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Emerging Technologies in Bioenergy Production from Agricultural Residues in Developing Countries: A Review Paper

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***Abstract:** Agricultural residues represent a considerable yet untapped source of sustainable bioenergy, particularly in developing countries, where biomass accounts for 0.01-4% of global energy demand, with 2% in rural areas. This review is guided by the PRISMA 2020 guidelines and examined more than 600 papers, of which 60 were selected. Thermochemical conversion technologies, such as pyrolysis and gasification, achieve higher efficiencies (60-80%) and are ideal for industrial applications, whereas biochemical technologies, such as anaerobic digestion (efficiencies of 50-70%), are best suited for decentralized rural areas. Improvements in biorefinery technology, precision agriculture, and biotechnology can increase biomass output by up to 20% and reduce costs by 15-30%. However, challenges such as capital expenses, limited technical know-how, and competition for food-energy uses persist, with most technologies having Technology Readiness Levels (TRLs) between 4 and 7.*

***Keywords:** Agricultural Bioenergy; Bioenergy; Biomass; Biorefineries; Biofuel; Climate Change Mitigation*

Nomenclature:
AI: Artificial Intelligence
BECCS: Bioenergy with Carbon Capture and Storage
CHP: Combined Heat and Power
DOAJ: Directory of Open Access Journals
CO_2: Carbon Dioxide
GHG: Greenhouse Gas
IPCC: Intergovernmental Panel on Climate Change
IoT: Internet of Things
IEA: International Energy Agency
IRENA: International Renewable Energy Agency
LCA: Life Cycle Assessment
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
TRL: Technology Readiness Level
UNDP: United Nations Development Programme

I. INTRODUCTION

Agricultural bioenergy production is a crucial point of intersection between sustainable energy production and resilient agricultural systems. Biomass can play a critical role in addressing challenges related to mitigation and energy supply [1]. The combination of biomass production and sustainable agriculture increases the efficiency of resource use and helps with carbon sequestration, which is in favour of environmental sustainability goals [2]. Technological development in biomass conversion, including thermochemical and biochemical methods, is crucial for improving production efficiency [3]. This allows for conversion of agricultural wastes into energy sources [4]. However, the problem of land-use conflicts and other challenges has to be addressed for the successful implementation of the biomass potential for agriculture [5].

Agricultural bioenergy encompasses various ways of transforming biomass into energy, including thermal, biochemical, and physical processing. While the conventional practice of burning biomass is still prevalent, new developments have expanded the scope to the production of liquid biofuels such as ethanol and biodiesel and biogas from anaerobic digestion [5]. With the use of diverse feedstocks ranging from fast-growing energy crops, biomass wastes, and livestock waste, bioenergy systems offer flexibility, facilitate proper waste management practices, and minimize pollution to the environment [7]. Furthermore, these bioenergy systems promote sustainable development through nutrient cycling and minimization of greenhouse gas emissions [6].

Technological advancements have significantly increased the importance of bioenergy in agriculture, transforming it from a supplementary energy source to a vital component of global energy systems. Improvements in thermochemical and biochemical conversion technologies, including gasification, pyrolysis, and anaerobic digestion, enhance biomass production and minimize its ecological footprint, facilitating biofuel, biogas, and other useful compounds production [8]. Additionally, precision agriculture and biotechnology increase feedstock efficiency and improve their resistance, which is important for sustainable resource management [9]. Biorefineries' development is another important aspect since it allows converting biomass into valuable products, such as bioplastics and biochemicals, which contributes to the implementation of the circular economy principles [4], [10]. Overall, these developments help to address energy requirements, mitigate climate change, and support rural areas [3], [4].

Despite considerable efforts in biomass conversion research, there

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remains an inadequacy in the development of technologies that combine precision agriculture with biorefineries, particularly in developing countries. Agricultural bioenergy is considered the primary pathway to enhancing energy security, reducing greenhouse gas emissions, and fostering sustainable rural development by efficiently using agricultural waste. However, the reviewed technologies are not well integrated in the current literature, and there is little focus on integrating them into more complex systems, such as agriculture or the energy sector.

To develop scalable, efficient, and environmentally friendly technologies, it is necessary to understand how they can be integrated with digital agriculture, efficient resource use and circular bioeconomy models. Also, empirical knowledge of how the system works in practice, its impacts on soil, socio-economic aspects, and sustainability is lacking. Thus, the purpose of this literature review is to provide an overview of current bioenergy technologies, analyse their interdependencies and implementation challenges, and explore possible ways to develop a specific integrated bioenergy system. The objectives of the review are to (1) review current bioenergy technologies, (2) identify trends in bioenergy, and (3) suggest future technologies.

A. Enhanced Research Gap and Novel Contribution

The primary drawback of current research on agricultural bioenergy technology lies in its technological aspect. Most research analyses technology in isolation, without considering system integration, inter-industry dynamics, or the sustainability of these technologies. Therefore, there are few comprehensive models of how these bioenergy technologies affect agricultural efficiency, climate resilience, IT advancements, rural industry development, and circular resource management.

