



# From waste to energy and fertilizer: Optimizing laying hen manure valorization via anaerobic digestion and composting in Benin Republic, West Africa

Egbemimon Daniel Ahlonsou<sup>1,2</sup>, Paterne Johanès Médessè Sevalou<sup>3</sup>, F.C. Alexis Togbé<sup>1,2\*</sup>, Théodora Atchade<sup>4</sup>, Claude Kiki<sup>5</sup>, Joachim K. Dalohoun<sup>6</sup>, Jacques K. Fatombi<sup>1</sup> and M. Frédéric Houndonougbo<sup>3</sup>

<sup>1</sup>Université Nationale des Sciences, Technologies, Ingénierie et Mathématiques, Benin

<sup>2</sup>Laboratoire de Chimie Physique, Matériaux et Modélisations Moléculaires, Benin

<sup>3</sup>Faculté des Sciences Agronomiques, Université d'Abomey-Calavi, Benin

<sup>4</sup>National Institute of Agricultural Research of Benin

<sup>5</sup>Institute of Urban Environment, Chinese Academy of Sciences, China  
finagnon.togbe@unstim.bj

Available online at: [www.isca.in](http://www.isca.in), [www.isca.me](http://www.isca.me)

Received 3<sup>rd</sup> August 2025, revised 7<sup>th</sup> September 2025, accepted 13<sup>th</sup> October 2025

## Abstract

*This research assesses the potential of composting and anaerobic digestion (AD) to convert laying hen manure into valuable resources in Benin Republic, offering solutions to pressing environmental and agronomic issues. Field surveys revealed that 85% of farms use litter systems, producing 38.5 tons/month of manure, primarily managed by direct spreading (95% of farmers), leading to plant burns and ammonia emissions. Physicochemical analysis showed litter manure (LM) had higher organic matter (OM: 16.2% vs. 5.7%) and potassium (1.22% vs. 0.61%) than battery manure (BM), but both exhibited low nitrogen (<1%) and imbalanced C/N ratios (5.4 - 15.8). Composting with sawdust improved C/N (17.5) and OM (37.9%), meeting fertilizer standards. AD of LM yielded 32.6m<sup>3</sup> biogas/ton, significantly outperforming BM (3.4 m<sup>3</sup>/ton). Kinetic modeling identified the modified logistic model ( $R^2 = 0.993$ ) and first-order kinetic model ( $R^2 = 0.999$ ) as best describing biogas production, respectively for LM and BM, with LM showing biphasic degradation of complex organics. Temperature profiles confirmed efficient composting, with thermophilic phases (>55°C for 15 days) ensuring hygienization. The results underscore the promise of a dual-output system that generates renewable biogas alongside nutrient-rich compost. Optimal amendments included LM (C/N 15.8, OM 16.2%), composted BM (N 1.64%, OM 34.7%), and sawdust-amended LM compost (OM 37.9%, C/N 17.5). Digestates required further composting (N 0.07%, C/N 43.4). These findings advocate for replacing direct spreading with circular economy approaches, emphasizing scalable C/N adjustment and substrate optimization for West African contexts. Future research should pilot these methods with techno-economic analyses to facilitate adoption.*

**Keywords:** Laying hen manure, composting, anaerobic digestion, biogas, Benin, circular economy, sustainable development goals.

## Introduction

Poultry production, particularly the rearing of laying hens, generates significant quantities of manure rich in organic matter and nutrients<sup>1-3</sup>. In Benin, a country with an economy essentially based on agriculture and livestock<sup>4,5</sup>, these manures are continuously available, with a total population of 17,638,841 heads of poultry in 2023<sup>6</sup>.

However, the current management of animal waste in Benin, mainly based on direct spreading or artisanal composting<sup>7-9</sup>, could be the source of major environmental problems, such as soil pollution, greenhouse gas emissions (NH<sub>3</sub>, N<sub>2</sub>O) and plant burn due to unbalanced mineralization.

International and local regulations (FAO, EU, Beninese standards...) govern the use of organic fertilizers, requiring minimum nitrogen levels (N<sub>2</sub> ≥ 0.5%), an optimal carbon/nitrogen

(C/N) ratio (10–25) and an organic matter content (OM ≥ 20%) to ensure their agronomic effectiveness and limit environmental impacts<sup>10-15</sup>. However, raw manures or those poorly composted can present marked imbalances, highlighting the need to evaluate current practices in order to propose more efficient recovery methods. Furthermore, Benin, like many developing countries, faces an energy deficit, with limited access to renewable sources despite resources availability<sup>16,17</sup>.

The methanization (AD) of laying hen manures could offer a dual solution: producing biogas (renewable energy source) while generating stabilized or stabilizable digestates, usable as organic amendments. This approach is part of a circular economy logic, and directly support Sustainable Development Goal (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

This study thus evaluates current practices for managing hen manures, compares composting and methanization methods, and suggests ways to optimize their recovery, considering aspects related to agronomic interest and environmental, economic, and social issues in a Beninese context.

## Materials and Methods

**Surveys and sample collections:** We conducted surveys with 20 farms and 21 market gardeners in Atlantique, Benin, to assess manure management practices.

**Physicochemical characterization: Dry matter % (DM):** The dry matter content (Equation-1) was determined according to European standard EN 14774<sup>18</sup>.

$$\%DM = \frac{M_{105^{\circ}C}}{M_{sample}} \times 100 \quad (1)$$

**Total phosphorus:** For total phosphorus analysis, we employed the molybdenum blue method, where the sample undergoes acid digestion ( $HNO_3$  and  $HClO_4$ ) before spectrophotometric determination at 880 nm<sup>19</sup>.

**Potassium:** Potassium is determined using the atomic absorption spectrometry (AAS) method. After acid digestion of the sample, the digestate is injected into a spectrometer after dilution, and the potassium concentration is detected by a potassium-specific lamp<sup>20</sup>.

**Total nitrogen:** Total nitrogen is measured by the Kjeldahl method<sup>21</sup>.

**Organic matter content %OM:** Following standard protocols, organic matter content was ascertained by measuring the mass reduction after heating the samples to 550 °C (Equation-2)<sup>22</sup>.

$$\%OM = \frac{M_{105^{\circ}C} - M_{550^{\circ}C}}{M_{105^{\circ}C}} \times 100 \quad (2)$$

**Total organic carbon:** Equation-3 was used to determine carbon content<sup>23</sup>.

$$\%C = \frac{\%OM}{1.724} \quad (3)$$

Finally, the C/N ratio was determined from the N and C contents.

These parameters were determined first for raw manures and then for compost and digestive. Each parameter was determined three times, and the means were calculated.

**Compost Preparation and Monitoring:** Four compost piles were prepared on plastic tarps using either 30 kg of pure manure or 45 kg of manure-sawdust mix (2:1 w/w). Each was layered, starting with a moistened 10 kg base, followed by incremental additions. Piles were covered with breathable fabric to retain

moisture and heat. During the first two weeks, piles were turned every 72 hours, followed by watering to maintain moisture; afterward, both turning and temperature monitoring were done weekly for the remainder of the three months<sup>24</sup>. Temperature data were used to assess decomposition efficiency (Figure-1).

**Anaerobic digestion:** In four identical 500 ml plastic jerrycans (two for each type of excreta), 1:1 w/w mixtures of each type of excreta with water are made<sup>25</sup>, and these hermetically sealed cans are connected to graduated test tubes via perfusers nozzles, and filled with water to measure gas production. The amount of the mixture in the first canister is less than that in the second to study the reactor's effect on the gas production efficiency. Gas production was recorded daily (every 24 hours) by measuring the displacement of the water level in the test tubes for 91 days (Figure-1).



**Figure-1 (a&b):** Compost piles; **Figure-1 (c&d):** Anaerobic digestion sets.

**Kinetic modeling:** To control the experimental data and to determine other important parameters for accuracy, four kinetic models (Equations 4-7) were applied to the cumulative gas productions<sup>26-28</sup>.

