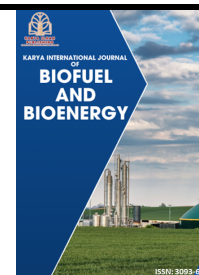




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Electricity Generation Potential from Agricultural Residues: A Comparative Review of Biomass Characteristics and Conversion Technologies

Zul Fahmi Rusdy Harahap^{1,*}, Muh Rasya Ramadhan¹, Nuraulia Army Syamsuddin¹, Shafa Nabillah¹, Nashwa Adilla Tsaniya¹

¹ Department of Engineering Technology, Power Plant Engineering Technology, Fakultas of Vocational, State University of Malang, 65145 Malang, Jawa Timur, Indonesia

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ABSTRACT

Agricultural residues have emerged as promising renewable energy resources due to their abundance and potential to reduce dependence on fossil fuels. This review evaluates the potential utilization of agricultural waste biomass for electricity generation by comparing feedstock characteristics, pretreatment strategies, and conversion technologies. Various residues, including oil palm residues, rice residues, corn residues, and coconut residues, were analyzed based on moisture content, ash content, heating value, and lignocellulosic composition. The results indicate that biomass properties significantly influence conversion performance, where residues with lower moisture content, lower ash content, and higher heating value generally exhibit better fuel quality. Palm kernel shell (PKS) and coconut shell showed favourable characteristics for thermochemical conversion due to their high energy density, while rice husk and field residues require additional treatment to overcome ash and handling limitations. Pretreatment methods, such as drying, densification, torrefaction, and carbonization, improve biomass quality by enhancing storage characteristics and conversion efficiency. Different electricity generation pathways, including combustion, gasification, co-firing, and combined heat and power (CHP), demonstrate varying performance depending on feedstock characteristics and system scale. Overall, agricultural residues provide significant opportunities for sustainable electricity production; however, future implementation requires integrated consideration of biomass availability, conversion efficiency, environmental impacts, and economic feasibility.

1. Introduction

Energy demand continues to increase with the development of human activities and energy-intensive sectors, encouraging the utilization of renewable resources to reduce dependence on conventional energy sources. Biomass is a renewable resource with considerable potential because it can be derived from agricultural and plantation residues [1], [2]. Biomass can be converted through thermochemical processes, such as combustion, gasification, and pyrolysis, or biochemical processes

* Corresponding author.

E-mail address: zul.fahmi.2509347@students.um.ac.id

such as anaerobic digestion [1], [6]. The selection of conversion technology depends on feedstock characteristics and process conditions [3].

Oil palm, rice, corn, and coconut generate various residues with different physical and chemical characteristics [7], [9]. Important properties include moisture content, ash content, volatile matter, fixed carbon, heating value, and elemental composition [3], [6]. High moisture content reduces the effective energy available during conversion, while ash content can affect combustion performance and cause operational problems [3]. Although heating value indicates the energy content of biomass, electricity output is also influenced by conversion technology, system efficiency, and operating conditions [3].

Different conversion pathways produce different energy products and electricity-generation characteristics. Combustion produces heat for steam and turbine operation, while gasification produces combustible gas that can be utilized for electricity generation [1], [3]. Anaerobic digestion produces biogas that can also be used for electricity generation, whereas pyrolysis primarily produces bio-oil, biochar, and gas [6]. Therefore, energy output and electricity output need to be distinguished when synthesizing biomass studies. Biomass utilization also involves environmental impacts [19], [22], while collection, transportation, and storage influence the practically available biomass supply [35], [36]. Life-cycle assessment can further be applied to evaluate environmental impacts comprehensively [51].

