



Development Model of Gamal (*Gliricidia sepium*) Biomass-Based Agroindustry as a Renewable Energy Source within Sustainable Agroforestry Systems

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Abstract: Biomass-based renewable energy development is a strategic solution to address the energy crisis and environmental degradation. The gamal plant (*Gliricidia sepium*) has high potential as a biomass source due to its rapid growth, adaptability to marginal land, and role in increasing soil fertility in agroforestry systems. This study aims to formulate a model for developing a gamal biomass-based agroindustry as a renewable energy source within a sustainable agroforestry framework. The method used is a literature study with a critical analysis and synthesis approach to various relevant studies. The results of the study indicate that gamal biomass has high energy conversion potential through technologies such as biopellets and biogas that are efficient and applicable. This is evident from the analysis of the review results conducted on 15 articles that have gone through a screening process to be used as scientific literature material in this study. Integration of gamal biomass into agro-industrial systems can create economic added value, improve local energy security, and support environmental sustainability by reducing carbon emissions. The novelty of this study lies in the development of a conceptual model that integrates biomass production, energy conversion technology, and sustainability dimensions in a single agroforestry-based agro-industrial system. These findings provide a strategic contribution to the development of locally resource-based renewable energy and strengthening the rural economy.

Keywords: Agroindustry; Biomass; Gamal; Renewable Energy; Sustainable Agroforestry

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Introduction

The increasing global energy demand and limited fossil fuel resources are driving the development of sustainable and environmentally friendly renewable energy. Biomass is a potential alternative due to its abundant availability, particularly in agricultural countries like Indonesia. In this context, the development of biomass-based agro-industry serves not only as an energy provider but also as an effort to increase the added value of the agricultural and forestry

sectors (García-López *et al.*, 2024; Hendrasetiafitri *et al.*, 2025; Mulyana *et al.*, 2020; Prima *et al.*, 2018;).

One plant with significant potential as a source of biomass energy is gamal (*Gliricidia sepium*). This plant is known as a fast-growing species with high biomass productivity and adaptability to various land conditions, including marginal land. Furthermore, gamal has the capacity to increase soil fertility through nitrogen fixation, thus playing a crucial role in sustainable agroforestry systems (Akinifesi *et al.*, 2006;

Alamu *et al.*, 2023; Sileshi *et al.*, 2020). Furthermore, gamal has the ability to improve soil fertility through nitrogen fixation, thus playing a crucial role in sustainable agroforestry systems. Integrating gamal into agroforestry allows farmers to periodically harvest firewood or biomass pellets without sacrificing food plots, creating a mutually supportive system of energy production and agriculture (symbiotic mutualism).

In practice, gamal is integrated into agroforestry systems through alley cropping techniques or as a living fence around the main cultivated area. This pattern allows farmers to periodically prune gamal twigs and branches to harvest them as raw material for wood pellets or firewood without killing the main crop. Through this continuous pruning cycle, gamal-based agroforestry systems not only maintain a stable, self-sufficient supply of biomass energy at the local level but also provide microclimate protection for the food commodities grown within them.

The utilization of gamal biomass as an energy source has been developed through various conversion technologies, such as biopellet, wood pellet, and biogas production. Studies show that gamal biomass has physical and chemical characteristics that support its use as an alternative fuel with relatively high efficiency. Anaerobic digestion technology also enables the conversion of gamal biomass into biogas, which can be used as a renewable energy source for households and industries (Ejigboye *et al.*, 2025; Masendra *et al.*, 2025; Mulyana *et al.*, 2020; Putri *et al.*, 2024).

From an agro-industrial perspective, the development of gamal biomass has the potential to create an integrated production system from upstream to downstream. Biomass-based agroindustry is not solely focused on energy production but also encompasses resource management, distribution, and increasing economic value for rural communities. The integration of agroforestry and bioenergy systems can create a sustainable and efficient development model (García-López *et al.*, 2024; Mulyana *et al.*, 2020; Prima *et al.*, 2018; Sileshi *et al.*, 2020). The development of biomass-to-energy conversion technologies has made significant progress in recent years (Adewale *et al.*, 2022; Kumar *et al.*, 2023; Rahman *et al.*, 2021; Zhang *et al.*, 2024).