*First-order kinetic model:*

$$P_c(t) = P_{max} (1 - e^{-at}) \quad (4)$$

*Second-order kinetic model*

$$P_c(t) = P_{max} (1 - e^{-\omega P_{max} t}) \quad (5)$$

*Modified Gompertz model*

$$P_c(t) = P_{max} \times \exp \left( -\exp \left( \frac{k \cdot e}{P_{max}} (\lambda - t) + 1 \right) \right) \quad (6)$$

Modifies Logistic

$$P_c(t) = \frac{P_{max}}{1 + \exp\left(\frac{4 \cdot k}{P_{max}}(\lambda - t) + 2\right)} \quad (7)$$

Where  $P_c(t)$ ,  $P_{max}$ ,  $\alpha$ ,  $w$ ,  $k$  and  $\lambda$  are respectively cumulative biogas yield at time  $t$  (ml/g VS), ultimate biogas yield (ml/g VS), first-order kinetic rate constant ( $\text{day}^{-1}$ ), second-order kinetic rate constant (g/ml.day), maximum biogas production rate (ml/g VS/day) and lag phase time (day)

**Static analysis tools:** We evaluated differences in physicochemical parameters using a one-way ANOVA (Python 3.12), preceded by the Shapiro-Wilk test to verify normality of residuals. For datasets violating normality assumptions, the non-parametric Kruskal-Wallis's test was applied instead. Significant results ( $p < 0.05$ ) were further analyzed with post hoc tests: Tukey's HSD following ANOVA, and the Dunn test after Kruskal-Wallis, to compare group means. Kinetic analyses were conducted in Excel, while all graphical representations were generated using Prism software (version 8.3.0).

## Results and Discussions

**Survey results:** The survey results indicate that most (85%) of farmers raise laying hens exclusively on litter system, compared to 15% who have mixed battery and litter systems (Figure-2a). This choice of system can be justified by its ease of installation and affordable cost compared to the battery system, which requires more investment.

Considering the twenty farms in the Atlantic, 38.5 bags of 50kg of manure are generated per month per farmer, i.e. an average of 1.925 tons produced. At least 5 bags, i.e. 250 kg of manure, are produced per month; this quantity can go up to 120 bags, i.e. 6 tons of manure, with a combined total production of 770 bags, representing 38.5 tons per month (Table-1). The quantity of

manure produced on the farms varies depending on the size of these farms.

Similarly, (Table-1) shows a varied but significant demand for laying hen manures by market gardeners. On average, each market gardener buys about 56 bags (2.8 tons) per month, with individual quantities ranging from 2 bags (100 kg) to 500 bags (25 tons) with a cumulative total purchase of 1175 bags, representing 58.75 tons per month.

Furthermore, 55% of breeders sell their manures directly, compared to 20% who use them as compost and 25% for direct spreading (Figure- 2b). Among market gardeners, 95.24% directly spread the manure, while only 4.76% compost them before use (Figure-3c).

All farmers and market gardeners mentioned the burning of plants and odor nuisance, while also mentioning the low-cost accessibility and rapid growth of vegetables when the dejecta are applied to the crops.

These surveys have revealed that laying hen manures are available in large quantities and continuously, and their current management remains ineffective, posing environmental problems beyond those visible. Current ways of recovering these manures, direct spreading or composting, do not explore the full transformable and beneficial potential of animal waste in general, particularly laying hen manures. This expresses the need to provide scientific data on a comprehensive and efficient way of valorizing waste for sustainable environmental sanitation.

**Physicochemical characteristics:** Table-2 present the mean values and the variation of the physicochemical parameters in the samples considered in this study.

**Table-1:** Quantity of manure produced by breeder and purchased by market gardener per month.

Farm	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Production	40	50	120	50	25	40	80	100	5	5	6	5	20	15	15	12	90	30	50	12	
Purchased	20	10	2	100	5	50	15	30	100	25	1	40	500	20	10	50	25	60	12	10	90

**Table-2:** Means of physicochemical parameters on raw manures, composts and methanization digestates

	BM	LM	CBM	CBMS	CLM	CLMS	DBM	DLM	p-value
DM%	87.242±1.696	78.396±0.919	80.287±0.423	85.826±0.596	94.22±0.401	79.434±0.072	91.538±0.134	93.068±0.107	2.35E-03
N%	0.608±0.025	0.599±0.042	1.635±0.161	0.521±0.068	0.364±0.077	1.266±0.113	0.773±0.102	0.073±0.010	1.60E-10
P %	0.054±0.004	0.064±0.001	0.06±0.003	0.062±0.009	0.072±0.013	0.042±0.005	0.071±0.033	0.06±0.009	1.33E-01
K %	0.606±0.089	1.217±0.139	0.42±0.161	0.284±0.068	0.897±0.077	0.361±0.113	0.462±0.102	0.584±0.010	1.93E-06
OM%	5.736±1.633	16.166±0.784	34.696±0.423	33.404±0.668	26.699±0.401	37.909±0.075	6.555±0.134	5.372±0.107	2.58E-03
C%	3.327±0.948	9.377±0.455	20.126±0.423	19.376±0.611	15.487±0.379	21.989±0.121	3.802±0.134	3.116±0.107	5.65E-18
C/N	5.427±1.346	15.755±1.603	12.398±0.901	37.791±4.659	44.126±7.531	17.493±1.384	5.034±0.876	43.401±5.358	8.53E-09

Dry matter varied significantly ( $p < 0.05$ ) in the 8 samples, with BM (87.2%) higher than LM (78.4%). In the composts and digestates of these manures, the DM are 80.287%, 85.826% and 91.538% respectively for BM, CBMS, and DBM; then 94.22%, 79.434% and 93.068% respectively for CLM, CLMS, and DLM (Table-2). These contents exceed a little bit the EU standards<sup>29</sup>. Although these DM contents may promote better retention of nutrients (phosphorus, potassium), humidification before spreading or mixing with the soil may be necessary before their use as fertilizer.

Organic matter (OM) enhances soil fertility by supplying nutrients, forming humus, and stimulating microbial activity<sup>30,31</sup>. OM content varied significantly among manure types ( $p < 0.05$ ). Although the volatile organic matter content of LM is almost three times that of BM (16.166 % versus 5.736 %), these contents remain low compared to international standards and well below those (69.74%) of chicken manure studied by Chen et al.<sup>32</sup>. Moreover, the difference between these values can be explained by the nature of the system; manures litter are often mixed with straw or wood shavings, which can increase the OM content, unlike battery manures, which are exclusive and liquid. Furthermore, the low OM levels in these manures can be explained by the diet of laying hens, their metabolism, their digestive types, their hydration and even the environmental conditions in which they are raised<sup>33</sup>.

These contents are enriched during the composting of manures to 34.696% and 33.404% respectively for CBM and CBMS; then 26.699% and 37.909% for CLM and CLMS. These new values are comparable to the quality standards of organic fertilizers. The observed enrichment likely results from the breakdown of complex organic compounds like lignin and cellulose, a process that releases volatile organic compounds (e.g., volatile fatty acids) and gases including ammonia.<sup>34,35</sup>

However, the OM content remains practically invariable for digestates from the methanization of manure on battery 6.555%, then drops to 5.372% for digestates from the methanization of manure on litter. This depletion may lead to the digestates being composted again.

Closely linked to organic matter, total organic carbon shows the same trend and effects, with contents of 3.327% in BM and 9.377% in LM, both below standards and levels reported in previous studies on poultry manure<sup>36,37</sup>.