This study conducts a structured literature review of agricultural residues from oil palm, rice, corn, and coconut. The review focuses on residue characteristics, conversion technologies, operating conditions, energy and electricity output, environmental aspects, economic indicators, and supply-chain conditions. Differences in feedstock, technology, operating conditions, analytical basis, and system boundaries are considered when synthesizing the literature [35]. The review aims to provide a structured overview of agricultural residues for electricity generation and identify limitations in existing studies, particularly incomplete feedstock characterization, inconsistent electricity-output reporting, limited large-scale validation, and insufficient integration of technical, environmental, and economic aspects [45], [49], [51].

2. Methodology

2.1 Research Design and Literature Selection

This study employed a structured literature review approach to evaluate the utilization of agricultural residues as biomass feedstocks for electricity generation. The review aimed to analyze the relationship between agricultural residue characteristics, biomass conversion technologies, operating conditions, and electricity-generation performance. Biomass can be converted into energy through several pathways, including direct combustion, thermochemical conversion, and biochemical conversion, where each pathway requires different feedstock properties and process conditions [1–3].

The review focused on four major agricultural commodities, namely oil palm, rice, corn, and coconut, because these commodities generate significant quantities of residues with potential applications as renewable biomass resources [7,9]. Agricultural residues were analyzed at the residue level rather than only at the commodity level because different residue fractions may have different moisture content, chemical composition, heating value, and suitability for energy conversion [3].

Oil palm residues were classified into empty fruit bunches (EFB), mesocarp fiber (MF), and palm kernel shell (PKS) because these materials originate from different stages of palm-oil processing and possess different fuel characteristics [7]. Rice residues were separated into rice husk and rice straw because rice husk is produced during milling, whereas rice straw is generated during field harvesting

[12]. Corn residues were classified into corn cob and corn stover because corn stover consists of multiple above-ground biomass fractions, including stalks, leaves, husks, and cob components [16]. Coconut residues were categorized according to the investigated materials, particularly coconut shell and coconut-processing residues [9].

The literature selection included studies related to biomass availability, feedstock characterization, pretreatment, biomass conversion technologies, electricity generation, environmental impacts, economic assessment, and supply-chain considerations [35,45]. The selected studies were used as the basis for evaluating biomass characteristics and their relationship with electricity-generation performance.

2.2 Data Extraction and Feedstock Characterization

A standardized data-extraction framework was applied to collect comparable information from the selected literature. The extracted information included biomass source, residue type, physicochemical properties, conversion technology, operating conditions, energy output, electricity generation, environmental indicators, and economic parameters.

The extracted feedstock characteristics included moisture content, ash content, volatile matter, fixed carbon, heating value, elemental composition, and lignocellulosic composition. These parameters were selected because they influence biomass fuel quality, combustion behavior, gasification performance, and overall energy conversion efficiency [3,6].

Moisture content was evaluated because high moisture levels reduce the effective energy content of biomass and increase drying requirements before conversion [3]. Ash content was considered because inorganic components may influence combustion performance, ash deposition, slagging, and fouling during thermochemical conversion processes [3].

Heating value was extracted from reported higher heating value (HHV) and lower heating value (LHV). However, heating value was not considered as the only indicator of electricity-generation capability because electrical output is also affected by conversion technology, system efficiency, and operational conditions [12].

Table 1
Agricultural Residue Classification and Feedstock Characteristics

Commodity	Residue	Moisture (%)	Ash (%)	HHV/LHV (MJ/kg)	Main Property
Oil palm	Empty Fruit Bunch (EFB)	60–70	Moderate	~17	High moisture content
Oil palm	Palm Kernel Shell (PKS)	10–15	Low	~19–20	High carbon content
Oil palm	Mesocarp Fibre (MF)	Moderate	Moderate	~19	Suitable for combustion
Rice	Rice husk	10–15	High (silica)	~13–15	High ash content
Rice	Rice straw	~12	Variable	LHV ~14	High availability
Corn	Corn cob	Low (dry basis)	Low	~16	High volatile matter
Corn	Corn stover	High (fresh)	Low–moderate	~7–11	Mixed residue fraction
Coconut	Coconut shell	7–11	Variable	~18–19	High fixed carbon content

