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Analysis of Agricultural Waste Utilization as Biogas, Renewable Energy Management, and Compost Processing on Energy Efficiency in Bandung

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ABSTRACT

The increasing need for energy efficiency and sustainable waste management has driven the exploration of agricultural waste utilization in urban settings. This study analyzes the role of agricultural waste in biogas production, renewable energy management, and compost processing to enhance energy efficiency in Bandung City. Using a quantitative approach, data were collected from 40 respondents through a structured questionnaire with a 5-point Likert scale. The findings reveal that biogas production, renewable energy management, and compost processing significantly contribute to energy efficiency, with renewable energy management having the most substantial impact. The study underscores the importance of integrated agricultural waste management in achieving urban sustainability and provides actionable insights for policymakers and stakeholders to scale these practices.

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1. INTRODUCTION

The challenges of energy efficiency and sustainable waste management in urban areas are growing due to rapid urbanization and population growth. As traditional energy sources deplete and harm the environment, adopting renewable energy and innovative waste management practices is essential. These solutions address energy needs while promoting sustainability and resource efficiency. The Municipality of Athens has implemented waste-to-energy processes using biodegradable plant residues, reducing landfill waste and providing thermal energy for municipal facilities, yielding both environmental and economic benefits [1]. Advanced waste-to-energy technologies are key for sustainability, as shown in cities like San Francisco and Freiburg [2]. Integrated municipal solid waste (MSW) management strategies, which focus on maximizing resource recovery and minimizing environmental impacts, require collaboration between governments, industries, and communities [3]. The use of cloud and fog computing optimizes waste collection routes and boosts recycling infrastructure [4].

Legislative frameworks, public-private partnerships, and community involvement are crucial to overcoming challenges such as affordability and technological barriers [2]. The 3R principle (Reduce, Reuse, Recycle) and thermal treatment methods are vital for transitioning to a circular economy [5].

Bandung City faces challenges in managing agricultural waste due to rapid urbanization and agricultural activities, leading to environmental issues like methane emissions and water pollution. However, agricultural waste can be converted into renewable energy sources such as biogas and compost, supporting sustainable development. The city's waste management system is inadequate, as evidenced by the fire at TPA Sarimukti due to 8,000 tons of waste buildup [6], [7]. Despite programs like Kang Pisman, there is a need for greater digitalization and smart technology integration [6]. The conversion of municipal waste into refuse-derived fuel (RDF) has shown potential in other Indonesian cities and could be adapted for Bandung's agricultural waste [8]. Surabaya's waste-to-energy (WtE) solutions, such as anaerobic digestion and composting, demonstrate the potential for energy recovery from organic waste that could benefit Bandung [9]. To improve waste management, implementing IoT and AI technologies is essential [6], and promoting community participation, as seen in Jakarta's decentralized approach, could enhance waste reduction and recycling [10].

Biogas and compost from agricultural waste are vital for promoting sustainable energy and agricultural practices. Biogas, produced through anaerobic digestion of organic materials such as agricultural waste, animal manure, and municipal waste, provides a renewable energy source for cooking, electricity generation, and industrial processes [11], [12]. It consists mainly of methane (50-70%) and carbon dioxide (30-50%) with trace gases [11]. Biogas production also produces digestate, a byproduct that enhances soil fertility and reduces the need for chemical fertilizers [13], [14]. Compost derived from agricultural waste improves soil structure and supports sustainable practices by recycling nutrients and reducing dependence on synthetic fertilizers [13]. Enzymatic pre-treatments in anaerobic digestion can enhance digestate's nutrient content [13]. However, biogas production faces challenges like gas impurities affecting energy efficiency and the need for controlled fermentation [11], [14]. The adoption of biogas technology is hindered by a lack of technical knowledge, insufficient subsidies, and the need for comprehensive policies [14]. Despite mitigating CO2 emissions, biogas production requires careful management to avoid pollution [15].

Despite the apparent benefits, the adoption of these technologies in Bandung City remains limited due to factors such as lack of awareness, inadequate infrastructure, and insufficient policy support. This study aims to analyze the utilization of agricultural waste in Bandung City for biogas production, renewable energy management, and compost processing, focusing on its impact on energy efficiency. By employing a quantitative approach, this research seeks to provide empirical evidence on the potential benefits and challenges of agricultural waste utilization in achieving energy efficiency. The findings of this study are expected to offer insights for policymakers, stakeholders, and urban planners in developing strategies for sustainable energy and waste management.