The nitrogen concentration in animal manure is a critical factor in selecting a recycling method, as it directly affects the agronomic value and environmental footprint of the resulting products. Nitrogen contents in both manures are similar ( $< 1\%$ ), with 0.608% in battery and 0.599% in litter, both below international standards<sup>38,39</sup> and those reported by other researchers<sup>37,40,41</sup>.

These low concentrations are well suited for direct application on nitrogen-rich soils or in low-demand systems like permanent

grasslands and legumes<sup>42,43</sup>. The gradual mineralization of nitrogen from these dejecta lowers the risk of nitrate ( $\text{NO}_3^-$ ) leaching, making them more suitable for building soil organic matter than for providing a immediate nitrogen boost<sup>44</sup>. However, they may have a low impact on the nitrogen requirements of crops and may require additional mineral nitrogen fertilizer to meet the needs of plants. Also, these low nitrogen levels reduce ammonia ( $\text{NH}_3$ ) losses during the composting process<sup>45</sup>, limit the formation of free ammonia ( $\text{NH}_3$ ), and reduce the risk of inhibition of methanogens during methanization<sup>46</sup>.

Furthermore, C/N ratios of these raw manures are not statistically different ( $p > 0.05$ ), 5.427 and 15.755, respectively, for manures on battery and on litter.

These values are similar to those reported for chicken and chicken manures with residues by Hwang et al.,<sup>47</sup> and for chicken dung<sup>48</sup>. Regarding compliance, the C/N ratio for battery manures was non-compliant with commercial fertilizer regulations, while the ratio for litter manures was compliant.

Given their low nitrogen content and unbalanced C/N ratios, battery manures may cause fertility issues and nitrogen losses, potentially explaining burns reported by farmers. Their limited carbon content hinders stabilization, leading to ammonia or  $\text{N}_2\text{O}$  emissions during spreading or composting, and toxic  $\text{NH}_3$  buildup during methanization. In contrast, litter-based manures are more suitable for direct fertilization.

These findings show that direct manure spreading is neither agronomically nor environmentally optimal, requiring carbon-rich additives (e.g., straw, sawdust) to balance the C/N ratio. Composting battery manures increased nitrogen to 1.635%, though the C/N ratio (12.398%) showed no significant change ( $p > 0.05$ ). Still, this approach is more effective than direct use, with improved N content and a higher C/N ratio compared to some composted poultry manures reported in the literature<sup>49</sup>.

Sawdust addition significantly raised the C/N ratio to 37.79% ( $p < 0.05$ ), while nitrogen remained stable at 0.521% ( $p > 0.05$ ), potentially leading to crop nitrogen deficiency. In contrast, methanization had little effect on nitrogen (0.073%) or the C/N ratio (5.03%) ( $p > 0.05$ ). Thus, digestates need composting or co-composting to enhance nitrogen levels and balance the C/N ratio before use as fertilizer.

For litter-based manures, composting and methanization reduced nitrogen by 0.364% and 0.073%, while sharply increasing C/N ratios to over 43%, indicating a need for nitrogen supplementation before use. In contrast, sawdust addition significantly raised nitrogen by 1.266% ( $p < 0.05$ ) without altering the C/N ratio (17.493%,  $p > 0.05$ ), confirming its suitability for compost improvement.

Phosphorus levels (Table-2) are low in all samples ( $< 0.2\%$  P or  $0.5\%$   $\text{P}_2\text{O}_5$ ), slightly higher in metabolites than raw manure (p

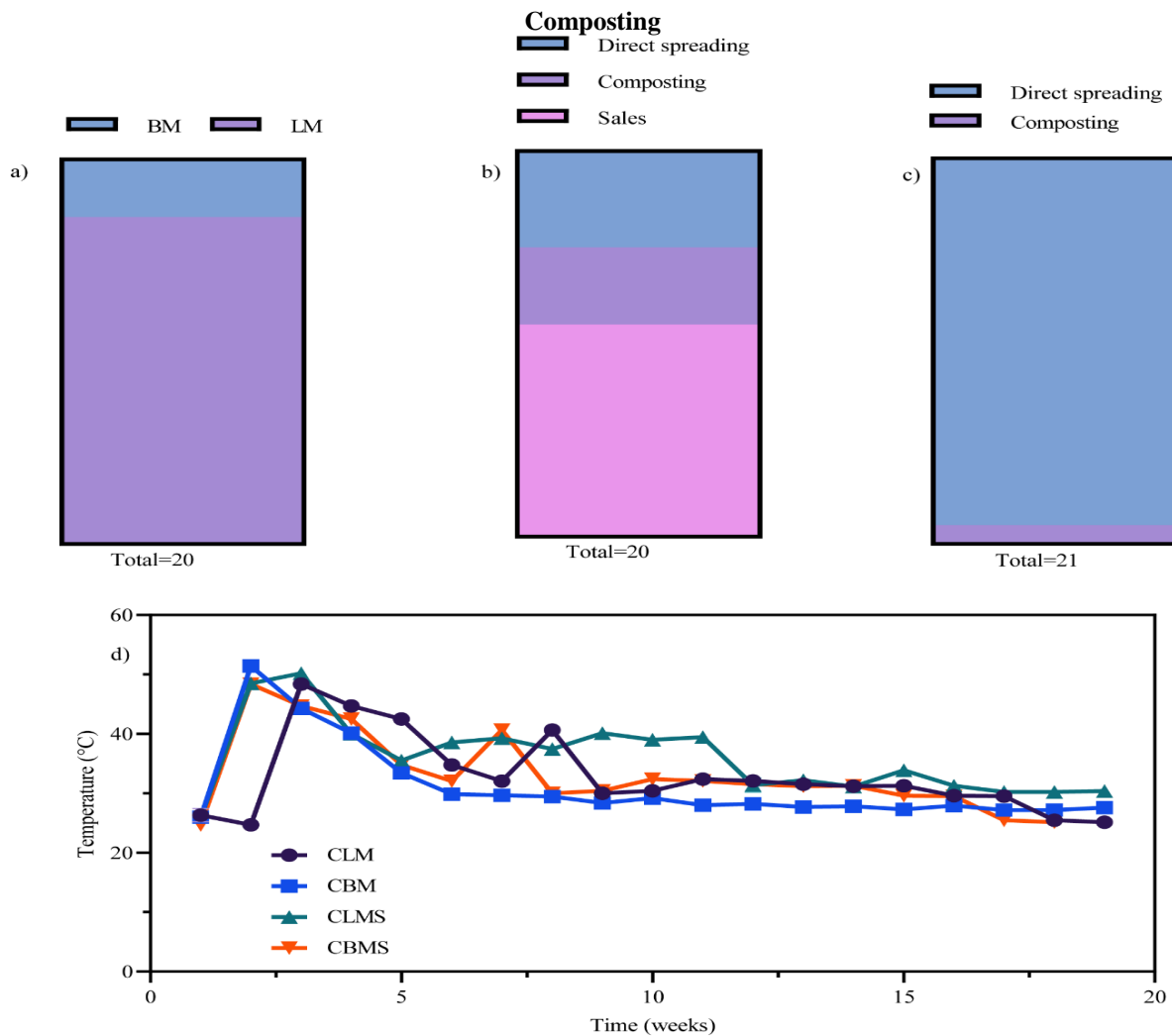
> 0.05). While supplementation with P-rich fertilizers may be needed, these amounts support key functions like root growth and stress resistance<sup>50,51</sup> without increasing leaching risks or eutrophication<sup>52</sup>.

Potassium, vital for plant growth and stress resistance, ranged from 0.284% to 1.20% (0.341% to 1.44% K<sub>2</sub>O) with significant differences between samples (p < 0.05). Litter manures contained about twice the potassium of battery manures (p < 0.05). Composting didn't affect potassium in litter manure, but sawdust addition and methanization reduced it. Potassium levels in battery manures remained stable, consistent with<sup>53</sup>. These potassium levels are adequate for crops, possibly needing minimal K<sub>2</sub>O fertilizer supplementation without risk of leaching pollution.

