World Journal of Advanced Engineering Technology and Sciences

eISSN: 2582-8266

Cross Ref DOI: 10.30574/wjaets

Journal homepage: https://wjaets.com/

(Review Article)

Policy approaches for bioenergy development in response to climate change: A conceptual analysis

Jephta Mensah Kwakye [1, *], Darlington Eze Ekechukwu [2] and Olorunshogo Benjamin Ogundipe [3]

[1] *Independent Researcher, Texas USA.*
[2] *Independent Researcher, UK.*
[3] *Department of Mechanical Engineering, Redeemer's University, Ede, Osun-State, Nigeria.*

World Journal of Advanced Engineering Technology and Sciences, 2024, 12(02), 299–306

Publication history: Received on 08 June 2024; revised on 17 July 2024; accepted on 19 July 2024

Article DOI: https://doi.org/10.30574/wjaets.2024.12.2.0292

Abstract

This review paper explores policy approaches for integrating bioenergy into agricultural practices to address climate change. It examines existing national and international policy frameworks, analyzes the potential synergies between bioenergy and agriculture, and identifies challenges and opportunities for bioenergy development. A conceptual model for policymakers is proposed, emphasizing policy instruments, stakeholder engagement, and monitoring frameworks to optimize bioenergy outcomes. The model underscores the importance of holistic approaches tailored to specific contexts. By prioritizing sustainability, equity, and inclusivity, policymakers can unlock the transformative potential of bioenergy to mitigate greenhouse gas emissions, enhance climate resilience, and promote sustainable development.

Keywords: Bioenergy; Policy Approaches; Agriculture; Climate Change; Conceptual Model; Sustainability

1. Introduction

Bioenergy, derived from organic materials such as crops, forestry residues, and organic waste, holds significant promise in the fight against climate change (Dahiya, 2020; Sri Shalini, Palanivelu, Ramachandran, & Raghavan, 2021). As the world grapples with the dual challenges of reducing greenhouse gas emissions and adapting to the impacts of a changing climate, bioenergy development emerges as a crucial component of sustainable energy solutions. Climate change poses unprecedented threats to ecosystems, economies, and human well-being (Adewumi, Olu-lawal, Okoli, Usman, & Usiagu, 2024; Saleh & Hassan, 2024). Burning fossil fuels for energy production is a major contributor to the accumulation of greenhouse gases in the atmosphere, exacerbating the climate crisis. In contrast, bioenergy offers a renewable and potentially carbon-neutral energy source. Through photosynthesis, plants absorb carbon dioxide from the atmosphere, which is later released when the biomass is converted into energy. Bioenergy systems can effectively sequester carbon when sustainably managed, mitigating climate change (Aresta & Dibenedetto, 2021; Barot, 2022).

Moreover, bioenergy holds promise in enhancing climate change adaptation efforts. Climate-induced disruptions, such as extreme weather events and shifts in precipitation patterns, pose significant challenges to agriculture. Integrating bioenergy production into agricultural systems can diversify income sources for farmers, improve soil health, and enhance resilience to climate variability. Bioenergy builds adaptive capacity in vulnerable communities by promoting sustainable land management practices and reducing dependence on fossil fuels (Buss, Mansuy, & Madrali, 2021; Nguyen, Grote, Neubacher, Do, & Paudel, 2023).

Realizing the full potential of bioenergy requires supportive policy environments that incentivize investment, innovation, and sustainable practices. Existing policy frameworks often lack coherence and consistency, hindering the

* Corresponding author: Jephta Mensah Kwakye

widespread deployment of bioenergy technologies. Furthermore, conflicting priorities and vested interests may impede the development of comprehensive strategies for integrating bioenergy into agricultural landscapes. Effective policies must balance promoting bioenergy deployment and safeguarding environmental integrity, food security, and social equity.

This paper aims to conceptualize policy approaches for bioenergy development in response to climate change. Specifically, it seeks to:

- Evaluate existing policy frameworks at the national and international levels aimed at promoting bioenergy production.
- Examine the potential synergies between bioenergy and agricultural practices in climate change mitigation and adaptation.
- Identify challenges and opportunities in integrating bioenergy into agricultural landscapes.
- Propose a conceptual model for policymakers to optimize bioenergy outcomes while addressing climate change challenges.

