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A Meta-Analysis of Biogas and Electrical Energy Production in Beef Cattle and Dairy Cow Farms

Muhammad Askari Zakariah[1*], Failal Ulfi Mauliah[2]

[1] Department of Animal Science, Universitas Sains Islam Al Mawaddah Warrahmah Kolaka, Kolaka 93511, Indonesia
[2] Department of Health, Universitas Sains Islam Al Mawaddah Warrahmah Kolaka, Kolaka 93511, Indonesia

Corresponding Author Email: askari@usimar.ac.id

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ABSTRACT

Biogas, derived from anaerobic digestion of organic waste, plays a crucial role in renewable energy generation and waste management. This meta-analysis aimed to compare biogas and electrical energy production between beef cattle farms and dairy cow farms by synthesizing data from 19 relevant articles. Hedges's effect size and t-tests were chosen to provide a robust measure of the magnitude and significance of differences in biogas production between the two types of farms. The statistical computations, including standard error of the mean (SEM) and p-value determination, were conducted using Microsoft Excel 2016. The results showed that the Hedges' effect size (d) of -1.79941 for Methane Production (m^3/day) indicates a significant difference in methane production between beef cattle farms and dairy cow farms. For electrical energy production (MWh/day), the effect size (d) of -14.645 also reflects a substantial difference between the studied conditions. These findings suggest that methane production is higher on dairy cow farms compared to beef cattle farms, likely due to variations in management practices, such as feeding methods, livestock waste management, and animal health. The implications of these results are significant for optimizing energy production and improving farm management practices.

1. INTRODUCTION

Biogas is one of the renewable energy sources gaining increasing attention due to its potential to reduce dependence on fossil fuels and simultaneously manage organic waste. The production of biogas involves the decomposition of organic matter by microorganisms under anaerobic conditions. In agriculture, both the beef cattle and the dairy cow farms serve as significant providers of raw materials for biogas production. The anaerobic digestion process, in which various microorganisms decompose organic matter through different metabolic pathways, has been known since ancient times and has been widely used in domestic households to provide heat and power for hundreds of years. Today, the biogas sector is rapidly expanding, with new advancements establishing biogas plants as advanced bioenergy factories [1].

Temperature is one of the critical parameters influencing the efficiency of anaerobic digestion. For instance, temperatures above 25℃ are more conducive to high biogas production efficiency [2], while fluctuations can significantly impact production rates. pH is another key factor, as most anaerobic bacteria, including methane-forming bacteria, function optimally at a pH of 6.8 to 7.6 [3, 4]. Additionally, volatile fatty acids (VFAs) are intermediates in the methane formation pathway and play a critical role in biogas productivity [5, 6].

Operational parameters such as temperature, pH, VFAs, and the quality of the feedstock—like its chemical composition and digester load—are essential for enhancing biogas production [1, 7, 8]. Given that beef cattle and dairy cow farms produce significant amounts of organic waste, these farms are crucial to the biogas industry. However, the efficiency and output of biogas production can vary significantly depending on the specific characteristics of the waste material, which differ notably between beef cattle and dairy cows.

Recent studies have significantly advanced our understanding of biogas production in livestock farming. This advancement is particularly notable through the optimization of feedstocks and the enhancement of anaerobic digestion processes. A pivotal study by Gemechu [9] highlighted the critical influence of feedstock variability on biogas yields in beef cattle farms, emphasizing that the chemical composition of manure, particularly the carbon-to-nitrogen (C:N) ratio, is essential for optimizing methane production efficiency. This finding is corroborated by Ahlberg-Eliasson et al. [10], who examined dairy cow manure in anaerobic digesters and identified that maintaining stable operational conditions, such as digester loading rates and temperature, is crucial for maximizing biogas output. These insights collectively underscore the necessity of tailored management strategies that consider farm-specific conditions to enhance biogas production.