Table 2
Data Extraction Framework for Biomass Assessment

Category	Extracted Parameters
Bibliographic	Author, year, journal/book, DOI
Feedstock	Commodity, residue type, origin
Proximate analysis	Moisture, ash, volatile matter, fixed carbon
Ultimate analysis	C, H, O, N, S
Structural composition	Cellulose, hemicellulose, lignin
Physical properties	Density, particle size
Pretreatment	Drying, grinding, crushing, pelletization, torrefaction
Conversion technology	Combustion, gasification, pyrolysis, co-firing, anaerobic digestion
Operating condition	Temperature, pressure, feed rate, residence time, ER/AFR
System information	Reactor type, capacity, plant scale
Energy output	Heat, syngas, bio-oil, biochar
Electricity output	kW, MW, kWh/year, MWh/year
Performance	Thermal, conversion, electrical efficiency
Environmental	CO ₂ , CO, CH ₄ , NO _x , SO _x , PM
Economic	CAPEX, OPEX, LCOE, payback period
Implementation	Collection, transport, storage, utilization

2.3 Biomass Conversion and Electricity Assessment

The biomass conversion technologies identified from the literature were classified into thermochemical and biochemical pathways. Thermochemical conversion included combustion, gasification, pyrolysis, carbonization, and co-firing, while biochemical conversion mainly included anaerobic digestion for biogas production [1,6].

Direct combustion converts biomass into thermal energy, which can subsequently be used for steam generation and electricity production through turbine systems [3]. Gasification converts biomass into producer gas or syngas containing combustible components that can be utilized in engines or turbines for electricity generation [12].

Pyrolysis was categorized separately because its primary products are bio-oil, biochar, and non-condensable gases rather than direct electricity generation [1]. Therefore, pyrolysis studies were considered supporting evidence for biomass conversion behavior unless electrical output was explicitly reported.

Electricity-related results were extracted separately from other energy products to prevent incorrect interpretation between thermal energy, chemical products, and electrical power.

Electricity results were classified into four categories: experimental output, calculated output, simulation output, and electricity potential. This classification was applied because biomass studies frequently report different levels of evidence that cannot be directly compared [35].

Table 3
Biomass Conversion Pathways and Electricity Assessment

Technology	Process	Main Output	Electricity Indicators
Combustion	Biomass oxidation → heat → steam turbine	Heat, electricity	Boiler efficiency, electrical output, MWh/year
Gasification	Biomass → producer gas/syngas → generator	Syngas, electricity	Gasification efficiency, capacity, electrical efficiency
Co-firing	Biomass mixed with coal	Heat, electricity	Mixing ratio, plant capacity, electricity contribution
Pyrolysis	Thermal decomposition under limited oxygen	Bio-oil, biochar, gas	Product yield, energy recovery, integrated electricity
Anaerobic digestion	Biomass → biogas → CHP	Biogas, electricity	Methane yield, biogas rate, CHP output
CHP	Combined heat and power generation	Heat, electricity	Electrical efficiency, overall efficiency

2.4 Data Comparability and Evidence Synthesis

Quantitative comparison was conducted by considering differences in feedstock type, analytical basis, conversion technology, system boundaries, and operating conditions. Biomass characteristics were retained according to the original analytical basis because moisture content, ash content, and heating value significantly influence energy conversion performance [35].

Efficiency values were interpreted according to their original definitions because combustion efficiency, gasification efficiency, thermal efficiency, and electrical efficiency may represent different stages within the conversion system [3].

The extracted evidence was synthesized using a commodity–residue–feedstock–technology–energy–electricity–environment–economics framework. Each residue was evaluated based on its origin, characteristics, conversion pathway, and reported electricity-generation performance [45]. Supply-chain aspects, including collection, transportation, storage, and biomass availability, were also considered because theoretical residue availability does not always represent the amount of biomass that can be practically supplied to energy facilities [36].

