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Original Research Article

Evaluation of Bio-Drying Cow Dung with Inoculation of *Bacillus* sp. as Refuse Derived Fuel (RDF) Material

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Abstract

Global warming, driven in part by livestock manure emissions, poses a major environmental challenge. Refuse Derived Fuel (RDF) offers a waste-to-energy solution by converting solid cow manure into an energy source. This study investigated the impact of *Bacillus* sp. inoculation on the biodrying process of cow dung. The main challenge in processing cow manure into RDF is ensuring that the moisture content and calorific value meet the minimum RDF standards. Therefore, a biodrying process was carried out on cow manure to achieve these required standards. Biodrying performance was assessed based on drying time, moisture content, pH, and calorific value. The results show that inoculation with *Bacillus* sp.. The results showed that inoculation with Bacillus sp. at 10^6 log cfu ml^{-1} kg^{-1} yielded the most efficient outcome, achieving the fastest drying time (12 days), lowest moisture content (9.64%), optimal pH (7.8), and highest calorific value (2,656.5 kcal/kg). These findings confirm a direct link between moisture reduction and calorific improvement. Hence, bio-dried cow dung treated with inoculation of *Bacillus* sp. 10^6 log cfu ml^{-1} Kg^{-1} is recommended as a viable RDF material.

Keywords: *Bacillus* sp.; bio-drying; cow dung biomass; RDF; thermophilic bacteria; waste to energy

1. Introduction

Climate change and global warming pose serious challenges to the world. Human-driven greenhouse gas emissions, especially from fossil fuels, have increased global temperatures. Global data on energy use that generate CO2 emissions in 2022 reached more than 36,800 metric tons (MT), an increase of 0.9% compared to 2021 (IEA, 2023). Considering this, effective measures are urgently needed to reduce greenhouse gas emissions, especially from sources that produce greenhouse gas emissions. One of the sources of greenhouse gas emissions is organic waste, such as animal manure. Livestock manure is a significant source of methane, contributing primarily to greenhouse gas emissions in agriculture (Cardenas et al., 2021). Livestock waste can be defined as a byproduct of the livestock industry that becomes waste or refuse, and in its nature and concentration contains toxic and hazardous substances, thereby directly or indirectly damaging the environment, disrupting health, and threatening the survival of humans and other organisms (Ning et al., 2021). To date, the management of livestock waste, with a cattle population in Indonesia reaching 18.61 million heads in 2022, still lacks proper and effective governance, leading to frequent environmental pollution, including soil, water, and air pollution (Ministry of Agriculture of Indonesia, 2022). Dairy cows are the largest emitters in livestock management, with 4,919.61 metric tons of CO_2-eq/year (Heriyanti et al., 2022).

A method for processing livestock waste, such as that from dairy cows, involves the production of refuse-derived fuel (RDF), which utilizes the waste-to-energy (WtE) concept. RDF represents a method of converting waste into energy by treating the waste to achieve a specific calorific value, followed by combustion to harness the resultant heat as an energy source (Chaerul & Wardhani, 2020). The calorific value of dried cow dung at a moisture content of 10.98% (dry basis) is 3,434.5 Kcal/kg (Fajobi et al., 2022). Projections suggest that by 2040, renewable energy sources will account for 8% of the total global energy demand (Rachmawatie, 2024). However, the biggest challenge in obtaining RDF from animal manure is achieving the moisture content that meets RDF standards as required by SNI 8966:2021 (Indonesian standard of RDF) regarding solid RDF for power plants, which states that the moisture content should be < 15%, < 20%, and < 25% for RDF classes 1, 2, and 3, respectively (Ismawati et al., 2022). Previous research has shown that the calorific value of solid fuel produced from cow dung decreases linearly with an increase in the moisture content of the solid fuel (Szymajda & Laska, 2019).

