ppm, where 10,000 ppm is equivalent to 1% by volume.

Kinetic Modelling and Statistical Analysis

Data were analysed in Python. Two-way analysis of variance at the 95% confidence level was used to assess the effects of additive type and proportion, digestion stage or time, and their interaction on substrate characteristics, biogas quantity and biogas composition. Tukey's Honestly Significant Difference test (Tukey, 1949) was used for mean separation where $p \leq 0.05$, because it controls the family-wise error rate when all pairwise comparisons among treatment means are made.

Cumulative biogas production for each treatment was fitted to two models to estimate production potential, maximum production rate and lag phase. The First Order model (Equation 1) treats gas production as proportional to the degradable substrate remaining:

$$y(t) = B [1 - \exp(-kt)] \quad (1)$$

Where $y(t)$ is the cumulative biogas production (L) at time t (days), B is the ultimate biogas production potential (L) and k is the first-order rate constant (day^{-1}). The Modified Gompertz model (Equation 2) describes a sigmoidal curve that includes an initial lag phase (Zwietering *et al.*, 1990):

$$y(t) = V_m \cdot \exp\{-\exp[(k_m \cdot e / V_m)(\lambda - t) + 1]\} \quad (2)$$

Where V_m is the maximum biogas production potential (L), k_m is the maximum biogas production rate ($\text{L} \cdot \text{day}^{-1}$), λ is the lag phase (days) and e is Euler's number (2.7183). Model performance was evaluated with the coefficient of determination (R^2), the adjusted R^2 , the root mean square error (RMSE; Equation 3) and the Akaike Information Criterion (AIC) (Akaike, 1974; Lower *et al.*, 2025):

$$\text{RMSE} = \sqrt{[(1/n) \sum (y_i - \hat{y}_i)^2]} \quad (3)$$

Where n is the number of observations and y_i and $\hat{y}_i$ are the observed and predicted cumulative volumes. Lower RMSE and AIC values indicate a better fit, and AIC additionally penalises the number of parameters estimated (two for the First Order model and three for the Modified Gompertz model), so that a more flexible model is not favoured merely because it has more parameters.

RESULTS AND DISCUSSION

Physicochemical Characteristics of the Substrates

The control, BC10 and PD10 treatments showed a decrease in pH after digestion, whereas BC15, PD15, BC20 and PD20 showed an increase, with the highest final pH in BC20 and the lowest in the control ($p = 0.001$). Percent TS and VS and COD decreased in all treatments ($p = 0.0001$ for all parameters; Tables 2 to 4), with the greatest reductions in the biochar-amended substrates; the COD reduction was greatest in BC15 (54.4%) and least in the control (20.6%).

Relative to their initial values, TS fell by 16.7% in the control and by 29.4% to 46.9% in the amended substrates, and VS fell by 16.9% in the control and by 29.8% to 51.6% in the amended substrates. Initial solids rose with additive proportion (27.0% TS in the control, 41.5% in BC20), reflecting the dry matter contributed by

Table 2: Percent total solids (TS) of the substrate mixtures before and after digestion

Substrate	Initial TS (%)	Final TS (%)	TS conversion (%)
CT	27.00 ± 0.05	22.50 ± 0.05	4.50
BC10	32.80 ± 0.05	22.00 ± 0.05	10.80
PD10	32.30 ± 0.05	22.80 ± 0.05	9.50
BC15	37.20 ± 0.05	19.75 ± 0.82	17.45
PD15	35.00 ± 0.05	20.20 ± 0.05	14.80
BC20	41.50 ± 0.05	22.50 ± 0.05	19.00
PD20	38.80 ± 0.05	24.50 ± 0.05	14.30

Table 3: Percent volatile solids (VS) of the substrate mixtures before and after digestion

Substrate	Initial VS (%)	Final VS (%)	VS conversion (%)
CT	19.50 ± 0.20	16.20 ± 0.25	3.30
BC10	24.00 ± 0.35	15.50 ± 0.30	8.50
PD10	23.50 ± 0.40	16.50 ± 0.45	7.00
BC15	28.50 ± 0.30	13.80 ± 0.25	14.70
PD15	26.50 ± 0.50	15.20 ± 0.40	11.30
BC20	31.00 ± 0.50	17.50 ± 0.60	13.50
PD20	29.00 ± 0.55	18.80 ± 0.65	10.20