Composts from battery manure have lower potassium and C/N ratios but higher nitrogen and carbon than those from litter manure. Sawdust addition lowers N and C in battery manure

composts and raises their C/N ratio compared to litter composts. Digestate characteristics mirror these trends, with higher nitrogen but lower DM, potassium, and phosphorus in battery manure digestates.

Among the eight samples evaluated according to FAO/EU criteria (C/N 10-25, N≥0.5%, OM≥20%), three profiles emerged. Optimal amendments included LM (C/N 15.8, K 1.22%, OM 16.2%), CBM (N 1.64%, OM 34.7%) and CLMS (OM 37.9%, C/N 17.5), which can be directly usable. Amendments requiring correction included BM (C/N 5.4), CLMS (C/N 37.8), DBM (C/N 5.0) and CLM (C/N 44.1), requiring nitrogen-carbon rebalancing; DLM (N 0.07%, C/N 43.4) was found to be unsuitable as is and could be further composted. This differentiation highlights the critical importance of the C/N ratio and nitrogen contents for agronomic and environmental efficiency. LM, CBM and CLMS samples have the most suitable biochemical characteristics for immediate use as high-performance organic amendments.



**Figure-2:** (a) type of farming system; (b) manure management by producer; (c) manure management by market gardener; (d) composting temperatures.

Temperature changes during manure composting were monitored to evaluate compost quality (Figure-2d). The mesophilic phase (<1 week) showed average temperatures of 26.3°C (litter manure), 26°C (battery manure), 26°C (litter+sawdust), and 24.7°C (battery + sawdust) during initial composting. Within this temperature range, mesophilic microorganisms thrive, accelerating the breakdown of readily available organic compounds like simple sugars and proteins<sup>54</sup>.

The second phase, thermophilic one, did not follow the same trend in the 4 different samples.

In the litter manures, there was a temperature jump of up to 58.5°C in the first 9 days after the mesophilic phase. This temperature gradually decreased to 41°C over the following 15 days. Thus, after 24 days, microbial activity intensified, promoting the rapid decomposition of complex organic matter such as cellulose and hemicelluloses and ensuring the hygienization of the compost by eliminating pathogens<sup>55</sup>.

However, for battery dejecta, this phase lasted only nine days in total. In the first three days, the temperature jumped to 51.4°C before dropping to 40.1°C over the following six days.

This significant difference in days and even temperatures can be explained by the fact that litter manures contain more organic matter and possibly more pathogens to decompose than manures on battery. The organic matter contents of these samples confirm this fact: 5.736% and 16.166%, respectively for manures on battery and those on litter.

Furthermore, the maximum average temperature reached by CLM is much higher than that reached by CBM during this phase. This, combined with the relatively long duration (24 days vs 9) of the phase by CLM, makes this type of compost more effective for hygienization and more stable than CBM<sup>56-58</sup>.

In the case of litter manures mixed with sawdust, there was a temperature jump of up to 50.2°C in the first six days after the mesophilic phase; then, this temperature gradually decreased to 40°C three days later. The thermophilic phase, therefore, lasted nine days in total.

In the raw battery-fed manure mixed with sawdust, there was a temperature jump of up to 48.4°C in the first three days after the mesophilic phase; then, this temperature gradually decreased to 42.5°C six days later. The thermophilic phase, therefore, lasted a total of nine (9) days.

The maximum temperatures reached by the two types of dejecta maintained with sawdust remained close but slightly lower than those of the raw manures during the thermophilic phase having the same duration (9 days). The addition of sawdust, therefore, standardized the hygienization and stability of both types of dejecta.

Then the composts enter the final phase of cooling and maturation, where the temperatures gradually decrease to 30.8°C and 27.6°C, respectively for raw manures on litter and on battery, then 30.4°C and 24°C, respectively for manures on litter and on battery mixed with sawdust.

During this last phase, the gradual reduction in temperature enables mesophilic microorganisms to colonize and mature the composts, resulting in a stable product rich in humic compounds<sup>59</sup>. These results showed that battery dejecta reached maturation earlier than litter dejecta.

**Anaerobic digestion: Biogas production:** In the case of battery manure, biogas production increased rapidly to last only a few days, 5 and 6 days respectively for BM-Water 1:1 w/w 1 and 2 (Figure-3). At the end of the process, biogas production is 68.032 ml/g VS i.e. 3.404 m<sup>3</sup>/ton of raw manure or 3.90E-03 m<sup>3</sup>/kg DM for BM-Water 1:1 w/w (1), and 52.459 ml/g VS i.e. 2.625 m<sup>3</sup>/t of raw manure or 3.01E-03 m<sup>3</sup>/kg DM for BM-Water 1:1 w/w (2). These yields are negligible compared to those estimated for Chicken litter in the works<sup>15</sup>.

Although these yields seem relatively low, it is noted that reducing the substrate in the reactor has slightly improved the gas production yield, with BM-Water 1:1 w/w (1) representing 75% of the BM-Water 1:1 w/w (2) in VS or raw manures.

Concerning the manures on litter, gas production starts quite slowly and remains very low for about the first 10 days, then increases progressively without stopping throughout the process (Figure-3). At the end of the three months (91 days) considered in this study, biogas production yield from LM-Water 1:1 w/w (1) is 256.927 ml/g VS i.e. 32.562 m<sup>3</sup>/t of raw manures or 4.15E-02 m<sup>3</sup>/kg DM, whereas this yield is 147.391 ml/g VS i.e. 18.68 m<sup>3</sup>/t of raw dejecta or 2.38E-02 m<sup>3</sup>/kg DM for LM-Water 1:1 w/w (2). These yields are relatively good and even comparable to those found for the co-digestion of food waste and cow manure followed by rice straw co-digestion and poultry droppings<sup>27,60</sup>.

Similarly to battery manure, substrate reduction in the reactor considerably improved biogas yield, with LM-Water 1:1 w/w (1) being approximately 65% of LM-Water 1:1 w/w (2) in VS or raw manure. This finding implies the need to find the optimum TS rate for improved yield as it indicates that too high a TS rate can reduce digestion efficiency by limiting substrate diffusion and too low a rate can dilute nutrients, reducing microbial activity<sup>27</sup>.

On stop days (5<sup>th</sup> and 6<sup>th</sup>) of gas production by dejecta on battery, the gas yields were 3.452 ml/g VS for LM -Water 1:1 w/w (1) and 2.525 ml/g VS and 2.841 ml/g VS for LM -Water 1:1 w/w (2), respectively. These data indicate that the methanization of litter manures is energetically and economically profitable compared to that of battery manure. It

should be remembered that the amount of litter manure methanized are even lower than those of battery manure.

The difference between the yields and the gas production rate of the two types of excreta can be explained by daily biogas production (Figure-3).

Daily biogas production from both samples of battery manure reveals a single, well-pronounced peak during the first 24 hours of methanization. This indicates that battery manure, despite its low OM content, contains a significant proportion of easily degradable organic matter such as simple carbohydrates, soluble proteins, and lipids<sup>61</sup>.

On the other hand, for litter manures, the specific biogas production indicates two distinct peaks. The first peak appears

between days 19 and 21 for LM-Water 1:1 w/w (1) and day 14 for LM-Water 1:1 w/w (2). The second peak appears on days 45 and 33, respectively, for BM-Water 1:1 w/w (1) and (2). These two distinct peaks are framed by other intermittent peaks.

The appearance of the first peaks suggests the degradability of easily degradable organic compounds in these samples. The second late peak and intermittent peaks could indicate the decomposition of more complex compounds, such as fibers, lignocellulose, etc., which take longer to be degraded into simple compounds suitable for anaerobic digestion<sup>62</sup>. Fluctuations and successive peaks may indicate delayed solubilization and hydrolysis phases, where some organic fractions become accessible after a period of acid fermentation, exhibiting adaptation phenomena of microbial populations to complex substrates.