Research gaps were identified based on limitations reported in the reviewed literature, including incomplete feedstock characterization, inconsistent reporting of electricity output, limited validation of large-scale systems, and insufficient integration between technical, environmental, and economic assessments [49,51].

3. Results

3.1 Agricultural Residue Characteristics and Feedstock Potential

The characteristics of agricultural residues strongly influence their suitability for biomass-based electricity generation. Parameters such as moisture content, ash content, volatile matter, fixed carbon, heating value, and lignocellulosic composition determine fuel quality, conversion efficiency, and technology selection [1,3]. Different agricultural residues exhibit different energy properties because they originate from different plant structures and processing activities [7,9].

In this study, four major agricultural commodities were evaluated, including oil palm, rice, corn, and coconut residues. The comparison of these residues provides an overview of their potential as biomass feedstocks for electricity production.

Table 4

Moisture Content Comparison of Agricultural Residues

Biomass Residue	Moisture Content (%)	Energy Conversion Implication
Empty Fruit Bunch (EFB)	60–70	Requires drying before thermal conversion
Mesocarp Fiber (MF)	35–45	Moderate drying requirement
Palm Kernel Shell (PKS)	10–15	Suitable for direct combustion
Rice Husk	10–15	Suitable for decentralized power generation
Rice Straw	10–15	Requires storage management
Corn Cob	3–8	Favourable for combustion
Corn Stover	40–55	Requires moisture reduction
Coconut Shell	7–12	Suitable for thermal conversion

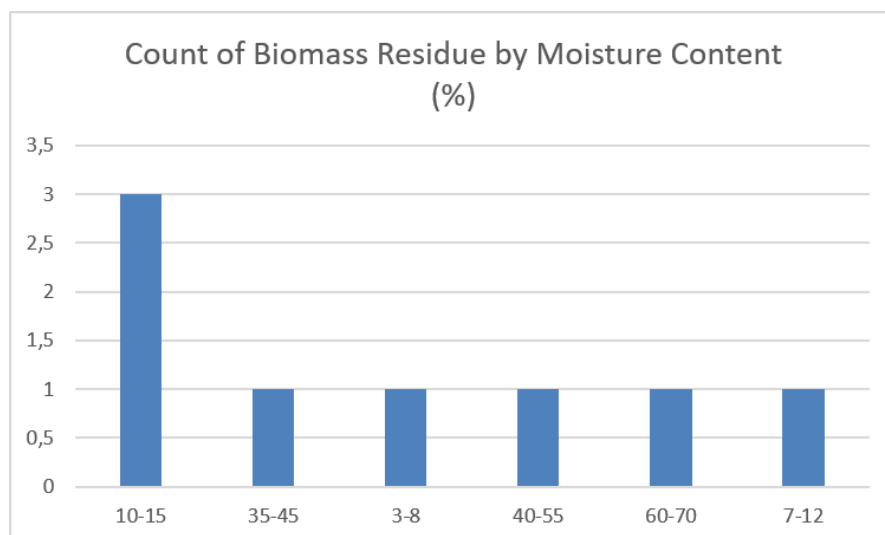
Moisture content represents one of the most important factors affecting biomass utilization because water contained in biomass reduces the net energy available during conversion. High-moisture residues require additional energy for drying, increasing operational costs and reducing overall efficiency [3]. EFB and corn stover show higher moisture content compared with other residues, which limits their direct utilization in combustion systems. In contrast, PKS and coconut shell have lower moisture content, resulting in higher fuel quality and easier handling during electricity conversion processes [7,9].

