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Socioeconomic sustainability of bioenergy exploitation in Uganda: A GBEP-indicator narrative review

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ABSTRACT

The socioeconomic implications of bioenergy exploitation in Uganda have not been sufficiently assessed through comprehensive frameworks, such as the Global Bioenergy Partnership (GBEP) sustainability indicators. Existing studies are fragmented and primarily sector-specific, which limits the identification of cross-cutting challenges and constrains evidence-based policymaking. This study applies, for the first time in Uganda, a comprehensive set of GBEP socioeconomic indicators through a structured narrative review organized into seven thematic domains. The analysis focused on three dominant bioenergy pathways: firewood, charcoal, and organic residues/waste, which define Uganda's bioenergy landscape. Relevant publications were selected based on their alignment with the selected indicators and bioenergy pathways in Uganda. Despite the scarcity of empirical data, particularly in peer-reviewed sources, the review demonstrates clear trends. Traditional bioenergy contributes significantly to employment and national energy access, while also presenting persistent gender disparities and environmental risks. Transitioning to modern bioenergy systems may exacerbate land tenure disputes and food security concerns. However, the sector holds notable untapped potential: bioenergy-based power generation has reached 112 MW, with an estimated capacity of 1.65 GW, and energy from residues and waste remains underutilized at 737.7 PJ/year. Key research priorities emerging from this assessment include cookstove performance metrics, the bioenergy–food nexus, human capital development, charcoal substitution strategies, and energy diversification. The findings not only underscore the novelty of applying GBEP comprehensively in Uganda but also provide actionable insights for policy aimed at balancing energy access, livelihoods, and sustainability.

1. Introduction

Access to energy is foundational to socioeconomic development. Affordable, clean, reliable, and sustainable energy services are enshrined in international frameworks, such as the United Nations (UN) 2030 Agenda for Sustainable Development (especially Sustainable Development Goal (SDG) 7 on universal modern energy) (Karanja and Gasparatos, 2019; UN, 2022). Energy access is not a siloed objective; it underpins multiple development outcomes, including economic productivity, healthcare, education, gender equity, food security, and environmental sustainability (Brinkman et al., 2020; Liisa, 2023; Röder et al., 2020; Holm-Nielsen et al., 2022). In this context, per capita energy consumption is a widely used strong proxy for human development (Baltruszewicz et al., 2021; Gereon et al., 2023; Vogel et al., 2021).

Uganda's energy landscape, however, reflects deep disparities. As of 2021, the country's per capita energy consumption was only 767 kWh, less than one-quarter of the Sub-Saharan African average (4726 kWh) and far below the global average (~20,954 kWh) (Hannah et al., 2023; IEA, 2023a; IEA, 2023b). Moreover, a recent study reported an energy poverty index of 66 % for Uganda, with one-third of the population experiencing severe energy deficiency and an overall energy deprivation score of 51 % (Ssennono et al., 2021). These figures illustrate the

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persistence of energy poverty in Uganda, underscoring the urgency of exploring sustainable energy pathways.

Bioenergy (woodfuels, charcoal, agricultural residues) dominates Uganda's energy supply, accounting for over 89 % of the nation's total primary energy supply (TPES) and meeting more than 94 % of household energy needs (IEA, 2024a; Joshua et al., 2024). While this highlights bioenergy's central role, it also signals severe sustainability challenges. Uganda's bioenergy use is largely traditional and inefficient, characterized by a heavy reliance on firewood, charcoal, and residues, coupled with outdated technologies and unsustainable harvesting practices (IEA, 2024a; MEMD, 2023). These practices contribute significantly to deforestation, land degradation, and indoor air pollution (IAP), posing heightened respiratory health risks, particularly for women and children in rural households. Despite the challenges facing the sector, bioenergy remains socioeconomically vital, providing widespread livelihoods through employment, income and energy security. The ubiquity, low cost, and cultural familiarity of bioenergy mean that woodfuel remains the primary energy source for most Ugandans.