The study addresses the following research questions:

1. To what extent does agricultural waste contribute to biogas production and energy efficiency in Bandung City?
2. How effective is renewable energy management in optimizing the utilization of biogas derived from agricultural waste?
3. What role does compost processing play in enhancing the sustainability of agricultural practices in the region?

2. LITERATURE REVIEW

2.1 *Agricultural Waste Management*

Agricultural waste, including crop residues, animal manure, and food waste, offers significant potential for renewable energy production and sustainable agricultural practices. By converting this waste into biofuels and biogas, it addresses environmental challenges such as greenhouse gas emissions and water pollution, while providing economic benefits for farmers. Processes like anaerobic digestion, fermentation, pyrolysis, and gasification help reduce reliance on fossil fuels and recycle soil nutrients [16], [17]. Anaerobic digestion, due to its high energy yields and decentralized nature, is particularly suitable for rural areas [18]. Utilizing agricultural waste for energy can reduce waste disposal issues and environmental pollution, such as nutrient runoff and methane emissions [19], and contribute to a circular economy by transforming waste into valuable products [20]. However, challenges such as logistics, transportation, and the need for pretreatment to improve efficiency remain [16], [17], and further research is needed to optimize conversion technologies and integrate agricultural waste into energy systems effectively [17].

2.2 *Biogas Production from Agricultural Waste*

Biogas production through anaerobic digestion is a well-established technology that converts organic waste into methane-rich gas, providing a renewable energy source for electricity, cooking, and industrial processes [11], [12]. This process contributes to waste management and environmental sustainability, as biogas is produced by microorganisms breaking down organic materials, resulting in methane and carbon dioxide [11], [12]. Derived from various feedstocks such as agricultural waste, food waste, and sewage, biogas is a versatile and environmentally friendly energy source [11], [21]. Factors influencing biogas adoption include feedstock availability, awareness, and government incentives [14]. Technological improvements, such as optimized reactor designs, enhance biogas yield and quality, increasing its appeal [22]. Economic analyses show that biogas systems, especially combined heat and power facilities, offer greater profitability than other waste management techniques [21]. Despite benefits, challenges like gas impurities and the need for controlled fermentation conditions remain [11]. Barriers such as a lack of technical know-how and insufficient policy support also hinder widespread adoption [14], though advancements in process optimization offer opportunities for improving efficiency and sustainability [22].

2.3 *Renewable Energy Management*

Integrating biogas systems into urban energy networks can enhance energy efficiency by optimizing generation, storage, and distribution, but challenges like limited infrastructure, inconsistent feedstock supply, and high initial costs hinder large-scale adoption. A Mixed Integer Linear Programming (MILP) approach can minimize pipeline network investment costs by optimizing network topology and pipe diameters, improving the connection of multiple production plants [23]. Combining biogas with other renewable sources like photovoltaics and battery storage can increase power generation capacity, reduce local load burdens, and cut costs and emissions, making it suitable for societal and industrial use [24], [25]. Utilizing waste heat from biogas power plants through the Organic Rankine Cycle improves efficiency by recovering energy from exhaust gases, optimizing electricity production [26]. A multi-energy management framework can boost energy utilization in biogas microgrids, enhancing biogas yield and reducing battery costs, supporting reliable energy in remote areas [27].

2.4 *Compost Processing and Sustainable Agriculture*

Composting agricultural waste is a sustainable waste management strategy that converts organic waste into a nutrient-rich medium, improving soil fertility and reducing reliance on chemical fertilizers. It supports circular agricultural systems by recycling nutrients, enhancing environmental sustainability and economic viability. Composting improves soil structure, organic matter, and nutrient content, leading to better crop yields and quality [28]. It also reduces greenhouse gas emissions by diverting waste from landfills and cutting the need for chemical fertilizers [29], [30]. Economically, composting offers a cost-effective alternative to expensive fertilizers, improving farming viability [31]. However, managing contaminants like heavy metals and microplastics is essential for compost quality [30], and technological advancements, such as microbial inoculants and in-vessel composting, are needed for greater efficiency [31]. Socioeconomic barriers, including public and political involvement, must also be addressed to promote widespread adoption [29].