The drying technology used in the process of producing fuel from animal manure determines the cost of RDF. One of the drying technologies is bio-drying. Bio-drying is a vaporization process that uses biological heat obtained from microbial reactions during the decomposition of organic components. The bio-drying process has various benefits, including the ability to reduce the required moisture content, decrease volume, and increase material density through the effective utilization of biological heat (Bilgin & Tulun, 2015; Cai et al., 2016; Tom et al., 2016). This study focuses on the effects of inoculating thermophilic bacteria (*Bacillus* sp.) at various dosages on the bio-drying of cow dung, particularly in relation to calorific value, moisture content, and drying time.

2. Methods

2.1. Characteristics of Livestock Manure

The sample was obtained via simple random sampling to guarantee representativeness. Simple random sampling is a prevalent technique in quantitative research, renowned for its capacity to yield representative and unbiased samples. This strategy guarantees that each unit in the population has an equal probability of selection, thus ensuring that the findings are statistically valid and generalizable. It reduces selection bias and offers a reliable basis for making inferences about the larger population (Noor et al., 2022). Fresh cow dung samples were randomly collected from cows in three different pens at Bubulak Slaughterhouse Bogor, Indonesia, for the initial testing of cattle manure characteristics. The samples were collected on October 9, 2024. Three fresh cow dung samples were taken in their pure form without any additives and sent to the Nature Chemlab Laboratory to check the moisture, ash, and organic carbon contents. Fresh cow dung was found to have an average moisture content of 68.84%, an ash content of 6. 39%, and an organic carbon content of 46.09% (dry weight). Various studies have shown that fresh cattle manure containing moisture content between 60% and 80% (Hossen et al., 2022; Lima & Victor, 2022).

2.2. Experimental Set-up

Bio drying of cow manure was tested using a bioreactor. A bioreactor is a device or system engineered to facilitate biochemical processes that involve biological catalysts, including substrates, enzymes, or living cells. The system offers a regulated environment that allows biocatalysts to perform their designated functions efficiently (Raganati & Procentese, 2022). The bioreactor used was a reactor tank equipped with stirring blades and a compressor that supplies air into the reactor tank (Xu et al., 2022). The bio-drying reactor employs a combination of physical and biochemical process techniques. The reactor may be constructed as a container that incorporates an aeration system. Bioreactors can be classified as closed containers, open tunnel-hall systems, or rotating drums, based on operational requirements and process design (Velis et al., 2009). The bioreactor used in this study is an open tunnel-hall type, with a height of 46 cm and a diameter of 21 cm, equipped with a 1-phase electric dynamo with a gearbox that constantly rotates the stirring blades at 50 rpm and a 1-phase electric air pump capable of blowing air at 1.5 L per min with a pressure of > 0.02 MPa, as shown in Figure 1.

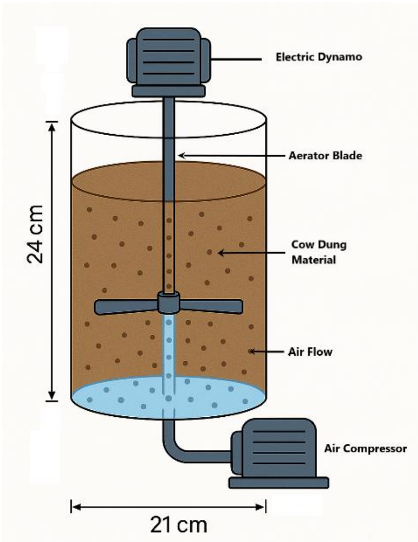


Figure 1. Bio-reactor for the bio-drying process of livestock manure.

2.3. Sample Laboratory Test

The sample results of the cow dung bio-drying process were tested for moisture content, gross calorific value, and acidity level. The testing of acidity level and moisture content was conducted at the Nature ChemLab laboratory in Bogor, Indonesia. The acidity level was measured using a pH meter. To ascertain the moisture content, we weighed 20-g samples as "wet samples" and dried them to a consistent weight using a suitable drying apparatus at a temperature that did not exceed 239 °F (115°C). We allowed the sample to cool after it dried. We recorded the "dry weight of the sample" by reweighing the sample after it cooled. The moisture content was calculated using Equation (1).

$$W = \frac{A-B}{B} x\ 100\% \quad (1)$$

where A denotes the weight of the wet sample in grams, B denotes the weight of the dry sample in grams, and W denotes the percentage of moisture in the sample.