In addition, there is little analysis of the integration of AI, IoT, and precision agriculture into the biomass supply chain; the integration of bioenergy systems with agro-processing and rural industry; the negative carbon footprint of agricultural bioenergy; and Socio-Technical constraints in developing countries.

II. MATERIALS AND METHODS

A. Literature Search Strategy and Screening

This systematic review was conducted in accordance with the PRISMA 2020 guidelines, which provide detailed guidance for transparent, thorough reporting of systematic reviews. This procedure consists of four steps: identification, screening, eligibility, and inclusion of studies, in accordance with the PRISMA flow guidelines. Literature on bioenergy technologies was obtained from different literature sources. The keywords used to evaluate the bioenergy trend are presented in Table I. Literature screening was conducted in accordance with the sections mentioned in this paper. Of more than 600 papers, 60 have been found relevant to this review.

Table-I: Keywords and Some of the Combinations Used to Search the Literature in the Web of Science, Directory of Open Access Journals (DOAJ), Google Scholar, and ResearchGate

Keywords	Combinations Used
Bioenergy	Agricultural bioenergy systems
Biomass	Biomass conversion technologies
Biofuels	Advanced biofuels production
Biogas	Anaerobic digestion of agricultural waste
Bioethanol	Lignocellulosic bioethanol production
Biodiesel	Biodiesel from oilseed crops
Agricultural residues	Crop residues for bioenergy
Feedstock	Sustainable biomass feedstock production
Biorefinery	Integrated biorefinery systems
Conversion technologies	Thermochemical and biochemical conversion
Pyrolysis	Fast pyrolysis of biomass
Gasification	Biomass gasification systems
Hydrothermal liquefaction	Hydrothermal conversion of wet biomass
Anaerobic digestion	Biogas production from manure and waste
Circular economy	Bioenergy and circular economy systems
Waste-to-energy	Agricultural waste valorization
Sustainability	Sustainable bioenergy production
Greenhouse gas emissions	Bioenergy and emissions reduction
Climate change	Bioenergy for climate mitigation
Energy efficiency	Efficiency of biomass conversion systems
Rural energy	Bioenergy for rural electrification
Energy access	Decentralized bioenergy systems
Adoption	Adoption of bioenergy technologies
Policy	Bioenergy policy and regulatory frameworks
Storage	Biomass storage and handling systems
Logistics	Biomass transportation systems
Innovation	Emerging bioenergy technologies
Biotechnology	Genetic engineering for bioenergy crops
Energy crops	Dedicated bioenergy crops
Soil fertility	Bioenergy and soil health
Food vs fuel	Food security and bioenergy production
Rural development	Socio-economic impacts of bioenergy
Modelling	Bioenergy system modeling
Simulation	Simulation of biomass conversion processes
Optimization	Optimization of bioenergy systems
Energy yield	Biomass energy yield estimation
Integrated systems	Bioenergy integration with agriculture

B. Criteria for Paper Selection

Selection criteria were formulated in accordance with PRISMA requirements to ensure consistency, relevance, and transparency in the article selection process. Articles on bioenergy generation, biomass conversion, novel technologies, emerging trends, or practical applications, published in scientific journals, conference proceedings, or reports, were selected. Only articles written in English between 2010 and 2026 were considered.