Table 5

Ash Content Comparison of Agricultural Residues

Biomass Residue	Ash Content (%)	Effect on Conversion
EFB	4–8	Moderate ash formation
MF	4–8	Suitable for boiler systems
PKS	1–3	High fuel quality
Rice Husk	15–22	High silica content; ash control required
Rice Straw	10–20	Higher ash management
Corn Cob	1–3	Suitable for combustion
Corn Stover	1–3	Low ash limitation
Coconut Shell	6–18	Moderate ash formation

Ash content affects biomass combustion behaviour because inorganic components may reduce heat transfer efficiency and cause slagging, fouling, and corrosion in conversion equipment [3]. Rice husk has the highest ash content because of its high silica concentration, which becomes a major challenge during thermal conversion [12].



Conversely, PKS and corn cob contain lower ash fractions, making them more suitable as solid fuels. Lower ash content improves combustion stability and reduces maintenance requirements in biomass power plants [7].

Table 6
Heating Value Comparison of Agricultural Residues

Biomass Residue	HHV/LHV (MJ/kg)	Energy Potential
PKS	19–20	Very high
Mesocarp Fiber	~19	High
Coconut Shell	18–19	High
EFB	~17	Moderate
Corn Cob	~16	Moderate
Rice Straw	~14	Moderate
Rice Husk	13–15	Lower due to ash content
Corn Stover	7–11	Low energy density

Heating value indicates the amount of energy stored in biomass and is an important parameter for evaluating fuel quality. Residues with higher heating values generally provide greater energy potential for electricity generation [3].

PKS shows the highest energy potential among oil palm residues because it combines high heating value, low moisture content, and low ash content. Coconut shell also demonstrates favourable characteristics because of its high carbon content and suitability for thermochemical conversion [9].

Although rice husk has a lower heating value, it remains an attractive biomass resource because it is generated at centralized milling facilities, reducing transportation difficulties [12].

Table 7

Lignocellulosic Composition of Agricultural Residues

Biomass Residue	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Suitable Conversion
EFB	35–45	20–30	20–25	Combustion, gasification
PKS	20–30	15–25	35–45	Thermal conversion
Rice Husk	35–45	20–30	20–30	Gasification, combustion
Rice Straw	30–50	10–20	10–30	Combustion, biochemical
Corn Cob	35–45	25–35	15–20	Pyrolysis, combustion
Corn Stover	35–40	30–35	10–15	Pretreatment-based conversion
Coconut Shell	25–35	20–30	30–40	Combustion, pyrolysis

Cellulose, hemicellulose, and lignin determine biomass degradation behaviour during conversion. Cellulose and hemicellulose contribute to volatile product formation, while lignin contributes to char formation and carbon retention during thermal processing [6].

Residues with higher lignin content, such as PKS and coconut shell, generally show higher carbon content and better thermal stability. Therefore, these materials are more suitable for combustion and pyrolysis applications [9].

3.2 Pretreatment and Feedstock Preparation for Energy Conversion

Agricultural residues often require pretreatment before conversion because raw biomass commonly has limitations including high moisture content, low bulk density, irregular particle size, and poor storage characteristics. Pretreatment improves biomass handling, fuel quality, and conversion efficiency [6,35].

The selection of pretreatment depends on the characteristics of the biomass and the targeted conversion pathway. Thermal conversion generally requires moisture reduction and densification, while biochemical conversion focuses on improving accessibility of cellulose and hemicellulose structures [6].

Table 8

Pretreatment Methods for Agricultural Residues

Pretreatment Method	Main Purpose	Suitable Residues	Expected Improvement
Drying	Reduce moisture content	EFB, rice straw, corn stover	Increase effective heating value
Grinding	Reduce particle size	Rice husk, corn cob	Improve feeding and reaction rate
Pelletization	Increase density	Agricultural residues	Improve transport and storage
Briquetting	Produce solid fuel	Rice husk, PKS	Improve combustion stability
Torrefaction	Thermal upgrading	PKS, coconut shell	Increase carbon content and energy density
Carbonization	Increase carbon fixed	Coconut shell, PKS	Produce high-carbon fuel

Drying is the most common pretreatment because moisture reduction directly improves biomass fuel characteristics. This process is particularly important for EFB and corn stover, which have relatively high initial moisture content [3].