Gross calorific testing was conducted at the Laboratory of Nutrition Science and Feed Technology, IPB University, Indonesia. A digital balance was used to weigh 1 g of cow dung. The "Start Pre-Weight" button was used to transmit the reading to the bomb calorimeter, where it was stored along with the sample name. A small crucible was used to contain the cow dung sample, which was then secured in the designated location under the bomb cover. Direct contact with the cow dung was guaranteed by cutting a segment of nichrome wire and connecting it to the two ignition rods concealed beneath the cover. The oxygen line was connected to the valve on the bomb cover, and the entire assembly was meticulously sealed. The "Oxygen Fill" button was pressed, which filled the bomb with oxygen to the specified pressure. The bomb was then precisely positioned within the calorimeter water jacket, ensuring that it did not contact the stirrer. The "Start" button was pressed, the machine lid was closed, and electrical leads were attached to the terminals on the bomb cover. The gross calorific value (GCV) was subsequently displayed on the screen after the cow dung sample was ignited by the system.

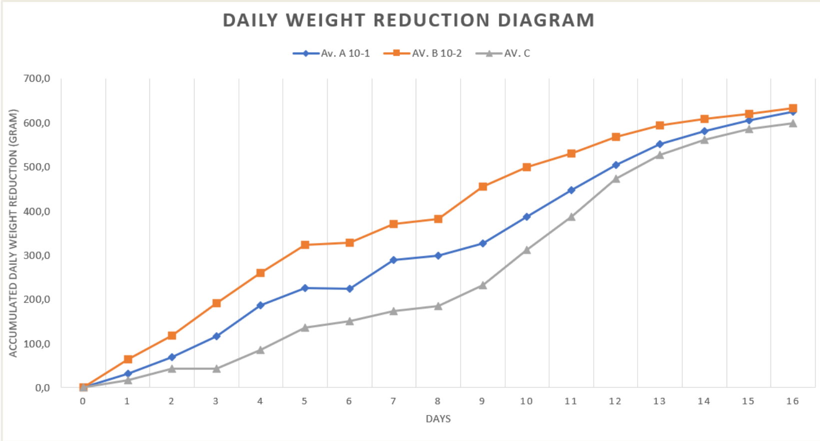
2.4. Descriptive and Statistical Analysis

The data from the bio-drying process measurements will be statistically tested using one-way analysis of variance (ANOVA) by Minitab version 21 software to observe the relationship between the treatment effects on the gross calories produced, treatment effects on the weight reduction of the cow dung test samples, and treatment effects on the rate of weight reduction of the test samples. One-way analysis of variance (ANOVA) is a statistical technique used to compare the means of three or more independent groups based on a single component or independent variable. By examining the variance within and across groups, this technique determines whether statistically significant variations exist among group means. Additionally, we examined the relationship between dry matter and gross calories produced using regression analysis with Minitab version 21 software. Regression analysis is a statistical technique for modelling and examining relationships between one or more independent variables and one or more dependent variables. This method is mainly utilized for quantitative data to discern patterns, forecast outcomes, and assess the strength of correlations. In addition to conducting statistical analysis on the test data, we also performed descriptive analysis to better understand the effects of treatment on the resulting test parameters. Furthermore, descriptive analysis was used to assess the suitability of cow dung as an RDF material by comparing the calorific value and moisture content produced with the minimum RDF quality standards (SNI 8966:2021). The results of the descriptive analysis can be presented in the form of cross-tabulations, frequency distribution tables, bar charts, line graphs, and pie charts (Sugiyono, 2013).