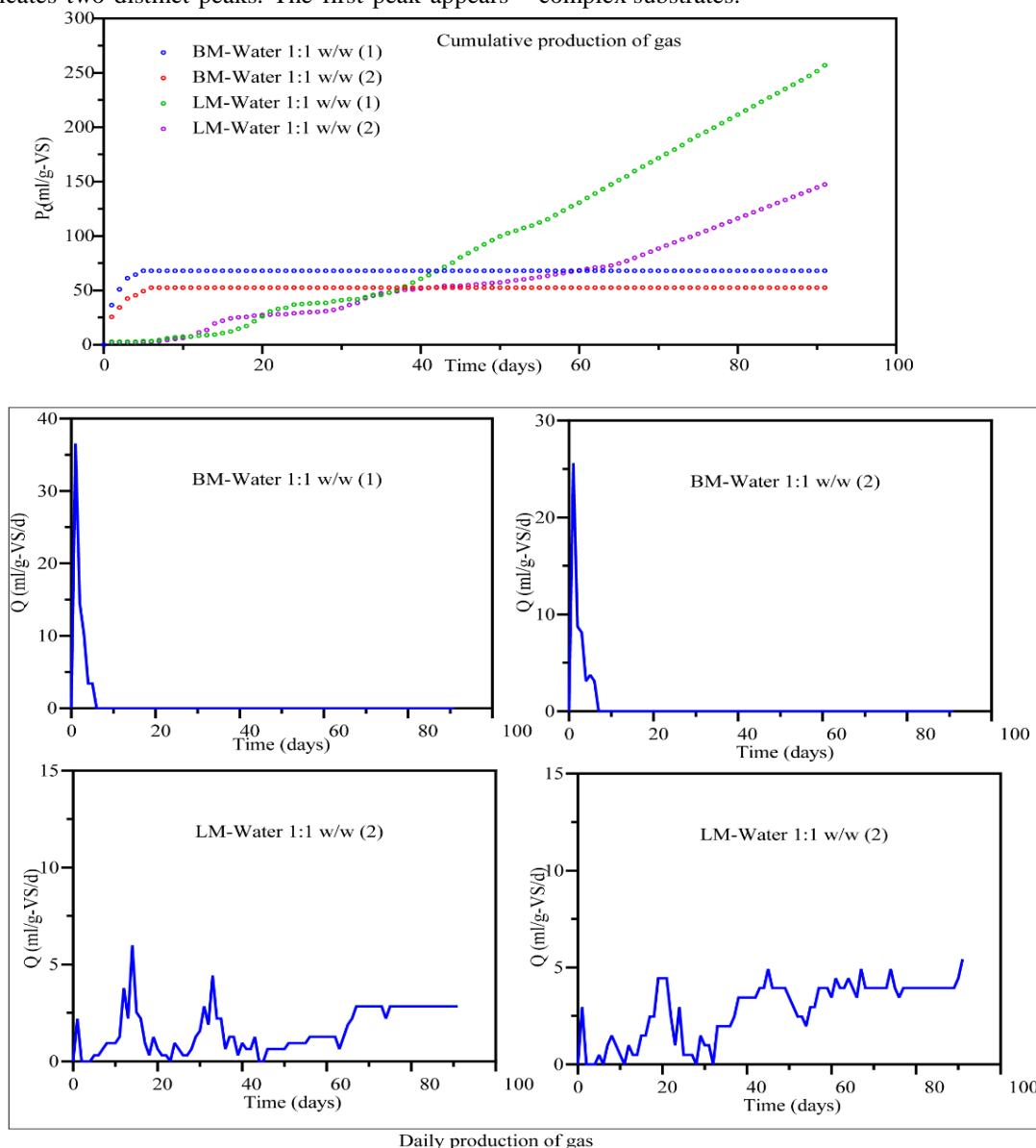


Figure-3: Cumulative & daily gas production.

**Kinetic study:** To analyze anaerobic digestion kinetics, cumulative biogas production data were evaluated using four kinetic models (Figure-4).

As shown in (Figure-4a&b), the cumulative biogas production from both battery manure systems was modeled with equivalent precision by the first-order and second-order kinetic equations, as indicated by their  $R^2$  and RMSE values). In the BM-Water 1:1 w/w systems (1), both models correlate with the same  $R^2$  0.999 and RMSE 0.281, while in the BM-Water 1:1 w/w systems (2), these coefficients are  $R^2$  0.996 and RMSE 0.425 as shown in (Table-3).

For its simplicity, the first-order kinetic model is considered to be the perfectible model for the describing the methanization of laying hens' battery manures.

In contrast, the modified logistic model provided the best fit for the methanization of litter manures, achieving an  $R^2$  of 0.993 and RMSE of 6.176 for LM-Water 1:1 w/w (1), and an  $R^2$  of 0.956 with RMSE of 8.189 for sample (2), as detailed in Table 3.(Figure-4e) reveals that all the models follow the same trends as the experimental data and all predict the same cumulative gas production exactly equal to the maximum production (68.032 ml/g VS and 52.459 ml/g VS) at the end of 91 days of methanization for battery manure. This justifies the reliability of the experimental data. However, the first-order and second-order kinetic models exhibit the greatest correlation (Table-3). As the statistical performances of the two models are equivalent, the choice of the model depends on the nature of the substrate and the biodegradation dynamics observed in the system. Given that the specific production indicates that battery manures are easily degradable, the first-order kinetic model is therefore better suited to prediction.

Similarly, all models show the same trend with experimental production for litter manures. The first-order kinetic model predicts the lowest production, 68.40% and 69.18% of the experimental production, respectively for LM-Water 1:1 w/w

(1) and (2). In addition, the Modified logistic model demonstrates the best reliable yields among all models 90.61% and 84.03% of the experimental cumulative production respectively for LM-Water 1:1 w/w (1) and (2). Also, the predictions of the Modified Gompertz are quite close to the Modified logistic, they are 86.15% and 79.64% of the experimental production, respectively, for LM-Water 1:1 w/w (1) and (2) (Table-3).

Next, the first-order kinetic model displays the kinetic constants  $0.747 \text{ day}^{-1}$  and  $0.575 \text{ day}^{-1}$  for the two samples of battery manures (Figure-4h). These constants, substantially equal to  $0.6 \text{ day}^{-1}$  justify the relative speed of biogas production by battery manures. This fact is further accentuated by the modified Gompertz and logistic models, which display the low average lag phase time equal to 0.99 day (Figure-4g) or approximately 24h, indicating the maximum biogas production in the first 24h for battery manures.

Although the lag phase time predictions by both modified models follow the same trend for litter manures, the Modified Logistic model indicates 27.511 days and 16.488 days as the times of maximum gas production for the two litter manures samples, respectively.

According to the logistic model, the maximum biogas production rates ( $k$ ) reached 4.217 and 1.802 ml/(gVS-day) for LM-Water 1:1 w/w samples (1) and (2), respectively (Figure-4f). The kinetic study shows data very close to the experimental ones. Contrary to other studies that used heated digesters, this study uses an unheated system (room temperature), which shows a comparable yield, which is promising for small Beninese farms. The yields of gas production, particularly for litter manure, encourage further exploration of the optimal conditions for the methanization of these manures as well as the characterization of the chemical composition of the biogas produced. Furthermore, battery manure may require optimal composting conditions or be co-methanized with litter manures.