However, the development of gamal biomass as an energy source still faces various obstacles, such as limitations in harvest cycle management, energy conversion efficiency, and environmental sustainability. Furthermore, a more in-depth analysis is needed regarding the environmental impacts of biomass utilization, such as carbon emissions and potential contributions to climate change mitigation (Diono *et al.*, 2025; Ejigboye *et al.*, 2025; Hendrasetiafitri *et al.*, 2025; Masendra *et al.*, 2025). Extensive research has been conducted on the use of gamal (*Gliricidia sepium*) in

agroforestry systems, particularly in the context of increasing soil fertility and agricultural productivity. Various studies have shown that gamal plays a significant role in improving soil quality through its contribution of organic biomass and nitrogen fixation, thus supporting sustainable agricultural systems (Alamu *et al.*, 2023; Akinnifesi *et al.*, 2006; Barreto *et al.*, 2012; Mesele *et al.*, 2025).

Furthermore, studies on the potential of gamal biomass as an energy source have also developed, particularly in aspects such as biomass estimation, carbon stocks, and energy crop development. Research shows that gamal has high biomass productivity and significant potential to support the development of bioenergy plantations in Indonesia (Diono *et al.*, 2025; Mulyana *et al.*, 2020; Prima *et al.*, 2018).

Technologically, the use of gamal biomass has been studied in various forms of energy conversion, such as biopellet, wood pellet, and biogas production. Research results indicate that gamal biomass has suitable characteristics for development as an alternative fuel and can increase energy efficiency in small- to medium-scale systems (Ejigboye *et al.*, 2025; Hendrasetiafitri *et al.*, 2025; Masendra *et al.*, 2025; Putri *et al.*, 2024). However, most research remains partial and does not comprehensively integrate aspects of biomass, energy technology, and agro-industrial systems. Existing studies tend to focus on technical or ecological aspects separately, thus failing to produce an integrated and sustainable agro-industry model for gamal biomass.

Thus, a research gap exists, stemming from the lack of studies integrating the potential of gamal biomass, energy conversion technologies, and.

Literature Review

Biomass as a Renewable Energy Source

Biomass is a renewable energy source derived from organic materials such as plants, agricultural residues, forestry waste, and other biodegradable resources. It has gained significant attention as an alternative energy source due to its abundant availability and renewable nature. Unlike fossil fuels, biomass can be replenished through natural biological processes, making it a sustainable energy option. The utilization of biomass contributes to reducing dependence on non-renewable energy resources while supporting energy security.

One of the major advantages of biomass is its carbon-neutral characteristic, as the carbon dioxide released during combustion is generally balanced by the carbon absorbed during plant growth. This characteristic makes biomass an environmentally friendly energy source with the potential to mitigate greenhouse gas emissions. In addition, biomass utilization promotes the efficient management of

agricultural and forestry waste, thereby reducing environmental pollution. Advances in biomass conversion technologies have further enhanced its efficiency and expanded its applications in heat, electricity, and biofuel production. Globally, biomass has become an essential component of the transition toward a more sustainable and low-carbon energy system, supported by increasing investments and policy initiatives (García-López *et al.*, 2024; Hendrasetiafitri *et al.*, 2025; Mulyana *et al.*, 2020; Prima *et al.*, 2018). Therefore, the development and optimization of biomass utilization play a strategic role in achieving sustainable energy goals and addressing global climate change challenges.

The development of biomass as an energy source is also supported by the abundant availability of raw materials in tropical countries. Biomass can be converted into various forms of energy, such as biofuel, biogas, and solid fuels, through technologies such as gasification, pyrolysis, and anaerobic digestion. The efficiency of biomass conversion into energy is greatly influenced by the characteristics of the raw materials and the technology used (Ejigboye *et al.*, 2025; Masendra *et al.*, 2025; Mulyana *et al.*, 2020; Putri *et al.*, 2024).