In addition to feedstock optimization, the integration of co-digestion strategies has emerged as a promising approach to further increase biogas yields. Rusanowska et al. [11]

demonstrated that co-digesting dairy cow manure with crop residues significantly boosts methane production, attributed to the balanced nutrient composition of the combined feedstocks. This aligns with the growing trend of diversifying feedstocks to improve the sustainability and efficiency of biogas plants, as evidenced by the findings of Ahlberg-Eliasson et al. [10], who noted that different forage types and manure origins can affect methane yield and microbial community structure. Such co-digestion practices not only enhance biogas production but also contribute to more sustainable waste management practices on farms.

Meta-analyses have also played a crucial role in elucidating the comparative potential of biogas production from different livestock species. A comprehensive review by Meegoda et al. [12] compared the anaerobic digestion of manure from various livestock species, including beef cattle and dairy cows, revealing that while beef cattle manure is generally higher in fiber content, dairy cow manure tends to yield more biogas due to its higher nitrogen content. This comparative analysis is vital for understanding the inherent differences in biogas production potential between these two types of livestock farming, thereby informing better management practices.

Emerging technologies, such as pre-treatment processes and microbial inoculation, have also been investigated to enhance biogas production. Wawrzyniak et al. [13] found that thermal pre-treatment of dairy cow manure can significantly improve biogas yield by effectively breaking down complex organic matter. Similarly, Mazurkiewicz [14] explored the introduction of specific microbial consortia in beef cattle farms, which accelerated the breakdown of fibrous materials, resulting in shorter digestion times and increased methane production. These technological advancements present new avenues for optimizing biogas production, making it more efficient and economically viable.

Despite these advancements, there remains a notable gap in the comparative analysis of biogas production between beef cattle and dairy cow farms, particularly in synthesizing findings from multiple studies. This study aims to bridge this gap through a meta-analysis that compares biogas production across these two farming systems. By integrating data from 19 relevant articles, this research will provide a comprehensive understanding of the factors influencing biogas quality and yield in both contexts. Such insights are crucial for stakeholders in the livestock and renewable energy sectors, as they contribute to the development of strategies and policies that optimize biogas feedstocks, ultimately promoting more efficient energy production and improved farm management practices.

In conclusion, the ongoing research into biogas production in livestock farming highlights the importance of feedstock optimization, co-digestion strategies, and technological innovations. By addressing the comparative aspects of biogas production between beef cattle and dairy cow farms, this meta-analysis will offer valuable insights that can enhance the sustainability and efficiency of biogas systems, thereby supporting the transition towards more renewable energy sources in agriculture.

2. MATERIAL AND METHODS

2.1 Literature search and selection method

Literature search was conducted through a literature database, i.e. Google Scholar, Scopus, and ScienceDirect in June 2024. The following keywords were used in the search: "biogas," "biogas production," "biogas beef cattle farm," and "biogas dairy cow farm." Further, the following criteria were used for literature selection:

- Published in English or Indonesia as full-text article.
- Peer reviewed published journal.
- Direct comparison between methane production beef cattle farm and dairy farm.
- Experimental studies involving anaerobic digestion of organic matter added to cow manure.

Table 1. List comparison studies used in meta-analysis

No.	Ref.	Number of Animal		Methane Production (m^3/day)		Electrical Energy Production (Mwh/day)	
		Beef Cattle	Dairy Cattle	Beef Cattle	Dairy Cattle	Beef Cattle	Dairy Cattle
1	[15]	5832	25963	2140.03591	10559.387	7.49072	36.96081
2	[16]	166605300	12088400	8302700	12088400		
3	[17]	140		772.5			
4	[18]		30		5.509780822		
5	[19]		479		431.890411		5.824658
6	[20]	15	15	23.01369863	10.95890411	0.023288	0.049315
7	[20]	52	52	78.35616438	37.80821918	0.082192	0.169863
8	[20]	97	97	145.4794521	70.4109589	0.150685	0.315068
9	[20]	147	147	220	106.3013699	0.227397	0.476712
10	[20]	214	214	321.6438356	155.6164384	0.334247	0.69589
11	[20]	363	363	545.4794521	263.5616438	0.567123	
12	[20]	714	714	1071.506849	518.0821918		1.180822
13	[20]	2196	2196	3296.164384	1593.150685	1.112329	
14	[21]		42		8.4		0.039
15	[22]		320876		160438		272.7
16	[23]		1532		919		
17	[24]		50		2.94286E-05		
18	[25]		180		5.30952E-05		
19	[26]		70		6.33		0.029751
20	[27]	9500		1093		5.136	
21	[28]	3		0.8			
22	[28]	5		1.6			
23	[28]	7		2.4			
24	[28]	9		3.2			