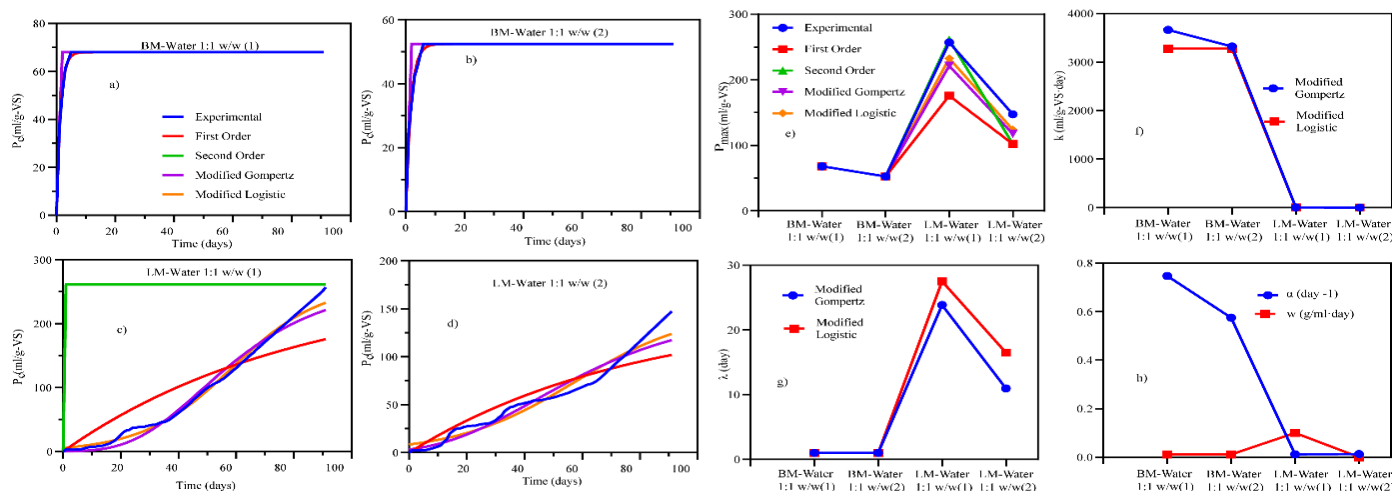


Figure-4: (a,b,c&d) cumulative gas production predicted by kinetic models; (e,f,g&h) Kinetic parameters evolution.

**Table-3:** Kinetic parameters.

Parameter	Model	BM-Water 1	BM-Water 2	LM-Water 1	LM-Water 2
$\alpha$ (day <sup>-1</sup> )	1st order	0.747	0.575	0.012	0.013
w (g/ml·day)	2nd order	0.011	0.011	0.100	0.000
k (ml/gVS·day)	Gompertz	3,664.283	3,320.110	4.002	1.672
	Logistics	3,276.864	3,276.914	4.217	1.802
$\lambda$ (day)	Gompertz	0.990	0.992	23.855	10.961
	Logistics	0.989	0.992	27.511	16.488
Pmax given (ml/gVS)	—	68.032	52.459	261.366	148.337
Pmax model (ml/gVS)	1st order	68.032	52.459	175.747	101.964
	2nd order	68.032	52.459	261.366	101.964
	Gompertz	68.032	52.459	221.353	117.386
	Logistics	68.032	52.459	232.790	123.859
Pmax experi (ml/gVS)	—	68.032	52.459	256.927	147.391
R <sup>2</sup>	1st order	0.999	0.996	0.892	0.898
	2nd order	0.999	0.996	0.017	0.898
	Gompertz	0.941	0.877	0.981	0.940
	Logistics	0.941	0.877	0.993	0.956
RMSE	1st order	0.281	0.425	34.668	14.594
	2nd order	0.281	0.425	179.808	14.594
	Gompertz	1.953	2.308	10.985	9.487
	Logistics	1.953	2.308	6.176	8.189

### Conclusion

This study reveals that laying hen manures in Benin, although available in large quantities, are undervalued, with current practices (direct spreading) generating environmental nuisances. Physicochemical analyses highlight nutritional imbalances (low N, unsuitable C/N), while composting and methanization offer promising alternatives.

Composting with the addition of sawdust produces organic amendments that comply with standards (MO > 20%, C/N = 17.5), but the methanization of manure on litter is distinguished by its high energy yield (32.6 m<sup>3</sup>/t). Kinetic models confirm the

feasibility of this method, with optimized production under controlled conditions.

This study is the first in Benin to combine physicochemical analyses, field trials and kinetic modelling (logistic model, R<sup>2</sup> = 0.993), thus providing a scientific basis for replacing direct spreading, the majority but unsustainable practice, with a dual approach (biogas + compost). This dual approach offers a scalable solution for West Africa’s circular agriculture, aligning with SDGs 7 (energy) and 13 (climate). Future research should test this approach on a pilot scale, integrating technical and economic analyses to facilitate its adoption by local stakeholders.

**Abbreviations:** AD: Anaerobic digestion, LM: Litter manures. BM battery manure, CLM Compost litter manures, CLMS Compost litter manures + Sawdust, CBM Compost battery manures, CBMS Compost battery manures +Sawdust, DLM Digestates Litter Manures, DBM Digestates Battery manures, TS Total solid, VS Volatile Solid.

## References

1. Ashworth, A., Chastain, J., & Moore Jr, P. (2020). Nutrient characteristics of poultry manure and litter. In *Animal manure: Production, characteristics, environmental concerns, and management* (pp. 63–87).
2. Hoover, N. L., Law, J. Y., Long, L. A. M., Kanwar, R. S., & Soupir, M. L. (2019). Long-term impact of poultry manure on crop yield, soil and water quality, and crop revenue. *Journal of Environmental Management*, 252, 109582. <https://doi.org/10.1016/j.jenvman.2019.109582>
3. Zoli, M., Mantovi, P., Ferrari, P., Ferrari, L., & Ferrante, V. (2023). Soil organic matter and nutrient levels in outdoor runs in organic laying farms. *Animals*, 13(3), 401. <https://doi.org/10.3390/ani13030401>
4. Gero, A. A., & Egbendewe, A. Y. (2020). Macroeconomic effects of semi-subsistence agricultural productivity growth: Evidence from Benin and extension to the WAEMU countries. *Scientific African*, 7, e00222. <https://doi.org/10.1016/j.sciaf.2020.e00222>
5. Moussa, A. (2018). Does agricultural sector contribute to the economic growth in case of Republic of Benin. *Journal of Social Economics Research*, 5(2), 85–93. <https://doi.org/10.18488/journal.35.2018.52.85.93>
6. Direction de la Statistique Agricole (DSA). (2024). \*Les chiffres définitifs de la campagne agricole 2023-2024 au Bénin\*. <https://dsa.agriculture.gouv.bj>
7. Boko, M., Dougnon, T., Bankolé, H., Dougnon, T., Ahouangninou, C., Cledjo, P., & Soumanou, M. (2015). *Poultry farming practices in South-Benin (West Africa) and impacts on the manures hygiene*.
8. Ganda, H., Zannou-Boukari, E., Kenis, M., Chrysostome, C., & Mensah, G. (2019). Potentials of animal, crop and agri-food wastes for the production of fly larvae. *Journal of Insects as Food and Feed*, 5(2), 59–68. <https://doi.org/10.3920/JIFF2018.0024>
9. Houenou, A. C. E. (2019). *Etude de l'efficacité des bokashis, du compost et de la solution de biopesticide promus par le Centre Songhaï pour améliorer la production de la laitue et de l'amarante au Sud du Bénin* [Master's thesis].
10. Brinton, W. F. (2000). *Compost quality standards and guidelines: An international view*. Woods End Research Laboratory, Inc.
11. Brondi, A. M., Daniel, J. S. P., de Castro, V. X. M., Bertoli, A. C., Garcia, J. S., & Trevisan, M. G. (2016). Quantification of humic and fulvic acids, macro-and micronutrients and C/N ratio in organic fertilizers. *Communications in Soil Science and Plant Analysis*, 47(22), 2506–2513. <https://doi.org/10.1080/00103624.2016.1253714>
12. Burtan, L., Lacatusu, A., Sîrbu, C., Cioroianu, T., Lazar, R., Lungu, M., & Lacatusu, R. (2018). Use organic fertilizers in the modern agriculture. \*Annals of the University of Craiova-Agriculture, Montanology, Cadastre Series, 47\*(1), 272–283.
13. Freyer, B., Ellssel, P., Nyakanda, F., & Saussure, S. (2024). *Exploring the off-farm production, marketing and use of organic and biofertilisers in Africa: A scoping study*. Report to the European Commission. DeSIRA-LIFT European Union.
14. Möller, K., & Schultheiß, U. (2015). Chemical characterization of commercial organic fertilizers. *Archives of Agronomy and Soil Science*, 61(7), 989–1012. <https://doi.org/10.1080/03650340.2014.993330>
15. Ngabala, F. J., & Emmanuel, J. K. (2024). Potential substrates for biogas production through anaerobic digestion—an alternative energy source. *Heliyon*, 10(23). <https://doi.org/10.1016/j.heliyon.2024.e34118>
16. Akpahou, R., Mensah, L. D., & Quansah, D. A. (2023). Renewable energy in Benin: Current situation and future prospects. *Clean Energy*, 7(5), 952–961. <https://doi.org/10.1093/ce/zkad050>
17. Mensah, J. H. R., dos Santos, I. F. S., & Tiago Filho, G. L. (2023). A critical analysis of the energy situation in the Benin Republic and its evolution over the last decade. *Renewable Energy*, 202, 634–650. <https://doi.org/10.1016/j.renene.2022.11.108>
18. Trancoso, M., Sousa, A. R., & Calisto, S. (2015). Procedure validation and laboratory performance monitoring for the measurement of moisture, ash and volatile matter mass fractions in solid biofuels. *Accreditation and Quality Assurance*, 20(2), 131–137. <https://doi.org/10.1007/s00769-015-1116-5>
19. Allen, S. E. (Ed.). (1989). *Chemical analysis of ecological materials*. Blackwell Scientific Publications.
20. Kalra, Y. (1997). *Handbook of reference methods for plant analysis*. CRC Press.
21. Bremner, J. M., & Mulvaney, C. (1982). Nitrogen—Total. In A. L. Page (Ed.), *Methods of soil analysis: Part 2 chemical and microbiological properties* (pp. 595–624). American Society of Agronomy.
22. Nelson, D. W., & Sommers, L. E. (1996). Total carbon, organic carbon, and organic matter. In D. L. Sparks