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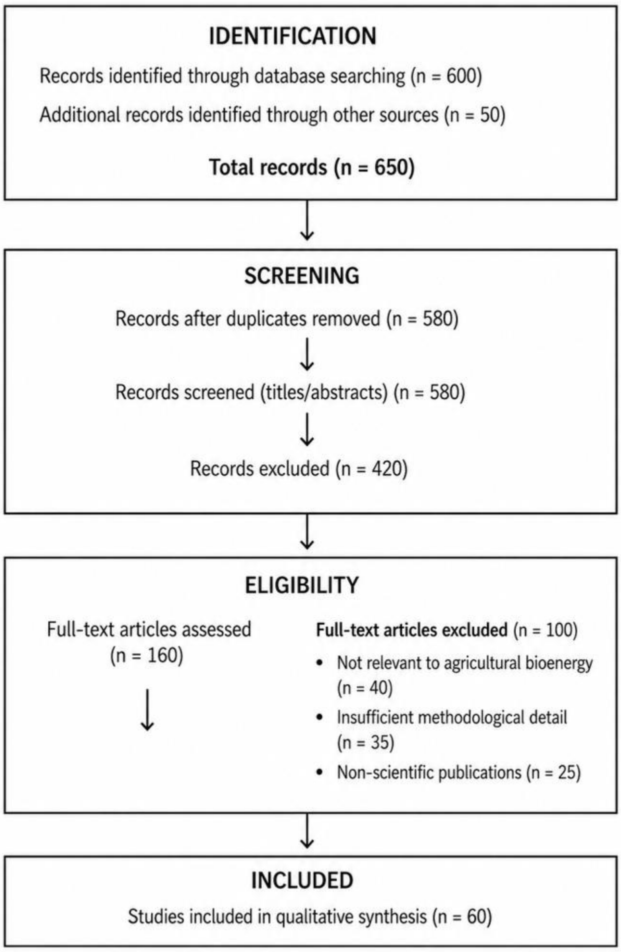
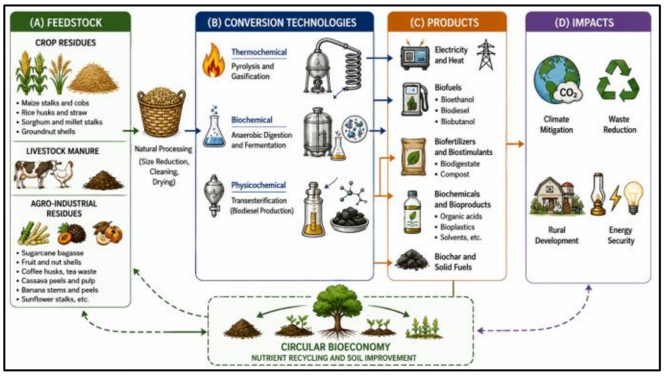
Articles that did not discuss agricultural biomass utilisation, editorial pieces, non-scientific writings, lacked methodological or technical details, were duplicates, or had full texts unavailable were excluded from consideration. The screening process is presented in Fig.1.



[Fig.1: Screening Flow Diagram (PRISMA)]

C. Conceptual Framework

Fig.2 illustrates bioenergy production from residues, showing how the process proceeds from feedstock to energy products via pre-treatment, conversion processes, and biorefinery, including the socio-environmental consequences of the circular bioeconomy model.



[Fig.2: A conceptual Framework for Bioenergy Production]

III. RESULTS

A. Current State of Agricultural Bioenergy Production

Agricultural bioenergy is of great importance to global renewable energy efforts as it converts agricultural biomass into energy forms such as heat, electricity, biofuel, and biogas. It provides a considerable share of energy requirements, accounting for about 10-14% of global energy consumption, with up to 90% in rural areas [11], [12]. Technological advancements, including improvements in biomass conversion and genetic engineering, enhance the effectiveness of agricultural bioenergy, thereby improving energy security and rural development [3], [4]. However, some problems, such as improper biomass handling, land-use conflicts, and cost-effective technology, among others, persist [12]. Overcoming such problems through cooperation and appropriate policies is important for realizing the potential of agricultural bioenergy for combating climate change and promoting economic growth in rural areas [12], [13]. As countries move towards cleaner energy sources, the significance of agricultural bioenergy in reducing carbon emissions, diversifying energy sources, and developing rural areas is growing. However, the current situation presents both promising and challenging aspects.

i. Recent Production Methods

Agricultural bioenergy uses biomass feedstock, comprising various organic materials from crops, plants, and agricultural residues. Traditional methods mostly utilize the combustion of biomass to obtain heat and energy, especially in areas that have many agricultural sources [12]. Furthermore, there is increasing use of liquid biofuels, such as ethanol and biodiesel, to replace fossil fuels in transport applications. Such biofuels are usually made from feedstocks including sugarcane, corn, and soybeans using methods such as fermentation and transesterification [5], [14].

Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen to produce biogas, which mainly consists of methane and carbon dioxide. The obtained biogas can then be used to generate energy, provide heat, and power transportation. Some common feedstocks include agricultural waste, animal manure, and other organic wastes, which are cheap sources that also minimize pollution and waste accumulation [15], [16].

ii. Bioenergy Opportunities in Developing Countries

Table II presents opportunities, efficiency, costs, and sustainability for bioenergy technologies.

Table-II: Bioenergy Technologies: Opportunities, Efficiency, Costs, and Suitability

Type of Bioenergy	Opportunities	Efficiency (%)	Cost Level (Relative)	Suitability for Developing Countries	Image
Biogas (Anaerobic Digestion)	Clean cooking fuel, rural electrification, organic fertiliser (digestate), [17]	50–70	Medium (initial), Low (operational)	Highly suitable for livestock-rich rural areas; ideal for smallholder farmers and institutions	
Biomass Briquettes & Pellets	Waste utilization, an alternative to charcoal, income generation [18]	70–85	Low–Medium	Very suitable due to low technology requirement; supports SMEs and women/youth groups.	
Bioethanol	Transport fuel substitution, agro-industrial value addition [19]	60–75	High	Suitable where sugarcane/cassava is abundant; requires industrial-scale investment	
Biodiesel	Local fuel production supports oilseed value chains [20]	70–90	Medium–High	Suitable for countries with oil crops (e.g., sunflower, palm); scalable from small to large	
Biochar (Pyrolysis)	Soil fertility improvement, carbon sequestration [21]	30–50 (energy), high soil benefit	Low–Medium	Highly suitable for agroecological farming systems; low-tech options available	
Biomass Gasification	Electricity generation, Agro-processing energy [19]	60–80	Medium-High	Suitable for rural industries and mini-grids; requires technical capacity and maintenance.	