25	[28]	11		4.2		
26	[29]	70			0.424	66
27	[30]	327		131.6175		
28	[30]	263		105.8575		
29	[30]	175		70.4375		
30	[30]	233		93.7825		
31	[30]	221		88.9525		
32	[30]	176		70.84		
33	[30]	114		45.885		
34	[30]	176		70.84		
35	[31]		2		2	
36	[31]		3		3	
37	[31]		7		3.4	
38	[31]		8		3	
39	[31]		15		6	
40	[31]		25		8	
41	[32]	1411000	3040000	1521.554521	1989.397808	
42	[33]		9200		7360	

According to the initial tittle screening, as many as 95 reference were eliminated because the topic was irrelevant to the research. In the end, the screening yielded 19 articles for use in subsequent data coding and statistical data analysis (as shown in Table 1).

2.2 Statistical analysis

Effect size as hedges 'd' was applied to quantify parameter distance between the control group (beef cattle farm) and the treatment group (dairy cattle farm) This method was selected because of its ability to calculate the effect size regardless the heterogeneity of sample size, measurement unit, and statistical test result, and also suitability for estimating the effect of paired treatment [34-36]. Effect size (d) is calculated as:

$$d = \left(\frac{(X^E - X^C)}{S}\right)J$$

where, X^E is the mean value of the experimental group and X^C is the mean value of the control group. S is the pooled standar deviation and J is sample correction factor.

The factor J as the sample correction factor and S as the combined standard deviation has the following formula:

$$J = 1 - (\frac{3}{4(N^C + N^E - 2) - 1})$$

$$S = \frac{\sqrt{(N^E - 1)(S^E)^2 + ((N^C - 1)(S^E)^2}}{(N^C + N^E - 2)}$$

where, N^C is the sample size of the control group and N^E is sample size of the experimental group. S^C is standard deviation of the control group and S^E is standard deviation of the experimental group.

The variance of hedges (*Vd*) is obtained by the following formula:

$$Vd = \left(\frac{N^C + N^E}{N^C N^E}\right) += (\frac{d^2}{2(N^C + N^E)})$$

These statistical methods were chosen due to their suitability for estimating the effect of paired treatments, considering heterogeneity in sample sizes, units of measurement, and statistical test results.

The cumulative effect size (d_{++}) is formulated as follows:

$$d_{++} = \frac{(\sum_{i=1}^{K} W_i\, d_i)}{(\sum_{i=1}^{n} W_i)}$$

where, W_i is inverse of the sampling variance W_i =1/vd. The precision of the the cumulative effect size (d_{++}) is obtained using a 95% confidence interval, namely d ± (1.96 × sd). An effect size was considered significant if the 95% confidence interval did not include zero. The data analysis was performed using Microsoft Excel 2016, including a t-test to determine the Standard Error of the Mean (SEM) and the significance level (p-Value).

3. RESULT AND DISCUSSION

The result Effect size, Variance from hedges and cumulative effect size as shown in Table 2.