In conclusion, this paper seeks to contribute to the growing discourse on bioenergy development by providing insights into the policy mechanisms and strategies necessary for its effective integration into agricultural landscapes in the context of climate change mitigation and adaptation.

2. Policy Approaches for Bioenergy Development

Governments worldwide have recognized bioenergy's potential to mitigate climate change, enhance energy security, and promote rural development. As a result, numerous policy instruments have been implemented to incentivize bioenergy production and consumption. Countries have adopted various approaches at the national level, including renewable energy mandates, feed-in tariffs, tax incentives, and subsidies for bioenergy projects. Similarly, international agreements such as the Paris Agreement and the Sustainable Development Goals (SDGs) have underscored the importance of renewable energy, including bioenergy, in achieving global climate and development objectives (Daneshmandi, Sahebi, & Ashayeri, 2022; Daszkiewicz, 2020; Painuly & Wohlgemuth, 2021).

Successful bioenergy policies typically incorporate several key elements:

- Incentives: Financial incentives, such as subsidies, tax credits, and feed-in tariffs, are crucial in stimulating investment in bioenergy projects and incentivizing market uptake.
- Regulations: Regulatory frameworks that mandate renewable energy targets, emission reduction goals, and sustainability criteria provide clarity and certainty to investors and developers.
- Targets: Clear and ambitious targets for bioenergy deployment help drive investment and innovation in the sector, fostering growth and scalability.
- Supportive Infrastructure: Policies that support the development of infrastructure for bioenergy production, distribution, and consumption, including research and development funding and investment in transportation and storage facilities, are essential for the success of bioenergy initiatives.

Despite progress in policy development, several challenges and limitations persist in current approaches to bioenergy promotion. For instance, policy objectives related to bioenergy development may conflict with other policy goals, such as food security, biodiversity conservation, and land use planning, leading to trade-offs and compromises. Limited land, water, and biomass resource availability may constrain bioenergy projects' scalability, particularly in densely populated or ecologically sensitive regions (Ibe, Ezenwa, Uwaga, & Ngwuli, 2018; Omole, Olajiga, & Olatunde, 2024a; Thompson, Akintuyi, Omoniyi, & Fatoki, 2022).

Technological uncertainties and performance risks associated with bioenergy conversion technologies, such as biomass-to-energy processes and biofuel production methods, pose challenges to investment and deployment. Bioenergy production can have adverse environmental and social impacts, including deforestation, habitat loss, competition for land and water resources, and conflicts over land tenure and resource rights (Duguma, Kamwilu, Minang, Nzyoka, & Muthee, 2020; Reid, Ali, & Field, 2020; Varela Pérez, Greiner, & von Cossel, 2022).

Addressing these challenges requires innovative policy mechanisms and strategies tailored to local contexts and specific bioenergy applications. Policies promoting bioenergy integration into broader sustainable development strategies, such as agroforestry, conservation agriculture, and waste management, can maximize co-benefits and minimize trade-offs.

Comprehensive sustainability standards and certification schemes that address environmental, social, and economic criteria can help ensure that bioenergy projects adhere to best practices and mitigate potential negative impacts (Nguyen et al., 2023; Welfle & Röder, 2022).

Increased investment in research and development to improve bioenergy technologies, enhance resource efficiency, and develop innovative feedstocks can drive technological innovation and cost reduction. Finally, policies prioritizing community engagement, participatory decision-making, and benefit-sharing mechanisms can enhance social acceptance and equity in bioenergy development initiatives. While existing policy frameworks have significantly promoted bioenergy development, addressing challenges and maximizing benefits requires continued innovation and adaptation. By incorporating key elements of successful policies and exploring innovative approaches, policymakers can unlock the full potential of bioenergy as a sustainable energy solution in the transition to a low-carbon future (Aturamu, Thompson, & Banke, 2021; Eyo-Udo, Odimarha, & Kolade, 2024; Osuagwu, Uwaga, & Inemeawaji, 2023).

3. Integration of Bioenergy into Agricultural Practices

Bioenergy production and agricultural activities are inherently interconnected, offering opportunities for synergistic interactions. Agriculture generates vast quantities of biomass residues, such as crop residues, animal manure, and food processing waste, which can serve as feedstocks for bioenergy production. By valorizing these residues through bioenergy conversion processes, farmers can generate additional income streams, reduce waste disposal costs, and improve resource efficiency.