Characteristics and Potential of Gamal (*Gliricidia sepium*)

Gamal (*Gliricidia sepium*) is a legume often used in agroforestry systems due to its high adaptability and rapid growth. This plant can grow in a variety of environmental conditions, including marginal land, making it a highly potential source of sustainable biomass (Alamu *et al.*, 2023; Akinnifesi *et al.*, 2006; Mohammed *et al.*, 2023; Sileshi *et al.*, 2020).

Furthermore, gamal has high biomass productivity and the ability to improve soil fertility through nitrogen fixation and the provision of organic matter. This makes gamal not only an energy source but also a crucial component of sustainable agricultural systems (Alamu *et al.*, 2023; Barreto *et al.*, 2012; Mesele *et al.*, 2025; Sileshi *et al.*, 2020).

From an energy perspective, gamal has significant biomass potential with a relatively high energy content. Research shows that gamal can be used as a bioenergy feedstock through various conversion processes, and it also contributes to carbon storage and climate change mitigation (Mulyana *et al.*, 2020).

Gamal Biomass Conversion Technology into Energy

Utilization of gamal biomass as an energy source can be achieved through various conversion technologies, both thermochemical and biochemical. Thermochemical technologies such as pyrolysis and gasification enable the conversion of biomass into solid and gaseous fuels, while biochemical technologies such

as anaerobic digestion are used to produce biogas (Ejigboye *et al.*, 2025; Hendrasetiafitri *et al.*, 2025; Masendra *et al.*, 2025; Putri *et al.*, 2024).

The production of wood pellets and biopellets from gamal biomass is one of the most developed forms of utilization. This product offers advantages in terms of ease of storage, transportation, and combustion efficiency. Research shows that blending gamal biomass with other materials such as coconut shells or agricultural waste can improve fuel quality (Masendra *et al.*, 2025; Mulyana *et al.*, 2020; Putri *et al.*, 2024; Prima *et al.*, 2018). Biomass-to-electricity conversion technology continues to develop, with various approaches becoming increasingly efficient and sustainable (Balopi *et al.*, 2025).

Furthermore, the use of gamal biomass for biogas production also shows significant potential, particularly at the household and rural scale. Integrating gamal biomass with livestock waste in the anaerobic digestion process can increase biogas production efficiency and support locally based renewable energy systems (Ejigboye *et al.*, 2025; García-López *et al.*, 2024; Sileshi *et al.*, 2020).

Biomass-Based Agroindustry Concept

Agroindustry is a system that integrates the production, processing, distribution, and marketing of agricultural resource-based products. In the energy context, biomass-based agroindustry plays a role in converting biological raw materials into value-added energy products (García-López *et al.*, 2024; Mulyana *et al.*, 2020; Hendrasetiafitri *et al.*, 2025; Prima *et al.*, 2018).

The development of biomass agroindustry is not only oriented towards energy production but also encompasses aspects of environmental sustainability, resource efficiency, and improving community welfare. An integrated agroindustry model can create a circular economic system that utilizes waste as an energy source and reduces environmental impacts.

Theoretical Framework

This research is based on several main theoretical approaches, including the following.

1. **Renewable Energy Theory**
Emphasizes the importance of utilizing renewable resources to reduce dependence on fossil fuels.
2. **Agro-Industry Theory**
Explains the integration of the agricultural and industrial sectors in creating added economic value.
3. **Agroforestry Theory**
Emphasizes the integration of forestry and agricultural crops to increase productivity and sustainability.

4. Circular Economy Theory
Optimizes resource utilization through recycling and reusing waste as production inputs.

4. Outcome: Energy security, Community economic development, Environmental sustainability

Conceptual Research Model

The conceptual model flow in this study can be seen in the following description.