3. Result and Discussion

3.1. The Relationship Between Treatment and The Weight Reduction of Test Samples

The results are presented in Figure 2, which shows the daily weight measurements of the samples. As shown in Figure 2, each treatment showed a tendency for the weight reduction of the test samples to decrease linearly. The average accumulated weight reduction of the samples, in descending order, was as follows: the highest reduction was observed in the treatment with the addition of *Bacillus* sp. at a dilution of 10^{-2} (633.3 g), followed by the treatment with the addition of *Bacillus* sp. at a dilution of 10^{-1} (625.0 g), and finally the control treatment without any bacterial addition (598.0 g). This indicates the metabolic activity of thermophilic bacteria, which generates heat, resulting in the evaporation of moisture from the bioreactor (Sadaka & Ahn, 2012; Yang et al., 2024). The experimental group inoculated with thermophilic bacteria demonstrated a markedly higher moisture removal rate than the non-inoculated group. Additionally, the breakdown of organic matter was significantly accelerated by the presence of thermophilic bacteria (Yang et al., 2024). Once the thermophilic phase (temperature exceeding 50 °C) was reached, the degradation of organic matter reached its maximum, and the annihilation of pathogens was at its most intense (Zhang et al., 2021). High temperatures can increase the evaporation rate and kill pathogens. Zhang et al. (2021) also found that the temperature of initial mesophilic phase of compost pile is increasing quickly and lasting some days. The compost pile then entered the thermophilic phase when its temperature exceeded 50 °C, during which the maximum degradation of the organic matter occurred, together with the destruction of pathogens.



Av. A 10-1 : sample with inoculation *Bacillus* sp. at concentration 10^7 log cfu ml^{-1} Kg^{-1},
Av. B 10-2 : sample with inoculation *Bacillus* sp. at concentration 10^6 log cfu ml^{-1} Kg^{-1},
AV. C: sample control without inoculation *with Bacillus* sp.

Figure 2. Accumulated daily weight reduction of test samples during the process of bio-drying.

Figure 3 shows the distribution of the daily weight reduction of the samples. Figure 3 shows that the weight reduction of the samples ranged between 0 and 120 g. The weight reduction of the test sample showed a significant difference between the first 8 days and the following 8 days of the bio-drying process. The treatment group inoculated with *Bacillus* sp. at a 10^{-2} dilution exhibited the highest average daily weight reduction during the first 8 days, with an average reduction of 58 g per day. The treatment with *Bacillus* sp. at a 10^{-1} dilution exhibited an average reduction of 42 g per day, while the control group experienced an average reduction of 23 g per day. Figure 2 also indicates that inoculating *Bacillus* sp. during the first 8 days of the bio-drying process led to a significantly greater average weight reduction than that in the control. The inclusion of *Bacillus* sp. can enhance the thermophilic phase in the bio-drying process, thus facilitating the weight reduction of the test samples (Cai et al., 2016). The results were reversed during the second 8 days of the bio-drying process, with the control exhibiting a greater average weight reduction than the *Bacillus* sp.-inoculated treatment. The highest average daily weight reduction was observed in the control sample, with an average reduction of 52 g per day, followed by the treatment with *Bacillus* sp. at a dilution of 10^{-1}, with an average reduction of 40 g per day, and finally the treatment with *Bacillus* sp. at a dilution of 10^{-2}, with an average reduction of 28 g per day. This is because the control sample started in the thermophilic phase for the second 8 days, and the other sample with the addition of *Bacillus* sp. had already passed through the thermophilic phase. This condition made the weight reduction of the control sample increase rapidly in the second 8 days, and the weight reduction rate of the sample with Bacillus sp. inoculation became slower than that during the first 8 days.

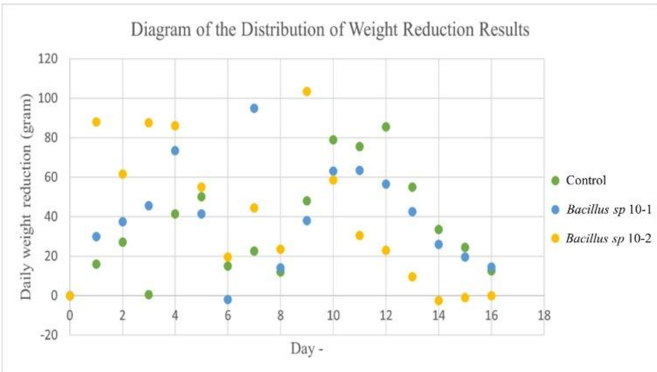


Figure 3. Diagram of the distribution of weight reduction in the test sample during bio-drying.