Furthermore, bioenergy production can complement agricultural practices by providing on-farm energy solutions, such as biogas for heating, electricity, and mechanized farming operations. This can enhance energy security, reduce dependence on fossil fuels, and promote rural electrification and economic development in agricultural communities (Odimarha, Ayodeji, & Abaku, 2024a, 2024b; Omole, Olajiga, & Olatunde, 2024b).

3.1. Review of Agricultural Practices Conducive to Bioenergy Production

Several agricultural practices are conducive to bioenergy production, including:

- Crop Residue Management: Harvest residues, such as straws, stalks, and husks, can be collected and utilized as feedstocks for bioenergy production, including biogas digestion, biomass combustion, and biofuel production.
- Dedicated Energy Crops: Growing dedicated energy crops, such as switchgrass, miscanthus, and willow, on marginal or underutilized land can provide sustainable biomass feedstocks for bioenergy production without competing with food crops.
- Agroforestry: Integrating trees and shrubs into agricultural landscapes through agroforestry practices can enhance biodiversity, soil fertility, and carbon sequestration while providing woody biomass for bioenergy production.

The integration of bioenergy into agricultural systems offers both environmental and socio-economic benefits, as well as trade-offs. Bioenergy production can contribute to greenhouse gas mitigation by displacing fossil fuels and sequestering carbon in biomass feedstocks. Additionally, bioenergy systems can improve soil health, reduce erosion, and enhance biodiversity by promoting sustainable land management practices. Bioenergy integration can enhance rural livelihoods by creating employment opportunities, generating additional income for farmers, and diversifying rural economies. Moreover, decentralized bioenergy production systems can improve energy access and resilience in remote and off-grid areas (Kuyah et al., 2020).

However, there are also potential trade-offs and risks associated with bioenergy integration:

- Land Use Competition: Intensive bioenergy production may compete with food production, leading to land use conflicts and potential trade-offs with food security and biodiversity conservation objectives.
- Resource Constraints: The availability of land, water, and biomass resources may limit the scalability of bioenergy projects, particularly in densely populated or ecologically sensitive regions.
- Environmental Impacts: Bioenergy production can have adverse environmental impacts, including deforestation, habitat loss, water pollution, and soil degradation, if not managed sustainably.
- Successful integration of bioenergy into agricultural systems requires careful planning, stakeholder engagement, and adaptive management. Key lessons learned from successful integration efforts include:
- Engaging diverse stakeholders, including farmers, policymakers, researchers, and local communities, is essential for designing and implementing effective bioenergy integration initiatives.

- Adopting context-specific approaches that consider local agro-ecological conditions, socio-economic contexts, and institutional arrangements can enhance the feasibility and sustainability of bioenergy projects.
- Investing in capacity building, technical assistance, and knowledge transfer to support farmers and rural communities in adopting sustainable bioenergy practices is critical for project success.
- Implementing robust monitoring and evaluation mechanisms to assess bioenergy integration projects' environmental, social, and economic impacts is essential for adaptive management and continuous improvement.

By capitalizing on synergies between bioenergy and agriculture, adopting sustainable practices, and addressing potential trade-offs, policymakers and practitioners can harness the full potential of bioenergy to promote rural development, enhance energy security, and mitigate climate change.

4. Climate Change Mitigation and Adaptation Strategies

Bioenergy holds significant promise as a renewable energy source that can mitigate greenhouse gas emissions and decrease reliance on fossil fuels. By harnessing organic materials such as crop residues, forestry residues, and organic waste, bioenergy systems can provide heat, electricity, and transportation fuels while sequestering carbon dioxide from the atmosphere. Through photosynthesis, plants absorb carbon dioxide during growth, and when converted into bioenergy, this carbon is released, forming a closed carbon cycle that is fundamentally different from the one-way emission of fossil fuels. As such, bioenergy can be crucial in decarbonizing energy systems and transitioning towards a low-carbon economy.