Main Components

1. Input: *Gliricidia* biomass, Land and agroforestry systems, Conversion technology
2. Process: Biomass production, Processing (pellets, biogas, etc.), Energy distribution
3. Output: Renewable energy, Agro-industrial products

Visual Conceptual Narrative Version Diagram

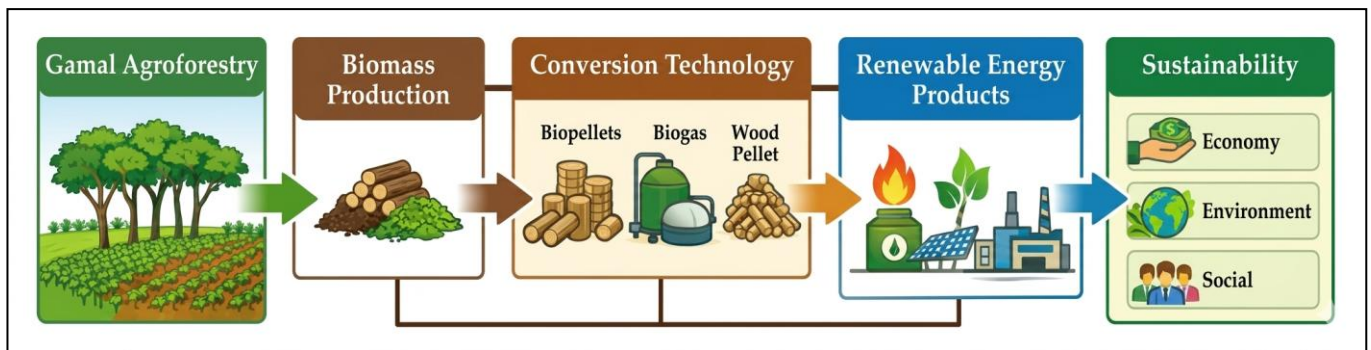
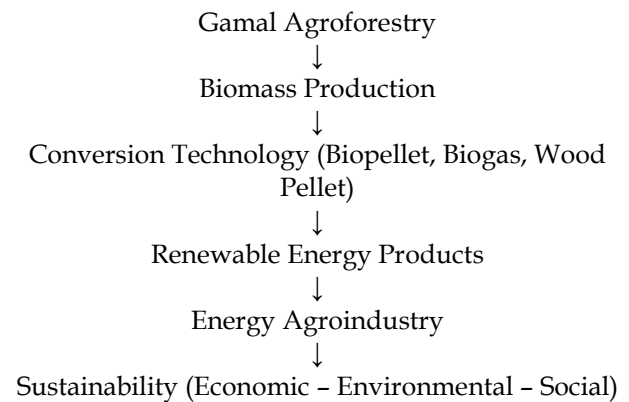


Figure 1. Conceptual Model Diagram

Method

This research employs a qualitative approach using a literature review method. The aim is to examine and analyze the development of a biomass-based agroindustry of gamal (*Gliricidia sepium*) as a renewable energy source, based on previous research findings. The data used are entirely sourced from reputable secondary sources, including international and national scientific journals, seminar proceedings, and official books and scientific reports. The literature was selectively selected based on inclusion criteria: strong relevance to the topics of biomass, energy, gamal, and agroindustry, and demonstrated valid scientific credibility.

The data collection process was conducted systematically through literature searches in various scientific journal databases. The collected articles were then rigorously selected to identify the most relevant literature, before finally being grouped according to the specific themes studied. In more depth, the analysis in this study focused on four main pillars: (1) the potential of gamal biomass as an energy source; (2) biomass

conversion technologies (such as biopellets, wood pellets, and biogas); (3) biomass-based agro-industry development strategies; and (4) sustainability aspects, which examine economic, environmental, and social dimensions. Next, the grouped data was analyzed using qualitative descriptive techniques through four continuous stages. The first stage was data reduction to filter and select information relevant to the research objectives. The second stage was data classification based on key themes (biomass, energy, and agro-industry). The third stage was synthesis, integrating and confronting previous research results to gain a comprehensive understanding. The final stage was drawing conclusions aimed at objectively answering the problem formulation. Overall, this research flow moved in a circular and systematic manner, starting with topic identification, literature collection, literature selection and classification, data analysis and synthesis, and finally, compiling the results and drawing conclusions. The following table presents the journal analysis matrix used in this study.