Recognizing these dualities, the Government of Uganda has enacted policies such as the Renewable Energy Policy (MEMD, 2008), and the updated Energy Policy (MEMD, 2023), which emphasize advanced biomass technologies, diversified household energy sources, and cooking solutions. Academic interest has also grown to address aspects such as biomass resource potential (Dastan et al., 2017; Khundi et al., 2011; MEMD, 2023; Hazelton et al., 2013; Buchholz and Da Silva, 2010; Okello et al., 2013), technological innovation (MEMD, 2023; Owusu and Banadda, 2017; Yusuf and Inambao, 2020; Tanui et al., 2018; Nabukalu and Gieré, 2019; Okello et al., 2013), and the environmental, social, and economic dimensions of bioenergy sustainability (Röder et al., 2020; Holm-Nielsen et al., 2022; Bamwesigye et al., 2020; Namaalwa et al., 2009; Mutumba, 2023; Ainembabazi et al., 2013; Woolley et al., 2020). Further studies have explored sectoral bottlenecks and bioenergy's role in climate mitigation and adaptation (Joshua et al., 2024; Nakora et al., 2020; Lubwama et al., 2023; Twinomuhangi et al., 2022; MEMD, 2013). However, the literature remains fragmented and sector-specific, often lacking integration across bioenergy pathways and indicators. As a