In addition to its mitigation potential, bioenergy can enhance the resilience of agricultural systems to climate change impacts. Climate change poses numerous challenges to agriculture, including shifts in temperature and precipitation patterns, increased frequency of extreme weather events, and changes in pest and disease dynamics. Bioenergy integration offers opportunities for climate change adaptation by promoting sustainable land management practices, enhancing soil fertility and water retention, and diversifying farmer income streams. For example, agroforestry systems that incorporate bioenergy crops can improve soil carbon sequestration, enhance biodiversity, and provide alternative sources of income during periods of crop failure.

The deployment of bioenergy entails both potential co-benefits and risks in the context of climate change. Bioenergy deployment can yield multiple co-benefits beyond climate change mitigation and adaptation, including rural development, job creation, energy access, and ecosystem restoration. Furthermore, bioenergy production from waste streams can reduce waste disposal and pollution, contributing to environmental sustainability (Abaku & Odimarha, 2024; Emmanuel, Edunjobi, & Agnes, 2024; Omole, Olajiga, & Olatunde, 2024c).

However, there are also risks associated with bioenergy deployment, such as land use change, competition for resources, and environmental degradation. Large-scale monoculture plantations for bioenergy feedstock production may lead to habitat destruction, biodiversity loss, and soil degradation if not managed sustainably. Additionally, there are concerns about the indirect land use change effects of bioenergy production, which may exacerbate deforestation and emissions if bioenergy crops displace food crops or natural ecosystems.

Bioenergy development interacts with various climate change mitigation and adaptation strategies, resulting in synergies and trade-offs (Cohen, Cowie, Babiker, Leip, & Smith, 2021; Moreno et al., 2023; Vera et al., 2022). Bioenergy development can complement other renewable energy sources, such as wind and solar, by providing dispatchable and baseload power, thereby enhancing the reliability and resilience of energy systems. Bioenergy integration with carbon capture and storage (BECCS) can also achieve negative emissions, further contributing to climate change mitigation efforts (Akinyi, Karanja Ng'ang'a, & Girvetz, 2021).

However, there are also trade-offs between bioenergy development and other climate change strategies. For example, bioenergy expansion may compete with food production, leading to conflicts over land use and potential trade-offs with food security objectives. Furthermore, there are trade-offs between bioenergy and biodiversity conservation goals, as large-scale bioenergy feedstock cultivation may encroach upon natural habitats and degrade ecosystem services.

5. Conceptual Model for Policymakers

The proposed conceptual model for policymakers aims to guide the design and implementation of effective bioenergy policies that maximize benefits while minimizing risks. It emphasizes the importance of holistic approaches, stakeholder engagement, and adaptive management to achieve sustainable bioenergy outcomes in diverse socio-economic and environmental contexts.

5.1. Key Components of the Model

5.1.1. Policy Instruments

Incentives are crucial in driving investment and market uptake of bioenergy projects. Financial incentives such as subsidies, tax credits, and feed-in tariffs can stimulate interest and investment in renewable energy ventures. By offering financial benefits to investors and project developers, governments can effectively lower the barriers to entry and encourage the adoption of bioenergy technologies. These incentives attract investment and promote the growth of a sustainable bioenergy market, contributing to a diversified energy portfolio and reducing reliance on fossil fuels.

Regulatory frameworks are essential to ensure the sustainability and effectiveness of bioenergy production and utilization. Governments should establish clear regulations that mandate renewable energy targets, emission reduction goals, and sustainability criteria for bioenergy projects. By setting these standards, policymakers can ensure that bioenergy development aligns with environmental and social objectives while minimizing adverse impacts. Additionally, robust regulations provide certainty for investors and stakeholders, fostering a stable and conducive environment for long-term investment in bioenergy. Regulatory measures and financial incentives form a comprehensive approach to promoting sustainable bioenergy development and combating climate change.

5.1.2. Stakeholder Engagement Mechanisms

Multi-stakeholder platforms serve as vital arenas for fostering inclusive dialogue and cooperation among diverse stakeholders. Through mechanisms such as advisory committees, working groups, and roundtable discussions, these platforms enable the exchange of ideas, expertise, and perspectives, ultimately facilitating consensus-building. By bringing together stakeholders from various sectors, including government, industry, academia, and civil society, these platforms help identify common goals, address concerns, and develop mutually beneficial strategies for advancing bioenergy initiatives. Through collaborative efforts, they can enhance the effectiveness and sustainability of bioenergy projects while promoting transparency and accountability in decision-making processes.