Table 4: Chemical oxygen demand (COD) of the substrate mixtures before and after digestion

Treatment	Initial COD (mg/L)	Final COD (mg/L)	Reduction (%)
CT	34,000 ± 200	27,000 ± 198	20.59
BC10	39,000 ± 204	24,500 ± 211	37.18
PD10	38,000 ± 200	26,000 ± 248	31.58
BC15	45,000 ± 204	20,500 ± 199	54.44
PD15	42,000 ± 206	23,500 ± 238	44.05
BC20	47,000 ± 198	26,000 ± 400	44.68
PD20	44,000 ± 234	28,500 ± 300	35.23

the additives. Even so, BC15 finished with the lowest TS (19.75%), VS (13.8%) and COD (20,500 mg/L). Absolute TS conversion was greatest in BC20 (19.00 percentage points), but the relative reduction was marginally larger in BC15 (46.9% compared with 45.8%), while VS conversion (14.70 percentage points) and COD reduction (54.44%) were greatest in BC15. For both additives, VS and COD reductions were smaller at 20% than at 15%, and PD20 retained the highest final TS (24.50%).

The contrasting pH trajectories are important because methanogens are considerably more sensitive to acidic conditions than the hydrolytic and acidogenic bacteria (Chen *et al.*, 2008; Ibro *et al.*, 2024). The decline in pH in the control, BC10 and PD10 is consistent with acid production during acidogenesis outpacing acid consumption by methanogens, whereas the rise in BC15, PD15, BC20 and PD20 suggests that the higher doses supplied enough buffering capacity to offset acidification. The highest final pH in BC20 is consistent with the alkaline character commonly attributed to biochar (Ambaye *et al.*, 2021; Lehmann & Joseph, 2015), while the rise in PD15 and PD20 indicates that biochar was not the only route to a higher pH; the detection of ammonia in these two treatments suggests that nitrogen mineralisation may have contributed. Because volatile fatty acids, alkalinity and ammonium nitrogen were not measured, this interpretation remains inferential.

The greater reductions in solids and COD in the amended substrates indicate enhanced organic matter conversion, with two caveats. First, part of the VS in biochar is thermally stabilised carbon that is unlikely to degrade within a batch test, so relative VS reductions in biochar treatments may understate conversion of the degradable fraction. Second, COD removal includes carbon assimilated into microbial biomass and carbon released by routes other than methanogenesis, so it sets an upper bound on methane-producing conversion.

Biogas Quantity and Production Rate

Cumulative biogas production increased progressively with digestion time in all treatments, most markedly between days 21 and 42. The control consistently recorded the lowest cumulative production, while amended substrates produced significantly more ($p = 0.001$). By day 56, BC15 recorded the highest cumulative volume at 37,200 mL, followed by PD15 at 33,400 mL, BC20, PD20, PD10, BC10, and CT at 14,800 mL. For both additives, the 15%

proportion outperformed the 10% and 20% proportions; at 10%, PD10 slightly exceeded BC10, but at 15% and 20%, biochar produced more biogas than the equivalent crushed-pod proportion. The production rate followed the same treatment ranking, peaking between days 21 and 28 in all treatments before gradually declining, and increased from 10% to 15% but declined at 20% for both additives ($p = 0.001$).

Expressed per kilogram of fresh chicken droppings, which each digester received at 1,000 g, the fifty-six-day yields were 37.2 L for BC15, 33.4 L for PD15 and 14.8 L for the control. BC15 therefore produced 2.5 times, and PD15 2.3 times, the volume produced by unamended droppings (increases of about 151% and 126%), and BC15 exceeded PD15 by about 11%. Averaged over the incubation, BC15 yielded about 664 mL of biogas per day compared with about 264 mL per day in the control. Yields are expressed per unit mass of fresh droppings rather than per unit of VS because the additives themselves contribute VS.