2.5 *Energy Efficiency and Urban Sustainability*

Energy efficiency is vital for sustainable urban development, particularly in cities like Bandung, where agricultural waste can be used for renewable energy and compost production to address both energy and waste management challenges. Integrating biogas and other renewable energy sources is essential for reducing energy consumption and greenhouse gas emissions, supporting global sustainable development goals. Biogas, derived from biomass residues like agricultural waste, is carbon-neutral and a sustainable alternative to conventional energy [32], [33]. This transition supports job creation and rural electrification, contributing to inclusive growth [32]. Biogas production can reduce reliance on fossil fuels and decrease cities' ecological footprints [33]. While waste-to-energy (WtE) systems are capital-intensive, they provide positive economic returns and support low-carbon urban development [34]. Effective WtE implementation requires supportive policies and public-private partnerships to overcome barriers [32], [34]. Economic viability depends on reducing social discount rates and offering subsidies to offset initial costs [34], while adopting sustainable biomass energy generation models like "design, build, and operate" can ensure success [34]. Addressing regulatory challenges and fostering international cooperation is crucial for scaling renewable energy projects in urban areas [32].

2.6 *Research Gaps and Objectives*

While existing literature underscores the benefits of agricultural waste utilization, there are notable gaps in understanding its application in specific urban contexts, such as Bandung City. Few studies have empirically examined the combined impact of biogas production, renewable energy management, and compost processing on energy efficiency in Indonesia. This study addresses this gap by focusing on the quantitative analysis of agricultural waste utilization in Bandung City, offering insights into its practical implications for urban energy sustainability.

3. METHODS

3.1 Research Design

The study adopts a quantitative research design to analyze the relationship between agricultural waste utilization, renewable energy management, and compost processing in achieving energy efficiency. The approach is descriptive and explanatory, aimed at identifying the contributions and interconnections between the variables.

3.2 Population and Sample

The population for this study consists of agricultural waste stakeholders in Bandung City, including farmers, waste management practitioners, and local policymakers. Using purposive sampling, a sample of 40 respondents was selected to ensure relevance and alignment with the study objectives. The selection criteria included respondents actively involved in agricultural waste management, renewable energy projects, or composting practices.

3.3 Data Collection

Primary data were collected using a structured questionnaire designed to capture respondents' perceptions and practices regarding agricultural waste utilization. Each question was measured using a 5-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree).

3.4 Data Analysis

The collected data were analyzed using SPSS version 26, applying several analytical techniques, including: first, Descriptive Statistics to summarize the demographic characteristics of the respondents and provide an overview of the data; second, Reliability Analysis using Cronbach's Alpha to test the internal consistency of the questionnaire items; third, Correlation Analysis to examine the relationships between biogas production, renewable energy management, compost processing, and energy efficiency; and fourth, Regression Analysis with multiple linear regression to identify the impact of the independent variables (biogas production, renewable energy management, and compost processing) on the dependent variable (energy efficiency).

4. RESULTS AND DISCUSSION

4.1 Respondent Demographics

The demographic profile of the respondents is summarized as follows: 65% of the respondents were male, and 35% were female. In terms of age, 25% were between 20–30 years old, 55% were between 31–50 years old, and 20% were older than 50 years. Regarding their role in waste management, 50% were farmers, 30% were waste managers, and 20% were policymakers. As for years of experience, 30% had less than 5 years of experience, 45% had 5–10 years, and 25% had more than 10 years of experience in agricultural waste management. The majority of the respondents were male (65%), aged between 31–50 years (55%), with 5–10 years of experience in agricultural waste management.

4.2 Descriptive Statistics

The descriptive statistics for the key variables are presented in Table 1.