Table 1. Analysis Metrics of Gamal Biomass Agroindustry Journal as Renewable Energy

No	Author & Year	Research Focus	Method	Key Results	Research Advantages	Limitations	Relevance
1	Alamu <i>et al.</i> (2023)	Gamal and soil fertility	Review	Improves soil and plant nutrition	Comprehensive	No energy discussion	Supporters
2	Mulyana <i>et al.</i> (2020)	Bioenergy plantation	Experimental	Energy development potential	Indonesian context	Not yet agro-industry	Major
3	Akinnifesi <i>et al.</i> (2006)	Gamal intercropping	Experimental	Increased productivity	Practical	No energy discussion	Supporters
4	Diono <i>et al.</i> (2025)	Gamal harvest cycle	Growth Model	Optimal bioenergy cycle	Energy specific	Limited scale	Major
5	Ejigboye <i>et al.</i> (2025)	Gamal biogas	Experimental	Effective for biogas	Clear technology	Needs further scale	Major
6	García-López <i>et al.</i> (2024)	Agroforestry-bioenergy	System Analysis	Rural energy integration	Holistic	Not specific to gamal	Major
7	Hendrasetiafitri <i>et al.</i> (2025)	Gamal biomass LCA	Life Cycle Assessment	Low emission impact	Environmental analysis	Focuses on sawdust	Major
8	Prima <i>et al.</i> (2018)	Biomass & carbon	Field Estimation	High energy potential	Empirical data	Limited locations	Major
9	Sileshi <i>et al.</i> (2020)	Gamal agroforestry	Review	Sustainable system	Strong conceptual approach	No detailed energy discussion	Supporters
10	Masendra <i>et al.</i> (2025)	Gamal wood pellets	Experimental	Good pellet quality	Applicable	Biomass mix	Major
11	Mesele <i>et al.</i> (2025)	Soil fertility	Long-Term Observation	Improved soil quality	Long-term data	Not specific to energy	Supporters
12	El Gamal <i>et al.</i> (2023)	Gamal leaf biomass	Experimental	Increased crop yields	Practical	Not specific to energy	Minor
13	Pati <i>et al.</i> (2025)	Ecological impacts	Ecological Analysis	Biodiversity risk	Critical perspective	Not specific to energy	Major
14	Putri <i>et al.</i> (2024)	Gamal biopellets	Experimental	Potential alternative energy	Energy specific	Small scale	Supporters
15	Barreto <i>et al.</i> (2012)	Gamal pruning	Experimental	Effects on soil and yields	Technical details	No energy	Supporters

Result and Discussion

The Potential of Gamal Biomass as a Renewable Energy Source

Analysis results indicate that gamal (*Gliricidia sepium*) has high biomass potential and can be utilized as a renewable energy source. *Gliricidia sepium's* rapid biomass productivity and ability to grow on marginal land make it a promising energy crop. Research indicates that gamal biomass has a relatively high energy content and contributes significantly to carbon storage (Mulyana *et al.*, 2020; Prima *et al.*, 2018)

Furthermore, agroforestry cultivation systems for gamal support sustainable biomass availability. Gamal improves soil fertility through nitrogen fixation and organic biomass production, thus serving not only as an energy source but also as a crucial component of sustainable agricultural systems (Alamu *et al.*, 2023; Sileshi *et al.*, 2020). Thus, gamal has advantages as an

energy raw material due to its productive, adaptive and sustainable nature, making it suitable for development in the energy agro-industrial system.

Gamal Biomass Conversion Technology

Utilizing gamal biomass as a renewable energy source can be achieved through various conversion technologies, both in solid and gaseous forms. Studies have shown that gamal biomass can be processed into biopellets, wood pellets, and biogas with considerable efficiency (Masendra *et al.*, 2025; Putri *et al.*, 2024).