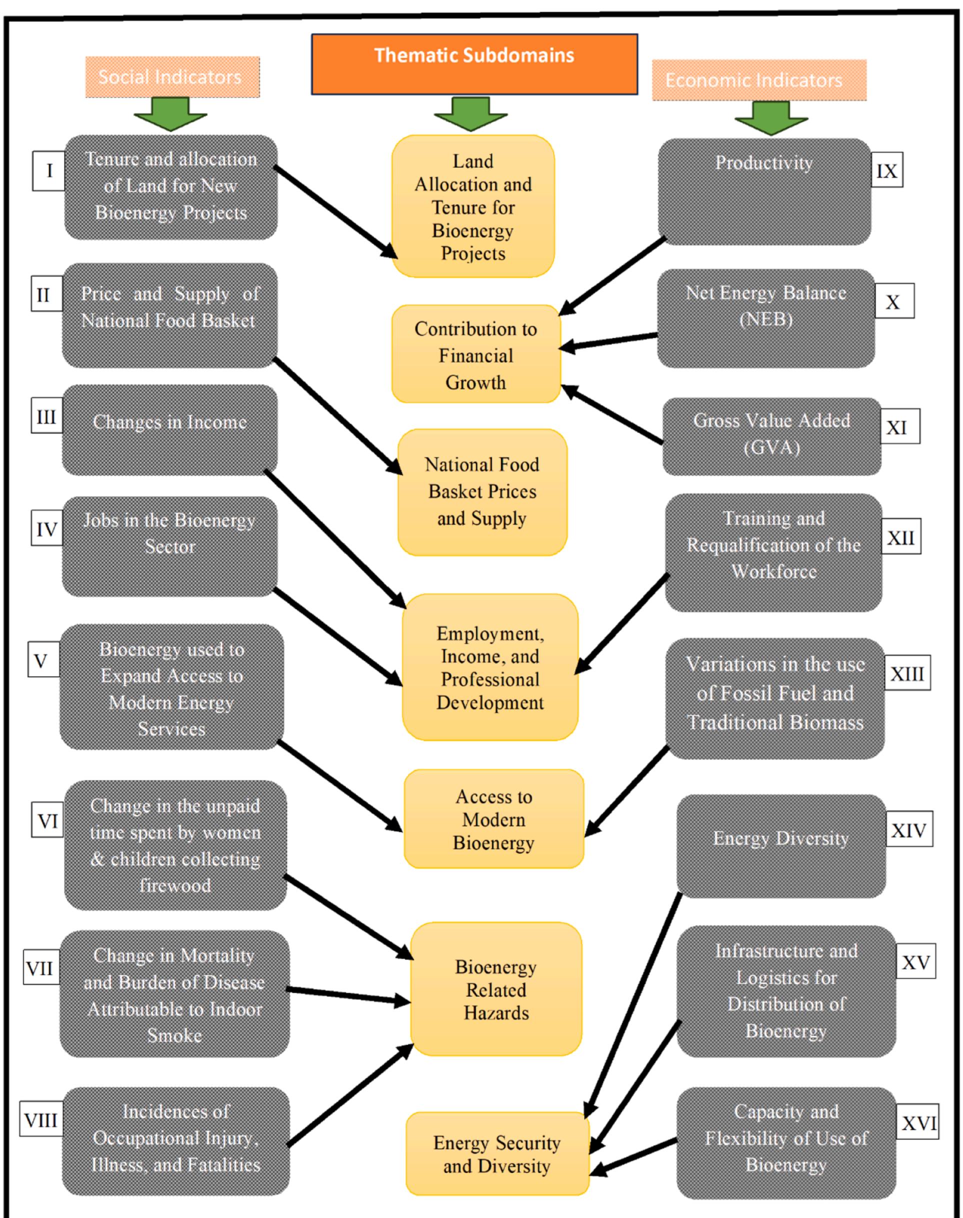

Fig. 1. Socioeconomic Sustainability Indicators (SSI) for Bioenergy and Thematic Domains used in this Study. (Adapted from (GBEP, 2011)).

result, critical gaps persist in understanding how bioenergy exploitation affects Uganda's social and economic sustainable development. This study addresses this gap for the first time through the comprehensive application of the GBEP socioeconomic sustainability indicators. The GBEP framework was chosen for its methodological rigor, cross-contextual adaptability, and relevance to policy and practice (FAO, 2024a; GBEP, 2024; Maria, 2024; UNEP, 2019). GBEP comprises 24 indicators across environmental, social, and economic dimensions, out of which this study used 16 indicators grouped into seven thematic domains aligned with socioeconomic outcomes (see Fig. 1 and Section 2.1.2).

In parallel, the study critically assesses existing literature and data for adequacy in covering these indicators, providing a comprehensive basis for analysis. This dual approach, combining indicator-based analysis with a literature review, enabled a multidimensional understanding of bioenergy's role in Uganda's development trajectory, while identifying empirical and methodological gaps that must be addressed to support a sustainable transition. The overarching aim is to inform Uganda's transition from traditional to modern bioenergy systems in line with global and regional commitments such as the Paris Agreement, the African Union's Agenda 2063, and the UN SDGs (MEMD, 2023; NPA, 2025).

Following this introduction, Section 2 details the materials and methods, including the identification of relevant bioenergy streams and the literature review methodology. Section 3 presents the results and discussion, structured around the seven thematic domains, and identifies critical knowledge and data gaps. Section 4 offers concluding reflections and synthesizes the study's key contributions. Finally, Section 6