As shown in Figure 3, the test sample supplemented with *Bacillus* sp. at a concentration of 10^6 log cfu/mL per kg cow manure (sample *Bacillus* sp. 10^{-1}) already reached stagnation in weight reduction by day 14 (0 g weight reduction). This contrasts with the other two treatments, which still showed potential for weight reduction. It can be concluded that the treatment with *Bacillus* sp. at a concentration of 10^6 log cfu/mL per kg cow manure (sample *Bacillus* sp. 10^{-2}) achieved harvest readiness for the bio-drying process two days faster. This treatment offered the added value of faster drying times and a better average daily reduction rate, reaching 39.6 g per day. This aligns with Xu et al. (2022), who found that microorganisms play the most significant role in reducing the moisture content of biogas residue compared to mechanical treatments, with thermophilic bacteria contributing to 78.7% of the total drying of biogas residue. Additionally, the addition of a thermophilic bacterial inoculant can quickly reduce the moisture content to 9.4% within 12 days in the bio-drying of biogas residue. The inoculation of thermophilic bacteria initiates the thermophilic phase faster in the bio-drying process. It s makes the weight reduction of the sample faster than that of the other treatments. Thermophilic bacteria significantly increased the amount of organic matter degradation (Yang et al., 2024). Upon entering the thermophilic phase (temperature above 50 °C), the degradation of organic matter was the greatest, and pathogen destruction peaked (Zang et al., 2021). Other research has also stated that for normal composting with increasing temperature, the average moisture content decreases rapidly from 59.5% at day 0 to 33.7% at day 37 (Ning et al., 2021). In other words, the inoculation of *Bacillus* sp. in the bio-drying process makes the drying process faster than that in normal composting.

Table 1. Daily percentage of weight reduction of the test samples.

Treatment Code	Days										
	0	1	2	3	4	5	6	7	8	9	10
***Bacillus* sp. 10^{-1}**	0%	5%	6%	8%	11%	6%	0%	10%	2%	4%	10%
Accumulation	0%	5%	11%	19%	30%	36%	36%	46%	48%	52%	62%
***Bacillus* sp. 10^{-2}**	0%	10%	8%	12%	11%	10%	1%	7%	2%	11%	7%
Accumulation	0%	10%	19%	30%	41%	51%	52%	58%	60%	72%	79%
Control	0%	3%	5%	0%	7%	8%	3%	4%	2%	8%	13%
Accumulation	0%	3%	7%	7%	14%	23%	25%	29%	31%	39%	52%

As shown in Table 1, the total weight reduction of the samples was 50% by the fifth day after the addition of *Bacillus* sp. at a dilution of 10^{-2} to the bio-drying process. This was followed by treatment with *Bacillus* sp. at a dilution of 10^{-1} by day 9, and finally the control variable by day 10. This indicates that the addition of thermophilic bacteria, specifically *Bacillus* sp. at a concentration of 10^6 log cfu/kg of fresh cow manure, is able to achieve a significantly higher percentage of weight reduction in the same number of days compared to the control. Xu et al. (2022) demonstrated that incorporating thermophilic bacteria during the drying of biogas residue achieved the greatest moisture reduction relative to the control and alternative treatments. The inoculation of thermophilic bacteria accelerates the thermophilic phase, thus enhancing substrate degradation. During the thermophilic phase, Actinobacteria and Bacillus exhibit dominance, resulting in elevated levels of volatile substrate degradation, water production, and water evaporation. The substantial bio-heat produced by thermophilic microorganisms, in conjunction with the convective circulation generated by mechanical aeration, may be responsible for the high evaporation rate (Cai et al., 2016). Thermophilic inoculation improved quorum sensing and glyoxylate and dicarboxylate metabolism, allowing microorganisms to more effectively adapt to high-temperature environments and release additional energy that aids in water evaporation, as demonstrated by additional metabolic pathway analysis (Yang et al., 2024).

3.2. Feasibility Study of Cow Manure as RDF Material

The gross calorific value, final moisture content, and acidity level of the final test samples from each bio-drying treatment were determined through laboratory testing. Table 2 presents the laboratory test results for each treatment.