Both additives increased biogas production relative to the control, alongside greater reductions in solids and COD. Biochar likely contributed by providing surfaces for microbial attachment and supporting digester stability (Ambaye *et al.*, 2021), while the higher production associated with crushed pods may relate to their composition, since *P. juliflora* pods contain substantial cellulose and hemicellulose but comparatively little lignin (Gayathri & Uppuluri, 2022), which likely improved the accessibility of organic matter to microbes. The lower production in the control, in which pH declined, is consistent with the low yields reported for unamended chicken manure (Song *et al.*, 2023).

The rise from 10% to 15% and the decline at 20% for both additives indicate a proportion-dependent, non-linear response in which a higher dose is not necessarily better. The 15% proportion coincided with a pH shift from 7.01 to 7.18, within the range generally considered optimal for methanogenic activity, approximately 6.8 to 7.2 (Ibro *et al.*, 2024), together with substantial solids and COD reduction. At 20%, solids and COD continued to decrease, but the additional amendment did not translate into proportionally higher output, possibly reflecting an imbalance between substrate availability and microbial conversion capacity (Kawai *et al.*, 2014; Nkuna *et al.*, 2022); this remains a plausible explanation rather than a confirmed mechanism, since the food-to-microorganism ratio and microbial biomass were not measured. A similar

pattern, in which moderate biochar doses enhanced methane production while excessive doses inhibited digestion, has been reported for sewage sludge (Zhang *et al.*, 2019), although the dosing basis was not directly comparable. The relationship between organic matter removal and gas production was strong but not one-to-one: BC15 combined the largest COD reduction, the largest VS conversion and the highest yield, the control combined the smallest reductions with the lowest yield, and at 20%, and both COD reduction and gas volume were lower than at 15%. These indicators are thus useful broad proxies for digestion performance.

Kinetics of Biogas Production

Cumulative biogas production was well described by both the First Order and Modified Gompertz models (Tables 5 and 6), with larger deviations during the early stages of digestion and closer agreement in the later stages.

The Modified Gompertz model gave a consistently closer fit than the First Order model, with R^2 values of 0.9987 to 0.9995 compared with 0.9641 to 0.9733, and lower RMSE and AIC values. Mean R^2 was 0.9699 for the First Order model and 0.9993 for the Modified Gompertz model, RMSE was 4.5 to 7.7 times lower with the latter, and AIC was lower by 25.0 to 34.9 units (mean 31.6), a margin

Table 5: First Order kinetic model parameters

Treatment	B (L)	k (day ⁻¹)	R ²	Adj. R ²	RMSE	AIC
CT	44.420	0.0079	0.9733	0.9723	0.8908	128.26
BC10	56.632	0.0098	0.9721	0.9711	1.3792	136.13
BC15	111.620	0.0078	0.9691	0.9676	2.4352	146.35
BC20	88.316	0.0086	0.9690	0.9678	2.0575	143.33
PD10	44.158	0.0148	0.9706	0.9695	1.4739	137.32
PD15	100.520	0.0079	0.9711	0.9700	2.1156	143.83
PD20	50.406	0.0177	0.9641	0.9627	2.0837	143.55

Table 6: Modified Gompertz kinetic model parameters

Treatment	V _m (L)	k _m (L/d)	λ (d)	R ²	Adj. R ²	RMSE	AIC
CT	15.797	0.4609	7.26	0.9995	0.99947	0.1150	93.41
BC10	23.664	0.7157	6.99	0.9993	0.99926	0.1796	101.43
BC15	39.957	1.1768	8.06	0.9992	0.99915	0.3649	114.19
BC20	33.337	1.0207	7.52	0.9995	0.99947	0.3412	112.99
PD10	24.294	0.7867	6.33	0.9994	0.99937	0.2182	104.94
PD15	35.821	1.0601	7.54	0.9993	0.99926	0.3236	112.03
PD20	30.500	1.0641	6.49	0.9987	0.99863	0.4658	118.59

well beyond the difference of about 10 units commonly regarded as decisive support for the model with the lower value (Burnham & Anderson, 2002). The superior fit is likely owing to the capacity of the Gompertz model to capture the lag phase, exponential phase and subsequent plateau characteristic of batch digestion (Rana *et al.*, 2025; Ulukardesler, 2023).