iii. Challenges and Limitations

Agricultural bioenergy production is hindered by competition for land and resources between food and energy crops. The expansion of bioenergy crops may affect food security, biodiversity, and soil degradation, especially when agricultural land is limited [23]. There are also environmental issues raised by the lack of neutrality of bioenergy with respect to carbon dioxide emissions, due to indirect land-use effects and emissions during crop cultivation [16], [17]. Financial issues, including commodity price volatility and poor infrastructure, hinder progress, underscoring the need for effective policies and technological innovations to address food and energy challenges [24], [26]. Solutions to these challenging questions must be multidimensional in addressing land use, water consumption, and ecological issues in bioenergy agriculture [22], [25].

B. Importance of Advancing Technologies

Advancements in technology are an important factor that positively influences bioenergy systems in agriculture. This implies the development of thermochemical and biochemical processes to maximise biomass utilisation, increase energy production, and minimise environmental impacts [3], [24]. This includes processes such as gasification, pyrolysis, and anaerobic digestion, in which agricultural waste biomass is converted into biofuels, biogas, and biochar to promote a circular economy and reduce greenhouse gas emissions [4], [27]. Furthermore, technological advancements in precision agriculture and genetic engineering lead to improved quality and quantity of feedstock, hence increased bioenergy efficiency [3], [26]. Biorefineries are an

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important part of these advancements, converting agricultural waste residues into valuable products using the aforementioned techniques [8], [27].

C. Cutting-Edge Innovations and Trends in Agricultural Bioenergy Development

Innovations in agricultural bioenergy are transforming biomass resource management through highly efficient conversion technologies and biorefineries. Substantial advances in technologies such as hydrothermal liquefaction, fast pyrolysis, and catalytic gasification have improved the conversion process of lignocelluloses and waste organic materials into high-quality biofuels with lower emissions and higher efficiency [9], [12], [28], [29]. The development of biorefinery models with multiple outputs, including biofuels, biochemicals, and bioplastics, is an example of a circular economy approach that promotes resource efficiency and waste management [3], [24]. In addition, the integration of different conversion processes contributes not only to improved financial perspectives but also to sustainability through reduced greenhouse gas emissions and the promotion of rural development [4]. Therefore, this comprehensive approach emphasizes the importance of agricultural bioenergy in creating a sustainable energy future.

New approaches in biotechnology and synthetic biology have made substantial contributions to the development of biomass feedstock through genetic engineering that enhances the biofuel production properties of crops such as lignin digestibility, biomass density, and environmental robustness, allowing crops such as switchgrass, jatropha, and camelina to flourish in marginal lands and be used as biofuels [15], [30], [31]. Such innovations are necessary for the development of cellulosic ethanol, given the emergence of commercial biorefineries and energy crops with high biomass yields [13], [39]. At the same time, innovations in microbial and synthetic biology improve fermentation processes by using engineered microbes and enzymatic pathways to produce advanced biofuels such as cellulosic ethanol and biobutanol [30]. Genome-editing techniques such as CRISPR-Cas and the BioBrick system improve lignin structure and saccharification, thereby increasing bioethanol yield [31], [39]. Creating genetically engineered plants that facilitate cellulose breakdown further decreases the environmental impact and production cost of biofuels [43], [52]. Thus, innovations in biotechnology and synthetic biology show great potential to transform biomass feedstock development and sustainable biofuel production [39].

IoT-based monitoring, AI crop analytics, smart irrigation, and autonomous machinery used in precision agriculture contribute to improved agricultural productivity and sustainability. Such innovations allow precise control of inputs, thereby increasing feedstock quality and yields and decreasing production costs. For instance, a combination of IoT and AI in precision agriculture enables real-time data collection and analysis, supporting decision-making and resource optimisation [32], [34], [41]. Research shows that precision agriculture technologies can increase yields by at least 20%, decrease operating costs by 15-30%, and reduce chemical use by 25%, thereby protecting the environment [35], [59]. Digital platforms can enable predictive modelling and logistics improvements, making bioenergy systems more adaptive and resilient [33]. Alongside these innovations, there is growing interest in low-carbon operations and environmental stewardship. Innovations such as CCS-linked bioenergy (BECCS), biochar production, and methane reduction are contributing to the development of agricultural bioenergy as one of the most important parts of global efforts against climate change [36], [53].