Table 2. Effect size, Variance from hedges and cumulative effect size

No.	Parameters	d (Effect Size)	J (Sample Correction Factor)	S (Standars Deviation Pooled)	Vd (Variance from Hedges)	d_{++} (Cummulative Effect Size)
1	Methane Production (m^3/day)	-1.79941	0.996089	74597.59	0.000261	-1.79941
2	Electrical Energy Production (Mwh/day)	-14.645	0.996089	2.064536	0.1195	-14.645

The significant effect size (d) value of -1.79941 for methane production (m^3/day) indicates a marked difference in methane emissions between beef cattle farms and dairy cow farms. This negative effect size suggests that methane production is lower in beef cattle farms compared to dairy cow farms, corroborating findings of studies [37, 38] which reported lower methane outputs in beef systems relative to dairy systems. The substantial effect size of -1.79941 implies that this difference is not only statistically significant but also practically relevant, indicating that the observed variation in methane emissions is unlikely to be attributable to random chance [37, 38]. This has important implications for agricultural management and environmental policies aimed at mitigating greenhouse gas emissions, as it highlights the need for targeted strategies that consider the distinct methane production profiles of different livestock systems [39, 40].

The beef cattle systems generally exhibit lower methane emission potential compared to dairy systems. This difference is primarily attributed to variations in feed types and digestion processes inherent to each livestock category [40-42]. The implications of these findings extend beyond mere academic interest; they underscore the necessity for agricultural practices that prioritize the reduction of methane emissions, particularly in dairy farming, which is a significant contributor to overall greenhouse gas emissions from the agricultural sector [43, 44].

In a parallel analysis, the d value of -14.645 for electrical energy production (Mwh/day) indicates a significant decrease in energy production under the studied conditions compared to reference conditions. This large negative effect size suggests that the production of electrical energy is substantially lower under these conditions. The integration of biogas technology in dairy farms typically yields higher energy outputs than in beef farms, primarily due to the larger manure volumes and more consistent waste management practices associated with dairy operations [42, 45]. This finding aligns with the observations, that the differences in energy production outcomes between livestock systems necessitate more efficient agricultural energy management practices [46, 47].

The negative values of both effect sizes emphasize substantial differences in production outcomes, which are crucial for optimizing agricultural practices and energy production. These findings suggest that enhancing the efficiency of energy production in livestock systems could lead to significant reductions in greenhouse gas emissions, thereby contributing to broader environmental sustainability goals [48, 49]. Furthermore, reinforce the need for a systematic approach to energy management in agriculture, particularly in light of the increasing pressures to reduce greenhouse gas emissions from livestock production [47, 49].

In both cases, the negative d values underscore substantial differences in production outcomes, highlighting the relevance of these findings for understanding and potentially optimizing agricultural and energy production practices.The duration of the biogas flame for beef cattle is 20.8 minutes per day, higher than the biogas flame for dairy cattle, which is 20.6 minutes per day [50]. On April 10, 2009, EPA published proposed mandatory greenhouse gas reporting rules to regulate greenhouse gas emissions. Manure management systems for livestock manure with combined CH_4 and N_2O emissions in amounts equivalent to 25,000 metric tons of CO_2 equivalent unit or more per year are required to report under this rule. The animal population threshold level below which facilities are not required to report emissions is 3,200 head for dairy and 29,300 head for beef [51].

The result of Methane and electrical production from Beef Cattle and Dairy Cow Farm is shown in Table 3.

The data shows that methane production on dairy cow farms is higher than on beef cattle farms. The average methane production values from the study are derived from several farm references, with an estimated total of 168,037,360 beef cattle and 15,490,680 dairy cows. Methane production per head is approximately 0.0019 m^3/day for beef cattle and 0.029 m^3/day for dairy cows. These differences may result from varying management practices, livestock types, feed formulations, and production intensities. Management practices like feeding methods, livestock waste management, and animal health management can influence methane production.

Table 3. Methane and electrical production from beef cattle and dairy cow farm

	Beef Cattle Farm	Dairy Cow Farm
Methane Production (m^3/day)	319,793.04±125.60[a]	454,551.83 ± 590.79[b]
Electrical Production (Mwh/day)	1.68± 0.000209[a]	32.03682±0.019948[b]

Note: Superscript letters indicate statistically significant differences between groups. Values with different letters (a vs. b) are significantly different at $p < 0.05$.