Variable	Mean	Standard Deviation
Biogas Production	4.202	0.62
Renewable Energy Management	4.106	0.70
Compost Processing	4.152	0.65
Energy Efficiency	4.259	0.60

The descriptive statistics indicate a generally positive perception of agricultural waste utilization and its impact on energy efficiency. All key variables—Biogas Production (Mean = 4.202, SD = 0.62), Renewable Energy Management (Mean = 4.106, SD = 0.70), Compost Processing (Mean = 4.152, SD = 0.65), and Energy Efficiency (Mean = 4.259, SD = 0.60)—show high mean values and relatively low standard deviations, suggesting strong agreement among respondents. Biogas production is seen as an effective solution, renewable energy management as important but with more varied opinions, and compost processing as valuable for sustainable agriculture. Energy efficiency received the highest mean, indicating widespread agreement that these practices significantly enhance energy efficiency. All variables show a high mean score, indicating positive perceptions and practices among respondents.

4.3 Correlation Analysis

The correlation matrix in Table 3 demonstrates the relationships between the variables.

Variables	Biogas Production	Renewable Energy Management	Compost Processing	Energy Efficiency
Biogas Production	1.00	0.68**	0.60**	0.72**
Renewable Energy Management	0.68**	1.00	0.65**	0.75**
Compost Processing	0.60**	0.65**	1.00	0.70**
Energy Efficiency	0.72**	0.75**	0.70**	1.00

The results indicate strong positive correlations between the independent variables (biogas production, renewable energy management, and compost processing) and energy efficiency.

4.4 Regression Analysis

The regression analysis results are presented in Table 4.

Independent Variables	Coefficient (β)	t-value	p-value
Biogas Production	0.353	4.208	<0.01
Renewable Energy Management	0.406	5.104	<0.01
Compost Processing	0.301	3.801	<0.01
Adjusted R^2	0.685		

The regression analysis shows that all three independent variables—Biogas Production, Renewable Energy Management, and Compost Processing—are significant predictors of Energy Efficiency ($p < 0.01$). Biogas Production ($\beta = 0.353$) increases energy efficiency by 0.353 units per increase, Renewable Energy Management ($\beta = 0.406$)

has the highest impact, improving energy efficiency by 0.406 units per increase, and Compost Processing (β = 0.301) contributes 0.301 units per increase. The adjusted R^2 of 0.685 indicates that these variables explain 68.5% of the variance in energy efficiency, underscoring their importance in promoting energy sustainability.

Discussion

The findings highlight the significant contribution of biogas production to energy efficiency in Bandung City. Respondents reported that agricultural waste conversion into biogas reduces dependency on traditional energy sources. This aligns with prior studies by [35], [36], which emphasize the role of biogas in achieving sustainable energy goals. Renewable energy management emerged as the most significant predictor of energy efficiency. Efficient management practices, including storage and distribution systems, optimize the benefits of biogas utilization. These findings support the work of [35]–[37], which underscores the importance of integrated energy management systems.

Compost processing positively impacts energy efficiency by reducing waste and supporting sustainable agricultural practices. Respondents highlighted the economic benefits of using compost as an organic fertilizer, consistent with findings by [28], [31]. The study demonstrates the synergistic effect of biogas production, renewable energy management, and compost processing on energy efficiency. The integration of these practices addresses waste management challenges while contributing to urban sustainability. These findings align with [38], [39], who emphasize the need for holistic approaches to waste and energy management.

Practical Implications

The results underscore the potential of agricultural waste as a resource for renewable energy and sustainable farming in Bandung City. Policymakers and stakeholders should prioritize investments in infrastructure, public awareness, and policy support to scale these practices.

5. CONCLUSION

This study demonstrates the significant potential of agricultural waste utilization in enhancing energy efficiency in Bandung City. The findings highlight that agricultural waste is a valuable resource for biogas production, which reduces reliance on conventional energy sources and mitigates environmental impacts. Efficient management of renewable energy systems optimizes the utilization of biogas, making it the most influential factor in achieving energy efficiency. Additionally, compost processing supports sustainable farming practices by reducing chemical fertilizer dependency and contributing to circular agriculture. The integration of biogas production, renewable energy management, and compost processing addresses urban waste challenges while promoting energy sustainability. The study emphasizes the need for policy interventions, awareness programs, and investment in infrastructure to scale agricultural waste utilization practices, which are essential for sustainable urban development in Bandung City and beyond. Future research should explore larger samples and diverse urban settings to validate these findings and develop comprehensive frameworks for agricultural waste management.

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