For the First Order model, the estimated potential B ranged from 44.2 L (PD10) to 111.6 L (BC15) and the rate constant k from 0.0078 day⁻¹ (BC15) to 0.0177 day⁻¹ (PD20). The two highest-yielding substrates, BC15 and PD15, had among the lowest rate constants (0.0078 and 0.0079 day⁻¹, the same as the control's 0.0079 day⁻¹), whereas PD10 and PD20 had the largest (0.0148 and 0.0177 day⁻¹) but comparatively small potentials. The estimated B values were about three times the volumes observed after fifty-six days (44.4 L compared with 14.8 L in the control and 111.6 L compared with 37.2 L in BC15), because a first-order curve has no lag phase and approaches its asymptote slowly at such low rate constants: only about 35% to 36% of the estimated potential is reached by day 56 in CT, BC15 and PD15.

Such extrapolated potentials should therefore be treated as model-dependent rather than as true ultimate yields.

For the Modified Gompertz model, the estimated production potential ranged from 15.797 L in the control to 39.957 L in BC15, the maximum production rate from 0.4609 to 1.1768 L per day, and the lag phase from 6.33 days (PD10) to 8.06 days (BC15). The estimated potentials were within about 7% of the observed cumulative volumes for the three substrates whose final volumes are reported (15.80 L compared with 14.8 L for CT, 39.96 L compared with 37.2 L for BC15 and 35.82 L compared with 33.4 L for PD15) and ranked the treatments in the same order, which suggests that the production curves were approaching a plateau within the incubation period and supports the use of Gompertz parameters for comparing treatments (Kegl *et al.*, 2025; Zwietering *et al.*, 1990). The maximum rate in BC15 and PD15 was about 2.6 and 2.3 times that of the control. Lag phases were longer at 15% than at 10% for both additives (6.99 to 8.06 days for biochar and 6.33 to 7.54 days for pods) before shortening again at 20% (7.52 days for BC20 and 6.49 days for PD20), which may reflect a

period of microbial adaptation to the amended substrate, consistent with the influence of amendment proportion on lag phase reported by Hakimi *et al.* (2023). Loading-dependent kinetics have likewise been reported by Hamzah *et al.* (2023). The maximum rate did not follow precisely the same order as the potential: PD20 combined a high maximum rate (1.0641 L per day) and a short lag phase (6.49 days) with only a moderate potential, which may indicate rapid conversion of the readily degradable fraction of the pods without a corresponding increase in the total amount of gas produced.

Biogas Composition

Methane, carbon dioxide, nitrous oxide, water vapour and ammonia concentrations varied significantly among treatments and across digestion time ($p \leq 0.05$ for all gases), with significant treatment by time interactions for methane and carbon dioxide ($p = 0.001$). Methane concentration was highest in PD20, followed by BC20, and lowest in the control, with the highest concentrations recorded between days 49 and 56. PD20 recorded the highest overall methane concentration at 191,870 ppm (about 19.2% by volume) compared with 108,114 ppm (about 10.8%) in the control, which is about 77% higher. Biochar amended substrates, particularly BC15 and BC20, showed relatively stable carbon dioxide, nitrous oxide and water vapour concentrations across the digestion period, whereas crushed pod amended substrates, especially PD20, fluctuated more markedly. Ammonia was detected only in PD15 and PD20, and only during early digestion, and was absent from the control and all biochar treatments ($p = 0.0148$).

The ranking of substrates by methane concentration differed from their ranking by cumulative volume: BC15 gave the most gas but PD20 the highest methane concentration, so that biogas quantity and composition reflect different, only partly overlapping aspects of digester performance (Haque *et al.*, 2024). The higher methane concentrations in the amended substrates, particularly at higher pod proportions, may reflect the greater availability of cellulose and hemicellulose derived degradation products for methanogenesis (Gayathri & Uppuluri, 2022; Song *et al.*, 2023), while the role of biochar in maintaining a favourable pH and supporting microbial attachment may similarly have promoted methanogenic activity (Ambaye *et al.*, 2021). The lower methane concentration in the control mirrors the lower biomethane output reported for chicken manure mono-digestion relative to co-digestion (Zhao *et al.*, 2021). Variation in carbon dioxide likely reflects the shifting balance between its production during acidogenesis and acetogenesis and its consumption by hydrogenotrophic methanogens (Zhang *et al.*, 2014), while the stable, lower levels in the 15% biochar treatment may indicate more efficient degradation and microbial support from the biochar matrix (Chaher *et al.*, 2021). The presence of ammonia only in the 15% and 20% pod treatments is consistent with the greater supply of degradable

nitrogenous material in the pod amendments (Tawfik *et al.*, 2023), since pods contain about 11.6% protein (Gayathri & Uppuluri, 2022), and the absence of ammonia in all biochar treatments with the ammonium-retention capacity often attributed to biochar (Ngo *et al.*, 2024).