Grinding and size reduction improve biomass feeding characteristics by increasing surface area and improving reaction efficiency. These treatments are commonly applied before gasification and combustion processes [12].

Densification methods such as pelletization and briquetting improve biomass transportation and storage because agricultural residues generally have low bulk density. These technologies are especially beneficial for residues that are widely distributed, such as rice straw and corn stover [35].

Table 9

Effect of Pretreatment on Biomass Properties

Treatment	Property Improved	Impact on Electricity Generation
Drying	Lower moisture content	Higher combustion efficiency
Grinding	Smaller particle size	Faster conversion rate
Pelletization	Higher density	Easier biomass feeding
Torrefaction	Higher heating value (HHV) and carbon content	Better solid fuel quality
Carbonization	Higher fixed carbon content	Improved thermal performance

Pretreatment plays an important role in converting low-quality agricultural residues into more suitable energy feedstocks. Torrefaction, for example, improves biomass hydrophobicity, energy density, and storage properties by reducing moisture and volatile components during thermal treatment.

Therefore, pretreatment selection should consider both technical benefits and economic costs because excessive processing may increase energy consumption and reduce overall sustainability.

3.3 Biomass Conversion Technologies and Electricity Generation Performance

Agricultural residues can be converted into electricity through several pathways, including combustion, gasification, co-firing, anaerobic digestion, and combined heat and power (CHP). The selection of conversion technology depends on biomass characteristics, availability, required energy output, and economic feasibility [1,6]. Recent studies indicate that thermochemical conversion remains dominant for lignocellulosic agricultural residues because of its ability to process various biomass types and directly produce heat, syngas, or electricity.

Different conversion technologies provide different advantages. Combustion is the most mature technology for electricity generation from solid biomass, while gasification provides advantages for small-scale distributed power generation through syngas production. Anaerobic digestion is more suitable for wet organic residues because it converts biodegradable materials into methane-rich biogas [12].

Table 10

Comparison of Biomass Conversion Technologies

Technology	Conversion Process	Suitable Feedstock	Main Product	Electricity Application
Combustion	Direct biomass burning to produce heat	PKS, MF, rice husk	Steam, heat	Large-scale power plants
Gasification	Partial oxidation producing syngas	Rice husk, corn cob, coconut shell	Syngas	Small- to medium-scale electricity generation
Co-firing	Biomass mixed with coal	PKS, EFB	Heat and electricity	Existing coal-fired power plants
Anaerobic Digestion	Microbial degradation without oxygen	Organic agricultural waste	Biogas	Combined heat and power (CHP) generation
Pyrolysis	Thermal decomposition	Coconut shell, corn residues	PKS, Bio-oil, biochar, gas	Indirect electricity generation
CHP	Combined heat and electricity production	Oil palm residues, agro-industrial waste	Heat and electricity	Industrial energy supply

Combustion remains widely applied because of its technological maturity and relatively simple operation. However, its efficiency is highly dependent on biomass moisture and ash content. Residues with high moisture require additional drying, while residues with high ash content may cause operational problems [3].

Gasification provides higher flexibility because biomass is converted into syngas that can be utilized in internal combustion engines or turbines. However, gas cleaning remains a major challenge because tar and particulate formation can reduce generator performance.

3.3.1 Electricity Generation Performance of Oil Palm Residues

Oil palm processing generates several biomass residues, including empty fruit bunch (EFB), mesocarp fiber (MF), and palm kernel shell (PKS). These residues have high electricity-generation potential because they are produced continuously at palm oil mills and can be directly integrated into biomass power systems [7].

Among oil palm residues, PKS generally shows the highest suitability for electricity generation due to its high heating value, low moisture content, and low ash content. EFB has high availability but requires pretreatment because of its high moisture level [7].