Table 2. Lab test results of bio-drying samples for each treatment

Treatment code	pH	Moisture content (%)	Caloric Value (Kkal/Kg)
***Bacillus* sp. 10^{-1}**	6.1	50.01	1,170.0
***Bacillus* sp. 10^{-2}**	7.8	9.64	2,656.5
Control	7.5	20.21	2,189.0

The bio-drying test results on the samples showed that the lowest average moisture content was obtained with the addition of *Bacillus* sp. at a concentration of 10^6 log cfu/ml, reaching 9.64%, and the resulting calorific value was 2,656.5 Kcal/kg. From these bio-drying test results, it can be concluded that pure cow manure is suitable for RDF material. The cow manure bio-drying process results can meet the minimum standard of SNI 8966:2021 for RDF type 3. The minimum standard of SNI 8966:2021 for RDF type 3 is a minimum calorific value of 2,388 Kcal per kg, a maximum moisture content of 25%, and a maximum ash content of 25% (Ismawati et al., 2022). Additionally, based on the results of the cow manure fuel analysis (Liu et al., 2019; Anwar et al., 2024), it is believed that fuel celll that is dried for approximately 6% is likely to be used as fuel by reaching the legal quality standard of 3,000 Kcal/kg for live stock excretion solid fuel. Bio-drying has proven to be an eco-friendly and efficient technology for reducing moisture content, utilizing metabolic heat generated from the degradation of organic matter in sludge without the need for additional external energy to enhance the drying process (Yang et al., 2024). Livestock manure, such as cow dung, is a promising renewable energy source because of its fuel characteristics, potential ignition difficulties, availability for operation, and viable ash disposal methods (Maj, 2022).

3.3. The Effect of *Bacillus* sp. Addition Treatment on The Moisture Content Produced in The Bio-Drying Process

Based on the statistical analysis results shown in Figure 4, the effect of the treatment involving the addition of thermophilic bacteria (*Bacillus* sp.) on the resulting moisture content showed a p-value of 0.003, which was lower than the significance level (α), indicating that the observed differences were statistically significant. Therefore, it can be concluded that the treatment exerted a statistically significant influence on the resulting moisture content in the bio-drying process. The statistical test data showed an R-sq of 97.80%, indicating that the treatment variable could explain 97.80% of the variability in the moisture content owing to the treatment. R-sq represents the proportion of the variance in the dependent variable that is predictable from the independent variables. This statistical analysis also strengthened the previous data in the research, which indicated that there was a significant difference in the final moisture content results for each treatment. We can conclude that inoculation with *Bacillus* sp. in the bio-drying process can have a significant impact on water evaporation in cow dung. Inoculation with *Bacillus* sp. yielded better moisture content results in the same time as bio-drying than without inoculation with *Bacillus* sp. This finding aligns with previous studies (Cai et al., 2016; Xu et al., 2022), which indicated that the thermophilic phase is the most intensive water evaporation stage in the bio-drying process. Inoculation of thermophilic bacteria in the bio-drying process enhanced moisture evaporation efficiency. Inoculation of thermophilic bacteria in sludge can shorten the bio-drying process (Quan et al., 2023; Anwar et al., 2024).

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	2311066	1155533	66.66	0.003
Error	3	52000	17333		
Total	5	2363067			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
131.657	97.80%	96.33%	91.20%

Figure 4. Statistical comparison of moisture content across treatments in the bio-drying process.

3.4. The Effect of *Bacillus* sp. Addition Treatment on The Final Calorific Value Produced in The Bio-Drying Process

The statistical significance of the observed differences is indicated by the p-value of 0.022, which is less than the significance level (α) in Figure 5. The calorific value of the bio-dried material was significantly affected by the treatment, as evidenced by these results. The data also showed an R-sq of 92.23%, indicating that the treatment variable could explain 92.23% of the variability in the calorific value produced, while only 7.77% of the results could not be explained by the treatment variable. Our research showed that the highest gross calorific value produced was from the bio-drying of cow manure with the addition of *Bacillus* sp. at a concentration of 10^6 log cfu/ml per kg of cow manure, reaching a calorific value of 2,656 kcal/kg (Table 2). Bacterial inoculation is responsible for the accelerated temperature increase and extended thermophilic phase, which in turn enhances moisture evaporation during the bio-drying process (Zhou et al., 2023). The calorific value of dried cow manure exhibited a linear decrease with increasing moisture content (Szyamajda & Laska, 2019).