- (Ed.), *Methods of soil analysis: Part 3 chemical methods* (pp. 961–1010). Soil Science Society of America.
23. Larney, F. J., Ellert, B. H., & Olson, A. F. (2005). Carbon, ash and organic matter relationships for feedlot manures and composts. *Canadian Journal of Soil Science*, 85(2), 261–264. <https://doi.org/10.4141/S04-015>
  24. Sun, S., Guo, C., Wang, J., Ren, L., Qu, J., Guan, Q., Dou, N., Zhang, J., Chen, Q., & Wang, Q. (2024). Effect of initial moisture content, resulting from different ratios of vegetable waste to maize straw, on compost was mediated by composting temperatures and microbial communities at low temperatures. *Chemosphere*, 357, 141808. <https://doi.org/10.1016/j.chemosphere.2024.141808>
  25. Pandia, S., Tanata, S., Rachel, M., Octiva, C., & Sialagan, N. (2018). Effect of fermentation time of mixture of solid and liquid wastes from tapioca industry to percentage reduction of TSS (Total Suspended Solids). *IOP Conference Series: Materials Science and Engineering*, 309(1), 012086. <https://doi.org/10.1088/1757-899X/309/1/012086>
  26. Alkhrissat, T., & Matarneh, S. (2025). Impact of anaerobic co-digestion of ryegrass (RG) and cow manure (CM) on methane production and kinetic analysis. *Results in Engineering*, 24, 104028. <https://doi.org/10.1016/j.rineng.2024.104028>
  27. Mohammadianroshanfekr, M., Pazoki, M., Pejman, M. B., Ghasemzadeh, R., & Pazoki, A. (2024). Kinetic modeling and optimization of biogas production from food waste and cow manure co-digestion. *Results in Engineering*, 24, 103477. <https://doi.org/10.1016/j.rineng.2024.103477>
  28. Pramanik, S. K., Suja, F. B., Porhemmat, M., & Pramanik, B. K. (2019). Performance and kinetic model of a single-stage anaerobic digestion system operated at different successive operating stages for the treatment of food waste. *Processes*, 7(9), 600. <https://doi.org/10.3390/pr7090600>
  29. Romadhon, M. R., Mujiyo, M., Suntoro, S., Dewi, W. S., Syamsiyah, J., Rahayu, R., Widijanto, H., Herdiansyah, G., Herawati, A., & Anggita, A. (2023). Assessing the quality of organic fertilizer products made from cow dung in Wonogiri Regency, Indonesia. *Agroindustrial Journal*, 10(2), 65–74.
  30. Maffia, A., Marra, F., Canino, F., Battaglia, S., Mallamaci, C., Oliva, M., & Muscolo, A. (2024). Humic substances from waste-based fertilizers for improved soil fertility. *Agronomy*, 14(11), 2657. <https://doi.org/10.3390/agronomy14112657>
  31. Piccolo, A., & Drosos, M. (2025). The essential role of humified organic matter in preserving soil health. *Chemical and Biological Technologies in Agriculture*, 12(1), 21. <https://doi.org/10.1186/s40538-025-00641-2>
  32. Chen, H., Awasthi, S. K., Liu, T., Duan, Y., Ren, X., Zhang, Z., Pandey, A., & Awasthi, M. K. (2020). Effects of microbial culture and chicken manure biochar on compost maturity and greenhouse gas emissions during chicken manure composting. *Journal of Hazardous Materials*, 389, 121908. <https://doi.org/10.1016/j.jhazmat.2019.121908>
  33. Seppänen, M. (2024). *Carbon and nitrogen losses from laying hens' manure in manure management chains* [Doctoral dissertation].
  34. Martinez-Alonso, C., Díaz-Cruz, E. B., Becerra-Paniagua, D. K., & Baray-Calderón, A. (2023). Biotechnological formation of biogas. In *Biotechnology in the generation of biofuels* (pp. 27–47). Springer. [https://doi.org/10.1007/978-3-031-36542-3\\_2](https://doi.org/10.1007/978-3-031-36542-3_2)
  35. Noor, R. S., Shah, A. N., Tahir, M. B., Umair, M., Nawaz, M., Ali, A., Ercisli, S., Abdelsalam, N. R., Ali, H. M., & Yang, S. H. (2024). Recent trends and advances in additive-mediated composting technology for agricultural waste resources: A comprehensive review. *ACS Omega*, 9(8), 8632–8653. <https://doi.org/10.1021/acsomega.3c07312>
  36. Adekiya, A. O., Ejue, W. S., Olayanju, A., Dunsin, O., Aboyeji, C. M., Aremu, C., Adegbite, K., & Akinpelu, O. (2020). Different organic manure sources and NPK fertilizer on soil chemical properties, growth, yield and quality of okra. *Scientific Reports*, 10(1), 16083. <https://doi.org/10.1038/s41598-020-73291-x>
  37. Rech, I., Kamogawa, M. Y., Jones, D. L., & Pavinato, P. S. (2020). Synthesis and characterization of struvite derived from poultry manure as a mineral fertilizer. *Journal of Environmental Management*, 272, 111072. <https://doi.org/10.1016/j.jenvman.2020.111072>
  38. European Parliament and Council of the European Union. (2019). \*Regulation (EU) 2019/1009 of the European Parliament and of the Council of 5 June 2019 laying down rules on the making available on the market of EU fertilising products and amending Regulations (EC) No 1069/2009 and (EC) No 1107/2009 and repealing Regulation (EC) No 2003/2003\*. <https://eur-lex.europa.eu/eli/reg/2019/1009/oj>
  39. Jin, S., Tang, J., Yang, X., Yu, T., Li, Y., & Ma, L. (2021). European Union organic fertilizer product standards, management mechanisms, and its enlightenment. \*Chinese Journal of Eco-Agriculture, 29\*(7), 1236–1242.
  40. Agbede, T. M., & Oyewumi, A. (2022). Benefits of biochar, poultry manure and biochar–poultry manure for improvement of soil properties and sweet potato productivity in degraded tropical agricultural soils. *Resources, Environment and Sustainability*, 7, 100051. <https://doi.org/10.1016/j.resenv.2022.100051>
  41. Mulyani, O., Machfud, Y., Setiawan, A., & Joy, B. (2019). Potential of local organic matters in Jatiningor West Java Indonesia as raw materials for organic fertilizer. *IOP*