The methane concentrations reported here, at most about 19.2% by volume, are lower than the 45% to 75% range typical of biogas (Aworanti *et al.*, 2023; Uddin & Wright, 2023), and several features of the experiment may explain this. The digesters were unseeded, so that methanogenic populations had to develop from the small numbers present in fresh droppings, and solids contents of 27.0% to 41.5% place the system in the range usually described as dry or high-solids digestion, in which mass-transfer limitations and the accumulation of intermediates are more likely (Wang *et al.*, 2023). Uncontrolled ambient temperature and dilution by residual headspace air at the start of digestion may also have contributed. Absolute concentrations should therefore not be compared directly with those of optimised, seeded or continuously fed digesters; the relative differences among treatments, such as the roughly 77% higher methane concentration in PD20, are the more informative outcome.

Practical Implications and Limitations

The results point to two different value propositions. Biochar at 15% gave the greatest gas volume and the greatest reduction in organic load, which is attractive where the aim is to maximise energy output and treat more waste per digester. Crushed pods at 20% gave the highest methane concentration, which matters where gas quality affects the efficiency of stoves or engines. Pods require only collection, drying and grinding, whereas biochar requires pyrolysis with additional equipment and energy, so pods may be more accessible to smallholders. Because both additives draw on a woody invasive species abundant in the drylands of Kenya (Eschen *et al.*, 2024; Mungoche *et al.*, 2025), their use links renewable energy generation with invasive species control and organic waste management, and contributes to Sustainable Development Goals 7, 12, 13 and 15. Capturing methane that would otherwise escape from unmanaged manure also reduces greenhouse gas emissions (Akingba & Agbetoye, 2025), and digestate may be valuable as an organic fertiliser (Castellano *et al.*, 2023; Rizzo *et al.*, 2022), with biochar-amended residues previously shown to improve soil pH, organic matter and crop yield when applied to farmland (Mahmud *et al.*, 2025), although the safety of digestate containing biochar or *Prosopis* residues was not evaluated.

Several limitations qualify these findings. The experiment was conducted at laboratory scale, in batch mode and at uncontrolled ambient temperature, so the results cannot be extrapolated directly to continuously fed farm-scale digesters, and no external inoculum was used. Volatile fatty acids, alkalinity, ammonium nitrogen and microbial community composition were not monitored, so the proposed mechanisms (buffering, microbial attachment,

and additional degradable substrate and ammonia retention) are consistent with, but not demonstrated by, the data. The properties of the biochar and pods (surface area, pH, ash content and lignocellulosic composition) and methane yield per unit of VS were not determined. Biogas composition was measured in parallel digesters rather than the units used for volume measurement, and only three proportions were tested, so the true optimum may lie between or beyond them.

CONCLUSION

Amending chicken droppings with *P. juliflora* biochar and crushed pods raised pH at 15% and 20%, reduced solids and chemical oxygen demand, and increased biogas yield over the control. Biochar at 15% gave the highest cumulative yield (37.2 L), whereas crushed pods at 20% gave the highest methane concentration (191,870 ppm versus 108,114 ppm), so the greatest gas volume did not coincide with the highest methane content. The Modified Gompertz model fitted better than the First Order model ($R^2 = 0.9987\text{--}0.9995$ versus $0.9641\text{--}0.9733$). The invasive *P. juliflora* can therefore be converted into effective additives for digesting chicken droppings, although these findings apply only to laboratory batch conditions.

Recommendations. Use 15% biochar to maximise biogas volume and 20% crushed pods to maximise methane concentration. Future work should characterise the additives, monitor volatile fatty acids, ammonium and microbial communities, test an adapted inoculum in semi-continuous mode, and assess techno-economic feasibility and digestate quality at pilot scale.

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