Combining bioenergy with solar, wind, or geothermal energy in hybrid renewable energy systems makes these systems more reliable and efficient, providing decentralized and sustainable energy solution [56], [57]. All these technological innovations contribute to sustainable, profitable agriculture by enhancing food security and profitability. Thus, innovations in precision agriculture can help to address challenges related to climate change and resource scarcity [33], [38]. Although precision agriculture technologies offer many advantages, their implementation is sometimes hindered by high costs, limited expertise, and limited connectivity. It is important to overcome these obstacles through well-designed public policies and infrastructural investments [26], [34], [58].

These innovative trends support such global objectives as energy independence, rural economic growth, and sustainable land use. They demonstrate current progress of agricultural bioenergy toward technological innovation, environmental friendliness, and economic sustainability. With advances in research, public policy, and intersectoral cooperation, agricultural bioenergy will become an important part of the future energy transition and sustainable agriculture. These leading global innovations under development are presented in Table III.

Table III: Innovations and Trends in Agricultural Bioenergy Development

Innovation Area	Technologies / Approaches	Engineering Application	Opportunities in Developing Countries	Advantages / Impact	Limitations / Challenges	TRL	Cost Level	Application Scale	Citations
Advanced Biomass Conversion	Hydrothermal liquefaction, fast pyrolysis, and catalytic gasification	Conversion of lignocellulosic biomass and organic waste into biofuels	Utilization of abundant agricultural residues (maize, rice husks); reduction of open burning; local fuel production	Higher energy yield, lower emissions, improved conversion efficiency	High capital cost, process complexity, and need for skilled operation	5-7	High	Pilot-Early commercial	[9], [16], [55]
Integrated Biorefinery Systems	Multi-product biorefineries (biofuels, biochemicals, bioplastics)	Resource recovery and waste valorization in agricultural systems	Value addition to agro-processing industries (sugar, coffee, palm oil); rural industrialization; export opportunities	Promotes circular economy, enhances economic viability, and reduces waste	Complex integration and supply chain coordination challenges	6-8	High	Pilot-Commercial	[3], [28], [29]
Biotechnology & Genetic Engineering	CRISPR-Cas, BioBrick systems, engineered crops	Development of high-yield, stress-tolerant bioenergy crops	Use of marginal lands; improved resilience to drought; increased feedstock supply without competing with food crops	Improved biomass productivity, enhanced lignin digestibility	Regulatory concerns, high R&D costs, and ecological risks	3-6	High	Lab-Pilot	[15], [30], [31]
Microbial & Enzymatic Engineering	Engineered microbes, advanced fermentation pathways	Conversion of biomass into cellulosic ethanol and biobutanol	Efficient utilization of crop residues; development of local biofuel industries; reduced dependency on imports	Higher conversion efficiency, improved biofuel yield	Process sensitivity, scalability challenges	4-6	Medium-High	Lab-Pilot	[50], [54],
Precision Agriculture Technologies	IoT sensors, AI analytics, smart irrigation, and autonomous machinery	Optimized feedstock production and resource management	Improved biomass yields; efficient input use; integration with mechanization programs; climate-smart agriculture	Increased yield, reduced costs, lower chemical inputs	High initial investment, training gaps, and connectivity issues	6-9	Medium-High	Pilot-Commercial	[26], [35], [38], [51]
Low-Carbon Bioenergy Innovations	BECCS, biochar systems, methane mitigation technologies	Carbon capture and emission reduction	Access to carbon markets; climate finance opportunities; improved soil health (biochar) for smallholders	Supports climate goals, reduces GHG emissions	High infrastructure cost, emerging technology limitations	4-7	High	Pilot-Early commercial	[36], [56], [59]
Hybrid Renewable Energy Systems	Integration with solar, wind, and geothermal	Decentralized and resilient rural energy systems	Rural electrification; powering agro-processing; energy access in off-grid areas	Improved reliability, energy security	Integration complexity, higher setup cost	6-9	Medium-High	Pilot-Commercial	[37], [20]
Digital & Supply Chain Optimization	Predictive modeling, digital platforms	Bioenergy logistics and distribution planning	Improved biomass collection networks; reduced post-harvest losses; efficient service delivery	Improved efficiency, resilience, and decision-making	Data dependency, infrastructure requirements	5-8	Medium	Pilot-Commercial	[33], [45]
Sustainability & Policy Integration	Energy policies, rural development frameworks	Large-scale bioenergy adoption and land management	Enabling environment for investments; job creation; scaling mechanization and energy services	Enhances energy independence, rural income	Policy gaps, funding limitations	7-9	Medium	Commercial-System level	[48], [26]

Table III categorizes Technology Readiness Levels (TRL) from early research (1-3) through pilot validation (4-6) to full commercialization (7-9). This allows bioenergy technologies to be grouped by their implementation timeline: short-term options like biochar, briquettes, biogas, and digital logistics deliver quick, affordable impacts; medium-term solutions such as gasification, hybrid systems, and precision agriculture need scaling; and long-term innovations, including biorefineries, BECCS, and genetic engineering, are more complex and transformative.