The production of biopellets and wood pellets from gamal is one of the most applicable technologies due to its advantages in terms of combustion efficiency, ease of transportation, and storage. Furthermore, the combination of gamal biomass with other materials such as coconut shells can improve fuel quality (Hendrasetiafitri *et al.*, 2025).

On the other hand, anaerobic digestion technology enables the conversion of gamal biomass into biogas, particularly through blending with livestock waste. This technology has great potential for rural application due to its simplicity and support for local energy independence (Ejigboye *et al.*, 2025; García-López *et al.*, 2024; Sileshi *et al.*, 2020). Pelletization and biogas technologies are the main approaches for efficient and sustainable biomass conversion (Kumar *et al.*, 2023; Rahman *et al.*, 2021; Sarkar *et al.*, 2022). However, the main challenges in this conversion technology are production efficiency, industrial scale, and the availability of supporting infrastructure.

Development of Gamal Biomass-Based Agroindustry

The development of a gamal biomass-based agroindustry focuses not only on energy production but also on creating added value throughout the production chain. The biomass agroindustry encompasses processes ranging from raw material production and processing to energy distribution to consumers (García-López *et al.*, 2024; Mulyana *et al.*, 2020; Prima *et al.*, 2018).

The integration of agroforestry and bioenergy systems allows for the creation of an efficient and sustainable agro-industrial system. In this system, gamal serves as the primary biomass source for energy production, while waste from the production process can be reused in the agricultural system (Alamu *et al.*, 2023; Ejigboye *et al.*, 2025; García-López *et al.*, 2024).

Furthermore, the development of the gamal biomass agroindustry has the potential to increase the income of rural communities through energy product diversification and job creation. Thus, the biomass agroindustry contributes not only to the energy sector but also to local economic development.

Sustainability Analysis of Gamal Biomass Agroindustry

Sustainability is a crucial aspect in the development of biomass-based agro-industry. Studies have shown that utilizing gamal biomass has positive environmental, economic, and social impacts. Environmentally, using biomass as energy can reduce carbon emissions and support climate change mitigation. Life Cycle Assessment (LCA) analyses show that gamal biomass has a relatively low emissions impact compared to fossil fuels (Hendrasetiafitri *et al.*, 2025; Mulyana *et al.*, 2020; Prima *et al.*, 2018).

Economically, developing a biomass agro-industry can increase the added value of agricultural products and create new business opportunities in rural areas. Meanwhile, from a social perspective, this system can improve community welfare by providing energy and employment (Alamu *et al.*, 2023; Ejigboye *et al.*, 2025; García-López *et al.*, 2024; Sileshi *et al.*, 2020).

However, it is important to note that large-scale gamal development also carries potential ecological risks, such as reduced biodiversity if not properly managed (Mesele *et al.*, 2025; Pati *et al.*, 2025; Sileshi *et al.*, 2020).

Gamal Biomass Agroindustry Development Model (Research Synthesis)

Based on the analysis of all the literature, an integrated model for developing gamal biomass agroindustry can be formulated.

This model consists of several main components:

1. Inputs include: gamal biomass, agroforestry land, and energy technology.
2. Processes include: biomass production and energy processing (pellets, biogas).
3. Outputs include: renewable energy and agro-industrial products.
4. Outcomes include: energy security, economic growth, and environmental sustainability.

This model demonstrates that the integration of biomass, technology, and agro-industry is key to developing gamal-based renewable energy.

Conclusion

The gamal plant (*Gliricidia sepium*) has high potential as a biomass source for renewable energy due to its rapid productivity and ability to grow on marginal land. *Gliricidia* biomass can be processed into various forms of energy, such as biopellets and biogas, which are quite efficient and applicable. Developing a gamal biomass-based agro-industry can provide added value, not only in energy supply but also in improving the community's economy. Furthermore, the use of gamal biomass supports sustainability through emission reduction and utilization of local resources. However, existing studies are still not fully integrated, necessitating the development of a more comprehensive agro-industry model.

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