Table 11

Electricity Generation Potential of Oil Palm Residues

Residue	Technology	Fuel Characteristics	Electricity Application
PKS	Combustion	High HHV, low moisture	Boiler and power generation
PKS	Co-firing	Similar characteristics to coal fuel	Coal substitution
EFB	CHP combustion	High availability, high moisture	Palm mill electricity supply
MF	Biomass boiler	Moderate-high HHV	Process heat and electricity

The results indicate that PKS has the greatest potential for electricity generation among palm residues because it combines favourable fuel characteristics with relatively easy handling. However, relying only on PKS may create supply competition because it is also used in other biomass markets.

Therefore, integrated utilization of PKS, EFB, and MF is considered more suitable for palm oil industries [7].

Table 12

Reported Electricity Performance of Oil Palm Biomass Systems

Feedstock	System	Reported Output
PKS	Biomass boiler	MW-scale electricity
EFB + MF + PKS	CHP system	Electricity and process steam
Palm residue mixture	Integrated biomass power plant	Industrial energy supply

3.3.2 Electricity Generation Performance of Rice Residues

Rice residues are among the most investigated agricultural biomass resources because of their large production volume. The two major residues are rice husk and rice straw. Rice husk has advantages because it is concentrated at rice mills, while rice straw has higher availability but faces greater collection challenges [12,35].

Table 13

Electricity Generation Performance of Rice Residues

Feedstock	Technology	Operating Condition	Electricity Output
Rice Husk	Gasification	650–900°C	100 kW generator
Rice Husk	Gasification model	Optimized condition	118,924.82 MWh/year potential
Rice Straw	Biomass power model	Large residue availability	~2,500 MW potential
Rice Straw	Combustion	Large-scale system	MW-scale electricity

Rice husk is suitable for gasification because of its availability at centralized milling facilities. However, its high silica content increases ash-related challenges during thermal conversion [12]. Rice straw has a larger theoretical energy potential because of its greater quantity, but practical utilization is limited by transportation, storage, and seasonal availability. Therefore, electricity potential does not always represent commercially achievable output [35].

3.3.3 Electricity Generation Performance of Corn and Coconut Residues

Corn and coconut residues represent additional biomass resources with potential for decentralized electricity generation. Corn residues mainly consist of corn cob and corn stover, while coconut biomass is dominated by coconut shell.

Corn cob has favourable properties because of its low ash content and moderate heating value, making it suitable for combustion and gasification. Coconut shell has higher carbon content, resulting in good performance in thermal conversion processes [9,16].

Table 14

Electricity Potential of Corn and Coconut Residues

Residue	Technology	Main Advantage	Electricity Application
Corn Cob	Gasification	Good syngas production	Small-scale electricity
Corn Cob	Combustion	Low ash content	Thermal power
Corn Stover	Combustion	Large availability	Biomass power plant
Coconut Shell	Combustion	High carbon content	Solid fuel electricity
Coconut Shell	Gasification	High energy density	Distributed electricity

3.3.5 Overall Electricity Generation Comparison

The electricity-generation performance of agricultural residues depends on the interaction between biomass properties and conversion technology. High-quality fuels such as PKS and coconut shell generally provide better thermal conversion performance, while rice husk and agricultural field residues require additional technological considerations because of ash content and supply-chain limitations.

Table 15

Overall Comparison of Agricultural Residue Electricity Potential

Residue	Energy Quality	Main Technology	Electricity Potential
PKS	Very high	Combustion/co-firing	High
Coconut Shell	High	Combustion/gasification	High
MF	High	CHP	Medium-high
EFB	Moderate	CHP after pretreatment	Medium
Rice Husk	Moderate	Gasification	Medium
Rice Straw	Moderate	Combustion	High theoretical potential
Corn Cob	Moderate-high	Gasification/combustion	Medium
Corn Stover	Low-medium	Pretreatment + conversion	Medium

3.3.6 Technical, Environmental, Economic Assessment and Research Gap

The utilization of agricultural residues for electricity generation provides technical and environmental benefits, but implementation depends on several factors, including feedstock availability, conversion efficiency, economic feasibility, and supply-chain management [35].