D. Future Bioenergy Pathways for Technological Innovation

Technological innovation plays an important role in enhancing agricultural bioenergy production, thereby greatly contributing to the world's transition to sustainable energy. Some innovations have emerged in biomass conversion technologies, including thermochemical, biochemical, and physical methods for converting organic matter into biofuels, biogas, and energy, which serve as alternatives to non-renewable energy sources and help reduce greenhouse gas emissions [4]. Genetic engineering and precision farming increase the efficiency and effectiveness of biomass production, and biorefining further improves resource utilisation [3]. Despite all this, there are still many obstacles, such as efficiency and cost issues, as well as land-use issues, that need to be addressed [42].

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i. Predicted Technological Developments

The future holds significant changes in agricultural bioenergy due to technological developments in biomass conversion processes, genetic engineering, and digital agriculture. Gasification, pyrolysis, and enzymatic hydrolysis will increase process efficiency, reduce costs and negative environmental impacts, and expand the range of available biomass [3], [4], [13]. Moreover, genetically engineered crops for energy purposes are being developed to increase their resilience and biomass production [3]. Moreover, innovations such as the use of smart farming devices, artificial intelligence, and satellite monitoring will make the biomass production process more efficient [3], [32]. These changes are expected to enable agricultural bioenergy to play an important role in renewable energy initiatives [3], [47].

ii. Latent Applications and Benefits

Novel methods of biomass conversion have great significance for enhancing sustainable energy production and fostering rural development. Such techniques, which include thermochemical and biochemical conversion methods, help transform biomass into biofuels and biogas that can serve as renewable energy sources with reduced greenhouse gas emissions [4], [43]. Cultivation of energy crops on marginal lands not only helps increase carbon sequestration and soil quality but also addresses food security problems by utilising non-food feedstocks [43], [44]. Moreover, agroforestry helps maximise socio-economic gains from energy crops by creating jobs and business opportunities for rural people [45].

iii. Challenges and Considerations

Despite the promising nature of innovations in agricultural bioenergy, several important factors should be addressed for effective implementation. There is a need to demonstrate the efficiency and effectiveness of many innovations at a commercial level to verify them [46], [47]. The high costs of implementing the technology and the unclear economic feasibility can make stakeholders hesitant to adopt them [47]. Also, technological transition is associated with various social consequences, including new opportunities and threats in the labour market, changes in livelihoods, and equity issues, particularly in rural communities that rely on traditional agriculture. Environmental concerns related to land-use changes, ecosystem changes, and biotechnology safety require proper assessment and control to prevent ecological damage [22]. Various ethical issues concerning the development of genetic modification and genome-editing technologies require comprehensive governance [15], [30], [31].

E. Comparison of Findings Across Studies

Many studies indicate that thermochemical technologies such as gasification and pyrolysis offer higher efficiency and scalability [3], [12]. High capital costs and complex operations hinder these in developing nations [44]. Biochemical technologies, on the other hand, are considered a suitable choice for decentralised regions, as they involve low costs and easy operation [21].

The concept of an integrated biorefinery is gaining popularity as a revolutionary technology because it generates multiple products and uses resources more efficiently [46]. But this requires infrastructure and an organized supply chain [47]. Technologies like biotechnology and precision farming improve feedstock production and overall process efficiency, but their adoption is hampered by cost and regulatory issues (Table IV).

Table IV: Comparative Analysis of Key Findings in Agricultural Bioenergy Studies

Technology/Aspect	Common Findings	Areas of Agreement	Areas of Variation	Implication
Thermochemical Conversion (Gasification, Pyrolysis)	High efficiency, flexible feedstock use [3], [12]	Suitable for large-scale energy production	High capital cost, complex operation [44].	Best for industrial applications
Biochemical Conversion (Anaerobic Digestion)	Effective for wet biomass, decentralized use [21]	Ideal for rural energy systems	Lower energy yield vs thermochemical methods [6]	Suitable for smallholder systems
Integrated Biorefineries	Multi-product output improves profitability [60]	Aligns with the circular economy	Requires complex integration [47]	Key for long-term sustainability
Biotechnology	Improves biomass yield and quality [54], [49]	Enhances feedstock productivity	Regulatory/ecological concerns	Critical for future systems
Precision Agriculture	Improves yield and efficiency [46]	Reduces input costs	High cost and skill requirements	Enhances optimization
Bioenergy Systems Overall	Improves energy security and reduces emissions [1]	Recognized as a sustainable alternative	Regional scalability differences	Context-specific application

F. Contradictions and Divergent Perspectives

In the context of carbon neutrality, the necessity of conducting life cycle analysis (LCA) arises from the possibility that emissions from changes in land use could cancel out the environmental benefits [31]. Despite the assertion that bioenergy systems work well alongside food production, land conflicts can arise [29].

Feasibility of economics emerges as another point of contention. While advanced forms of bioenergy systems are feasible over the long term, the high capital costs involved prevent immediate application, particularly in less developed countries. Moreover, technological adoption is limited by factors such as infrastructure, skill level, and institutional capacity. Table V illustrates the contradiction within agricultural bioenergy literature.