Participatory decision-making lies at the heart of ensuring the equitable development and implementation of bioenergy projects. By actively involving local communities, indigenous peoples, and marginalized groups in decision-making, their unique perspectives, needs, and priorities can be adequately recognized and integrated into project planning and execution. This approach fosters a sense of ownership and empowerment among these groups. It enhances the social acceptance and legitimacy of bioenergy initiatives. By prioritizing inclusivity and engagement, participatory decision-making processes contribute to more resilient and socially equitable bioenergy development, ultimately leading to more sustainable outcomes for both people and the planet.

5.1.3. Monitoring and Evaluation Frameworks

Developing robust indicators and metrics is essential for accurately assessing the multifaceted impacts of bioenergy projects and policies. These indicators should encompass environmental, social, and economic dimensions, including but not limited to greenhouse gas emissions, land use change, biodiversity conservation, and socio-economic benefits. By establishing comprehensive metrics, policymakers and stakeholders can gain insights into the holistic effects of bioenergy initiatives, facilitating informed decision-making and fostering sustainable development practices.

Baseline studies and impact assessments are imperative to establish benchmarks and track progress towards sustainability goals. These studies provide valuable insights into potential risks and trade-offs associated with bioenergy projects, enabling stakeholders to implement adaptive management strategies effectively. By systematically evaluating the initial conditions and potential impacts, stakeholders can mitigate adverse effects, maximize benefits, and ensure bioenergy endeavours' long-term viability and resilience. Additionally, ensuring transparency and accountability throughout the monitoring and evaluation process is crucial. By making data, methodologies, and findings publicly accessible and engaging stakeholders in review and validation processes, trust and credibility can be established, fostering collaboration and collective action towards sustainable bioenergy development.

5.2. Discussion of Implementation

The proposed conceptual model presents a pivotal tool for guiding the design and implementation of bioenergy policies, offering multifaceted benefits tailored to specific contexts. Firstly, it provides a structured framework that empowers policymakers to make well-informed decisions. This model facilitates strategic planning by systematically assessing the potential impacts, trade-offs, and co-benefits of bioenergy policies and projects, ensuring that initiatives align with overarching goals and priorities. Moreover, it catalyzes collaboration and dialogue among stakeholders. The model cultivates social acceptance and ownership of bioenergy initiatives by fostering engagement and facilitating multi-stakeholder partnerships. This inclusive approach enhances policies' effectiveness and sustainability and builds community trust and legitimacy.

Secondly, the model facilitates adaptive management by establishing robust monitoring and evaluation mechanisms. Policymakers can continuously evaluate the performance of bioenergy policies, identify emerging challenges, and seize new opportunities. This iterative learning and innovation process ensures strategies' agility and responsiveness over time, enhancing their long-term efficacy. Furthermore, the model underscores the importance of sustainability and equity in bioenergy development. By integrating principles of social justice and environmental conservation into policy design and implementation, it safeguards against inequities and ensures that bioenergy contributes to inclusive and environmentally sustainable development. In doing so, the model mitigates potential risks and harnesses bioenergy's full potential to address pressing societal and environmental challenges.

6. Conclusion

In conclusion, this review paper has comprehensively analyzed policy approaches for bioenergy development in response to climate change. Throughout the paper, we have explored the significance of integrating bioenergy into agricultural practices, examined existing policy frameworks at national and international levels, and discussed the potential synergies, challenges, and opportunities associated with bioenergy deployment.

We proposed a conceptual model for policymakers aimed at optimizing bioenergy outcomes while addressing climate change challenges. This model emphasizes the importance of policy instruments, stakeholder engagement mechanisms, and monitoring and evaluation frameworks in designing and implementing effective bioenergy policies tailored to specific contexts. By adopting holistic approaches, fostering multi-stakeholder collaboration, and promoting transparency and accountability, policymakers can unlock the full potential of bioenergy to mitigate greenhouse gas emissions, enhance climate resilience, and promote sustainable development.

Policymakers must prioritize the integration of bioenergy into broader climate change mitigation and adaptation strategies, considering the diverse socio-economic and environmental contexts in which bioenergy projects operate. Continued research, innovation, and capacity-building efforts are needed to address remaining knowledge gaps, technological uncertainties, and implementation challenges.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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