Table 16

Technical Assessment of Agricultural Residue-Based Electricity Systems

Residue	Technical Advantage	Technical Limitation
PKS	High heating value, low moisture	Limited supply competition
EFB	Large production volume	High moisture
Rice Husk	Available near mills	High ash content
Rice Straw	Large quantity	Difficult collection
Corn Residue	Abundant agricultural source	Seasonal availability
Coconut Shell	High carbon content	Limited large-scale supply

Table 17
Environmental Consideration of Biomass Electricity Systems

Aspect	Positive Impact	Challenge
Carbon emission	Reduces fossil fuel dependence	Life-cycle emissions from transport
Waste management	Converts residues into energy	Requires proper ash handling
Agriculture	Supports circular economy	Residue removal may affect soil nutrients
Energy security	Provides renewable energy source	Requires stable biomass supply

Biomass electricity systems can reduce greenhouse gas emissions when agricultural residues replace fossil fuels. However, environmental benefits depend on the entire life cycle, including collection, transportation, processing, and conversion efficiency [19,51].

Table 18
Economic Factors Affecting Biomass Electricity Development

Factor	Influence on System
Feedstock availability	Determines plant capacity
Transportation distance	Affects biomass cost
Pretreatment requirement	Increases investment cost
Technology selection	Determines efficiency
Plant scale	Influences economic feasibility

Overall, agricultural residues demonstrate significant potential as renewable electricity sources. However, future development requires integration between biomass characterization, conversion technology optimization, supply-chain management, and economic assessment. Recent reviews highlight that future biomass research is shifting from simple energy recovery toward integrated systems combining electricity, fuels, and value-added products.

4. Conclusions

Agricultural residues demonstrate significant potential as renewable feedstocks for electricity generation due to their availability, energy characteristics, and suitability for various conversion technologies. The comparison of biomass properties showed that residues such as palm kernel shell (PKS) and coconut shell provide better fuel quality because of their higher heating value, lower moisture content, and favourable combustion characteristics. Pretreatment processes, including drying, densification, and thermal upgrading, are important strategies to improve biomass quality and enhance conversion efficiency, particularly for residues with high moisture content. Among the evaluated conversion technologies, combustion, gasification, and combined heat and power (CHP) systems showed promising performance depending on biomass characteristics and application scale. Future development of biomass-based electricity systems requires integrated consideration of feedstock availability, conversion efficiency, environmental impacts, and supply-chain optimization to achieve sustainable renewable energy generation.

Acknowledgement

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Conflict of Interest Statement

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Author Contributions Statement

Zul Fahmi Rusdy Harahap served as the team leader and was responsible for coordinating the overall research activities and ensuring the progress of the study. Muh Rasya Ramadhan contributed to the research process, including literature searching, data collection, and research analysis. Nuraulia Army Syamsuddin was responsible for preparing the initial manuscript based on the research findings. Shafa Nabillah contributed to the development and completion of the manuscript. Nashwa Adilla Tsaniya was responsible for reviewing and correcting the language, grammar, and overall linguistic quality of the manuscript. All authors contributed to the review and finalization of the manuscript and approved its final version for publication.

Data Availability Statement

The data used in this study were obtained from relevant literature sources and processed research data that support the analysis, discussion, and conclusions presented in this manuscript. Supporting data and information may be made available by the authors for academic purposes upon reasonable request, subject to the applicable terms and conditions governing the use of the data.\

Ethics Statement

This study is based on literature analysis, data processing, and technical modeling; therefore, it does not involve human participants, animals, or the collection of personal information. Ethical approval from a research ethics committee was consequently not required. The study was conducted in accordance with principles of academic integrity, accurate data processing, and objective reporting of the research findings.

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