For instance, beef cattle diets typically focus on growth and body weight optimization, while dairy cow diets emphasize high milk production. These dietary differences impact nutrient composition entering the rumen, affecting the types of rumen microbes and fermentation processes, which subsequently influence methane production. The dry matter intake, NDF, ADF, forage proportion, and lignin content are critical factors in predicting methane output. Average methane production for beef cattle is 9.13 MJ/day (ranging from 2.81 MJ/day to 17.2 MJ/day), while for dairy cows, it is 14.3 MJ/day (ranging from 4.31 MJ/day to 24.9 MJ/day) [52]. Fresh manure characteristics, particularly water content, significantly affect methane production [53].

The production of methane in dairy cow farms is significantly higher than in beef cattle farms, which can be attributed to a variety of factors including management practices, dietary formulations, and production intensities. The average methane production values indicate that dairy cows produce approximately 0.029 m³/day, compared to 0.0019 m³/day for beef cattle. This discrepancy is largely influenced by the differing dietary requirements and feeding strategies employed in dairy and beef production systems. Dairy cows are typically fed high-energy diets aimed at maximizing milk production, which results in a higher intake of fermentable carbohydrates and subsequently greater methane emissions during digestion [53, 54]. In contrast, beef cattle diets are often optimized for growth and weight gain, which may not promote the same level of methane production due to differences in nutrient composition and fermentation processes in the rumen [55, 56]

The management of livestock waste also plays a critical role in methane emissions. Studies have shown that the characteristics of fresh manure, particularly its water content, can significantly affect methane production [54, 57]. That the organic matter content in dairy cow manure is higher than that in beef cattle manure, leading to increased methane generation [53, 54]. Furthermore, effective manure management practices, such as anaerobic digestion, can mitigate methane emissions and enhance biogas production, which is particularly beneficial for dairy operations that already produce higher methane outputs [58, 59].

The differences in methane production between dairy and beef cattle also suggest potential avenues for improving biogas production efficiency in beef cattle operations. By adopting enhanced manure management techniques, beef cattle farms could optimize their biogas output, although it is unlikely to reach the levels observed in dairy farms due to the inherent differences in methane production rates [59, 60]. Additionally, the integration of dietary supplements, such as nitrates or seaweed, has been shown to reduce methane emissions in both dairy and beef cattle, indicating that dietary interventions could be a viable strategy for managing methane production across different cattle production systems [61, 62].

The formation of biogas progresses through four stages:

1. Hydrolysis: Conversion of insoluble materials (e.g., cellulose, fats) into soluble materials like glucose.
   - Reaction: $(C_6H_{10}O_5)n + nH_2O \rightarrow n(C_6H_{12}O_6)$
2. Acidogenesis: Degradation of simple sugars, amino acids, and fatty acids into acetate, CO_2, and hydrogen.
3. Acetogenesis: Production of acetic acid by anaerobic bacteria.
   - Reactions:
     - $n\ C_6H_{12}O_6 \rightarrow 2n\ C_2H_5OH + 2n\ CO_2$ + heat
     - $2n\ C_2H_5OH + n\ CO_2 \rightarrow 2n\ CH_3COOH + n\ CH_4$
4. Methanogenesis: Production of methane and CO_2 from intermediate products.
   - Reactions:
     - $2n\ CH_3COOH \rightarrow 2n\ CH_4 + 2n\ CO_2$
     - $2H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ [34]

Methane production correlates with dry matter intake, gross energy intake, and factors like milk production and average daily gain in both beef and dairy cattle [63, 64]. The ratio of volatile fatty acids, particularly the acetate/propionate ratio, also influences methane production levels. Regression plots with 95% confidence limits validate these findings.

4. CONCLUSION

Methane and electrical production are higher on dairy cow farms compared to beef cattle farms. This difference can be attributed to various management practices, such as feeding methods, livestock waste management, and animal health strategies. These findings highlight the significance of optimizing management practices to reduce methane emissions and enhance energy production efficiency in agricultural systems. Understanding these differences can inform policy decisions and industry practices aimed at promoting sustainability in livestock farming.

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