Table V: Contradictions in Agricultural Bioenergy Literature

Issue	Supporting View	Opposing View	Source of Contradiction	Implication
Carbon Neutrality	Bioenergy reduces GHG emissions [4]	Emissions from land-use change offset benefits [31]	Lifecycle boundaries	Need for LCA
Food vs Fuel	Use of marginal lands reduces conflict [43]	Bioenergy crops compete with food production [29]	Practical land-use realities	Policy regulation required
Economic Viability	Long-term profitability [3]	High upfront cost limits adoption [48]	Scale and investment differences	Financing needed
Technology Adoption	Improves efficiency [60]	Limited adoption due to cost and skills	Socio-economic factors	Capacity building needed
Biotechnology	Improves productivity [54]	Ethical/ecological concerns [46]	Regulatory frameworks	Governance needed
Precision Agriculture	Enhances productivity [14]	Infrastructure limitations [60]	Digital divide	Investment in infrastructure

G. Evaluation of Strengths and Weaknesses of Technologies

This assessment shows that while advanced technologies such as thermochemical processes and biorefineries are relatively efficient, they are limited by high costs and complex technological requirements [8], [46]. Anaerobic digestion technology, on the other hand, provides a more viable solution for developing countries [15], [37].

New technologies such as biotechnology and genetic modification hold great potential but face challenges related to regulation and scale-up [40], [31]. On the other hand, precision farming and digital technologies increase efficiency but require investments in infrastructure and labour [35]. The table below highlights the advantages and disadvantages of different bioenergy technologies.

Table VI: Strengths and Weaknesses of Bioenergy Technologies

Technology	Strengths	Weaknesses	Suitability
Thermochemical	High efficiency, wide feedstock use [8]	High cost, complex operation [49]	Industrial scale
Biochemical	Low cost, waste utilization [15]	Lower energy yield [5], [8].	Rural systems
Biorefineries	Multi-output, resource efficiency [60]	Complex integration [29]	Large-scale systems
Biotechnology	High productivity, improved traits [39]	Regulatory risks, high R&D cost	Future systems
Microbial Systems	High conversion efficiency [40]	Scalability challenges	Pilot scale
Precision Agriculture	Improved efficiency, reduced inputs [26], [36]	High cost, skill requirement	Commercial farms
Low-Carbon Tech (BECCS, Biochar)	Carbon sequestration [36]	High infrastructure cost	Climate-focused projects
Hybrid Systems	Improved reliability [37]	Integration complexity	Decentralized systems
Digital Systems	Improved logistics [33]	Data dependency	Advanced regions

IV. DISCUSSION

A. Researchable Synthesis of Knowledge

As the literature review shows, agricultural bioenergy has transformed, shifting from the traditional waste-to-energy concept to an important part of the circular bioeconomy. One consistent message from the reviewed sources is that conversion technologies, biorefineries, precision agriculture, and biotechnology help make bioenergy systems more efficient and economically sustainable. It is important to note, however, that rather than presenting a single optimal technology, the research shows that different factors affect the performance and appropriateness of each technology.

One of the main conclusions from the above review is that thermochemical and biochemical conversion methods complement each other. On the one hand, thermochemical methods, such as pyrolysis and gasification, offer higher processing efficiency and speed, as well as a wider range of dry biomass feedstocks. For these reasons, they are well suited for large-scale industrial applications. At the same time, these technologies require higher capital investments, are complex, and require specialised conditions of use. On the other hand, biochemical technologies, especially anaerobic digestion, are more appropriate for decentralised operations owing to their low cost, ease of use, and the ability to use wet biomass, e.g., manure. These technologies, however, generate less energy and are slower.

As the reviewed literature shows, the concept of integrated biorefineries can be considered revolutionary, as it enables the simultaneous production of biofuels, biochemicals, and bio-based materials. In this way, resource efficiency increases, and the principles of the circular economy can be implemented. Still, scaling up biorefineries faces challenges related to logistics, infrastructure requirements, and technology integration. For these reasons, despite recognition of the advantages of biorefineries, there remains little empirical evidence of their efficiency.

It should also be noted that technologies such as precision agriculture, digital platforms, and genetic engineering are increasingly recognised as integral components of bioenergy systems. Their role is to improve the quality of biomass as a feedstock and to make its supply chains more effective. However, these technologies are not widely adopted in some developing countries due to their high cost and the lack of necessary infrastructure and competencies.