- Conference Series: Earth and Environmental Science, 393(1), 012048. <https://doi.org/10.1088/1755-1315/393/1/012048>
42. Malisch, C., Finn, J., Eriksen, J., Loges, R., Brophy, C., & Huguenin-Elie, O. (2024). The importance of multi-species grassland leys to enhance ecosystem services in crop rotations. *Grass and Forage Science*, 79(2), 120–134. <https://doi.org/10.1111/gfs.12656>
43. Schuster, J., Mittermayer, M., Mairl, F.-X., Näscher, L., & Hülsbergen, K.-J. (2023). Spatial variability of soil properties, nitrogen balance and nitrate leaching using digital methods on heterogeneous arable fields in Southern Germany. *Precision Agriculture*, 24(2), 647–676. <https://doi.org/10.1007/s11119-022-09966-4>
44. Priya, E., Sarkar, S., & Maji, P. K. (2024). A review on slow-release fertilizer: Nutrient release mechanism and agricultural sustainability. *Journal of Environmental Chemical Engineering*, 113211. <https://doi.org/10.1016/j.jece.2024.113211>
45. Mo, J., Xin, L., Zhao, C., Qin, Y., Nan, Q., Mei, Q., & Wu, W. (2023). Reducing nitrogen loss during kitchen waste composting using a bioaugmented mechanical process with low pH and enhanced ammonia assimilation. *Bioresource Technology*, 372, 128664. <https://doi.org/10.1016/j.biortech.2023.128664>
46. Kaur, G., Basak, N., & Kumar, S. (2024). State-of-the-art techniques to enhance biomethane/biogas production in thermophilic anaerobic digestion. *Process Safety and Environmental Protection*, 187, 1498–1518. <https://doi.org/10.1016/j.psep.2024.05.037>
47. Hwang, H. Y., Kim, S. H., Kim, M. S., Park, S. J., & Lee, C. H. (2020). Co-composting of chicken manure with organic wastes: Characterization of gases emissions and compost quality. *Applied Biological Chemistry*, 63(1), 1–10. <https://doi.org/10.1186/s13765-020-00542-w>
48. Matheri, A., Ndiweni, S., Belaid, M., Muzenda, E., & Hubert, R. (2017). Optimising biogas production from anaerobic co-digestion of chicken manure and organic fraction of municipal solid waste. *Renewable and Sustainable Energy Reviews*, 80, 756–764. <https://doi.org/10.1016/j.rser.2017.05.068>
49. Rothé, M., Darnaudery, M., & Thuriès, L. (2019). Organic fertilizers, green manures and mixtures of the two revealed their potential as substitutes for inorganic fertilizers used in pineapple cropping. *Scientia Horticulturae*, 257, 108691. <https://doi.org/10.1016/j.scienta.2019.108691>
50. Fathi, A., & Afra, J. M. (2023). Plant growth and development in relation to phosphorus: A review. *Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture*, 80\*(1), 1–7. <https://doi.org/10.15835/buasvmcn-agr:2022.0027>
51. Khan, F., Siddique, A. B., Shabala, S., Zhou, M., & Zhao, C. (2023). Phosphorus plays key roles in regulating plants' physiological responses to abiotic stresses. *Plants*, 12(15), 2861. <https://doi.org/10.3390/plants12152861>
52. Akinawo, S. O. (2023). Eutrophication: Causes, consequences, physical, chemical and biological techniques for mitigation strategies. *Environmental Challenges*, 12, 100733. <https://doi.org/10.1016/j.envc.2023.100733>
53. Bargougui, L., Guergueb, Z., Chaieb, M., & Mekki, A. (2020). Co-composting of olive industry wastes with poultry manure and evaluation of the obtained compost maturity. *Waste and Biomass Valorization*, 11, 6235–6247. <https://doi.org/10.1007/s12649-019-00879-4>
54. Finore, I., Feola, A., Russo, L., Cattaneo, A., Di Donato, P., Nicolaus, B., Poli, A., & Romano, I. (2023). Thermophilic bacteria and their thermozymes in composting processes: A review. *Chemical and Biological Technologies in Agriculture*, 10(1), 7. <https://doi.org/10.1186/s40538-023-00381-z>
55. Aboutayeb, R., Fijahi, S., Hssaini, L., & Azim, K. (2024). Quality assessment of poultry manure compost: Focus on organic amendment and bioremediation roles toward sustainable agriculture. *Euro-Mediterranean Journal for Environmental Integration*. <https://doi.org/10.1007/s41207-024-00523-1>
56. Manga, M., Muoghalu, C. C., & Acheng, P. O. (2023). Inactivation of faecal pathogens during faecal sludge composting: A systematic review. *Environmental Technology Reviews*, 12(1), 150–174. <https://doi.org/10.1080/21622515.2023.2238824>
57. Rizwan, H. M., Naveed, M., Sajid, M. S., Nazish, N., Younus, M., Raza, M., Maqbool, M., Khalil, M. H., Fouad, D., Ataya, F. S., & Alharbi, S. A. (2024). Enhancing agricultural sustainability through optimization of the slaughterhouse sludge compost for elimination of parasites and coliforms. *Scientific Reports*, 14(1), 23953. <https://doi.org/10.1038/s41598-024-75072-4>
58. Sharma, D., Saadi, I., Oazana, S., Lati, R., & Laor, Y. (2024). Distribution of residence time in rotary-drum composting and implications for hygienization. *Waste Management*, 179, 22–31. <https://doi.org/10.1016/j.wasman.2024.04.038>
59. Luo, C., Li, S., Ren, P., Yan, F., Wang, L., Guo, B., Zhao, Y., Yang, Y., Sun, J., & Gao, P. (2024). Enhancing the carbon content of coal gangue for composting through sludge amendment: A feasibility study. *Environmental Pollution*, 348, 123439. <https://doi.org/10.1016/j.envpol.2024.123439>
60. Saha, C. K., Nime, J., Khatun, M. L., Sharna, T. H., & Alam, M. M. (2025). Rice straw co-digestion potential with cow dung and poultry droppings for maximizing biogas production in Bangladesh. *Helicon*, 11(3).

61. Wang, K., Yun, S., Xing, T., Li, B., Abbas, Y., & Liu, X. (2021). Binary and ternary trace elements to enhance anaerobic digestion of cattle manure: Focusing on kinetic models for biogas production and digestate utilization. *Bioresource Technology*, 323, 124571. <https://doi.org/10.1016/j.biortech.2020.124571>
62. Qu, Y., Lv, X., Qin, N., Zhang, K., Ding, X., Luo, L., Qu, J., & Sun, Y. (2024). Mechanism of ball milling pretreatment to improve the anaerobic digestion performance and energy conversion efficiency of corn straw. *Fuel*, 366, 131409. <https://doi.org/10.1016/j.fuel.2024.131409>