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Treatment	2	1753.5	876.73	17.80	0.022
Error	3	147.7	49.24		
Total	5	1901.2			

Model Summary

S	R-sq	R-sq(adj)	R-sq(pred)
7.01726	92.23%	87.05%	68.92%

Figure 5. Statistical analysis results of the effect of treatment on the final calorific value produced in the bio-drying process.

3.5. The Effect of Moisture Content of Cow Manure From The Bio-Drying Process on The Calorific Value Produced.

Regression analysis was employed to investigate the impact of the moisture content of cow dung from the bio-drying test on the calorific value produced. The analysis assesses the correlation between the calorific values derived and the moisture content of the treated bio-drying samples. Figure 6 displays the findings of the regression analysis. The results of the correlation regression analysis of calorific value with the moisture content of cow manure test samples, statistically processed using Minitab, show a p-value of 0.000, which is lower than the significance level (α), indicating that the observed differences are statistically significant. Therefore, it can be concluded that the moisture content of cow manure resulting from the bio-drying process significantly affects the calorific value produced. The statistical data indicated that the calorific value was inversely proportional to the moisture content. The calorific value of bio-dried cow dung decreases as the moisture content increases. The regression equation indicates that a 1% increase in the moisture content of bio-dried cow dung results in a decrease of 34.81 kcal per kg in calorific value (Szymajda & Laska, 2019).

Regression Equation

Gross Caloric Value = 2931.8 - 34.81 KADAR AIR

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2931.8	89.8	32.67	0.000	
Moisture content	-34.81	2.80	-12.42	0.000	1.00

Coefficients

Term	Coef	SE Coef	T-Value	P-Value	VIF
Constant	2931.8	89.8	32.67	0.000	
Moisture content	-34.81	2.80	-12.42	0.000	1.00

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Regression	1	2303336	2303336	154.25	0.000
Moisture content	1	2303336	2303336	154.25	0.000
Error	4	59731	14933		
Total	5	2363067			

Figure 6. Regression analysis results of the effect of moisture content of cow manure from the bio-drying process on calorific value

4. Conclusions

The research results indicate that inoculating the bio-drying process with thermophilic bacteria (*Bacillus* sp.) significantly influences both the moisture content and calorific value of the final product. The inoculation of thermophilic bacteria *Bacillus* sp. at a concentration of 10^6 log cfu/ml per kg of pure cow manure resulted in higher moisture reduction and calorific value than the control (without bacterial addition). The addition of *Bacillus* sp. at a concentration of 10^6 log cfu/ml per kg of pure cow manure in the bio-drying process produced dried cow manure that met the standards of SNI 8966:2021 for RDF type 3 material. The dried cow manure from the bio-drying process is suitable as an RDF material and provides a new and renewable energy source. Treatment with *Bacillus* sp. at a concentration of 10^6 log cfu/ml per kg of cow manure significantly accelerated the drying process compared to no bacterial addition (12 days drying time). Increased moisture content in cow manure leads to a reduced calorific value. Further research may focus on identifying the optimal dosage of *Bacillus* sp. inoculation to obtain the best bio-drying performance. Additionally, studies could explore the effects of other thermophilic bacterial strains or combinations thereof to enhance the efficiency of the bio-drying process.

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Ethics Statement

The investigation did not involve any human participants or animals. Consequently, informed consent and ethical sanction were unnecessary.

CRediT Author Statement

Ardiansah Febriantoko: Idea Development, Research Design, Manuscript Draft Preparation. **Anuraga Jayanegara:** Resources, Manuscript Review and Revision, Project Administration, Supervision. **Novia Amalia Sholeha:** Manuscript Review and Revision, Visualization. **Qurrota A'yuni:** Visualization, Manuscript Review and Revision.

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