B. Critical Gaps and Pathways for Sustainable Agricultural Bioenergy Development

Notwithstanding major improvements in agricultural bioenergy, critical limitations have been identified in the existing literature. There is a lack of context-specific comparative analysis of thermochemical and biochemical bioenergy technologies in comparable real-world situations. There is a lack of information on soil health, particularly the long-term impact of residue removal. Many technologies remain in the pilot phase without commercial validation, and socio-economic aspects (e.g., farmers' willingness to adopt such technologies, financing, and institutional support) are insufficiently considered. Moreover, many studies use incomplete LCA analyses that overlook land-use changes, logistics, and co-products. In addition, there is insufficient research on integrated and hybrid systems. Finally, no solutions have been found to the regulatory, ethical, and governance problems in biotechnology and digital agriculture. To address such gaps, there should be a clear research agenda that includes techno-economic comparisons in real-world settings, sustainable residue management, full-scale validation, comprehensive LCA, and socio-economic and policy considerations. Overall, the future of agricultural bioenergy depends on developing integrated, context-specific systems that balance efficiency, cost, environmental sustainability, and social feasibility. Thermochemical approaches are appropriate for industrial applications; however, biochemical approaches are better suited to decentralised rural systems. Nevertheless, the major problem is the lack of integrated empirical data on the connections among bioenergy production, soil health, and economic and social sustainability, which are crucial to achieving sustainable bioenergy [57].

C. Conceptual Advancements Beyond Existing Literature

i. Transition from Technology-Centred to System-Centred Bioenergy Frameworks

Earlier studies have focused more on evaluating individual bioenergy systems, with an emphasis on energy conversion and generation efficiency or on the environmental impacts of these technologies. The novelty of this review lies in its systems-based approach, which considers bioenergy technologies within a broader socio-technical context.

ii. Integration of Precision Agriculture with Bioenergy Systems

One major concept that needs highlighting is the connection among AI, IoT, precision farming, and digital logistics applied in biomass production and transportation. Normally, these concepts are not associated, as most scholarly literature treats bioenergy and precision agriculture as separate domains. This review provides a conceptual bridge between smart farming technologies and the production and transportation of biomass energy.

iii. Advancement Toward Circular Bioeconomy and Integrated Biorefineries

In contrast to traditional reviews that consider only energy production, this review calls for integrating biorefineries that provide not only biofuels but also biochemicals, biochar, electricity, fertiliser, and biomaterials. This review identifies agricultural waste as a valuable component of the circular bioeconomy, rather than waste.

iv. Context-Specific Framework for Developing Countries

The majority of bioenergy studies consider case studies conducted in industrialised countries. The present review offers an expanded scope of analysis by including developing countries in general, and Sub-Saharan Africa and Tanzania in particular. Special attention is paid to decentralised technologies, cost-effective methods, the use of agricultural biomass, rural electrification, and innovations for small-scale farms.

v. Linking Bioenergy with Climate Resilience and Carbon-Negative Pathways

The review enriches the literature by situating agricultural bioenergy within broader strategies for climate change mitigation and carbon management. It considers new concepts such as Bioenergy with Carbon Capture and Storage (BECCS), the use of biochar, methane reductions, and low-carbon hybrid energy approaches. The shift thus takes place from the production of renewable energy to the creation of carbon-negative agriculture and climate-smart rural development.

vi. Multi-Dimensional Sustainability Assessment

Current research tends to analyze either energy efficiency or economic viability alone. This review, however, offers a more holistic outlook by taking into account technical viability, socioeconomic viability, sustainability, institutional readiness, policy viability, and Technology Readiness Levels (TRLs).

vii. Hybrid and Integrated Renewable Energy Perspective

The review not only focuses on individual biomass applications but also covers hybrid renewable energy systems in which bioenergy is combined with solar, wind, and geothermal energy. This way, bioenergy will be part of decentralised and resilient energy systems, rather than remaining a stand-alone source of renewable energy.

viii. Introduction of a Socio-Technical Transition Perspective

This paper contributes to the body of literature on bioenergy by incorporating socio-technical transitions into the research framework and arguing that technological innovations alone will not guarantee success. Governance, infrastructure, institutional capabilities, funding, farmer involvement, the digital divide, and policy play important roles in a successful bioenergy transition.

V. CONCLUSION

This paper reviewed the current state of technological innovation in agricultural bioenergy, as well as trends and prospects. The agricultural bioenergy sector is highly prospective, with significant potential to enhance production sustainability, ensure energy security, and support rural development. To achieve these goals, innovative measures and collaboration are needed. In particular, innovations in technology, biomass conversion, energy crop cultivation, and digital agriculture can enhance efficiency and sustainability in bioenergy.

To realise the full potential of the agricultural bioenergy sector, it is necessary to invest in research activities, build cross-sectoral partnerships, and promote technology transfer. Innovations should take into account the environmental, social, and economic aspects of the agricultural bioenergy sector to ensure a balanced use of the sector. By addressing climate change, energy insecurity, and rural poverty, agricultural bioenergy could become a promising renewable energy source.

The major theoretical advancement introduced by this review is the definition of agricultural bioenergy not as a biomass conversion technology alone, but rather as a climate-smart circular bioeconomy that promotes sustainable development in developing countries. Such a systems approach is the basis for further research and implementation measures.

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