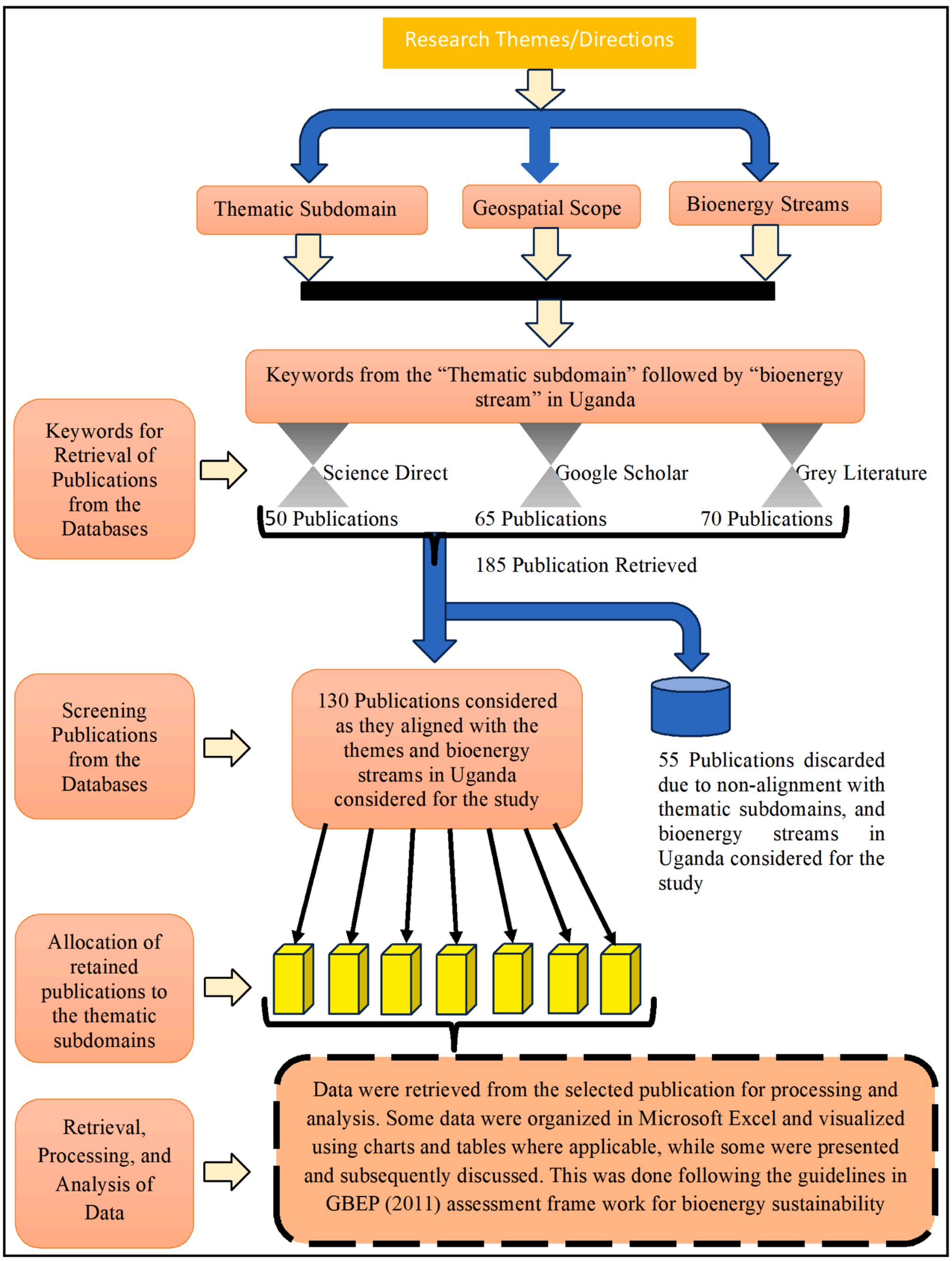

Fig. 2. Protocol for Selection of Publications for Assessment of Socioeconomic Sustainability for Bioenergy in Uganda. (Adapted from (Akakpo et al., 2024)).

outlines strategic research priorities to close existing evidence gaps and strengthen Uganda's empirical foundation for evidence-based bioenergy governance.

2. Materials and methods

This study employed a narrative review methodology with systematic elements to assess the socioeconomic sustainability implications of bioenergy exploitation in Uganda. Unlike the systematic review, which applies narrowly defined research questions, rigid inclusion/exclusion criteria, and often meta-analysis, this approach offered flexibility better suited to the interdisciplinary and data-scarce context of Uganda's bioenergy sector. Two factors motivated this choice. First, the topic spans energy studies, environmental science, socioeconomics, and development studies, making it difficult to restrict the evidence base to a single discipline. Second, the paucity of peer-reviewed empirical research meant that a purely systematic review risked overlooking relevant insights from grey literature. Such a narrative orientation allowed a comprehensive and integrative synthesis of diverse literature sources, including journal articles, policy documents, technical reports, and publications from governmental, international, and private sector entities across multiple disciplines.

This hybrid approach, therefore, balances the replicability and rigor of systematic reviews with the adaptability of narrative reviews, enabling a multidimensional understanding of the socioeconomic implications of bioenergy exploitation in Uganda. To ensure rigor and transparency, the study employed a structured search and screening protocol (Fig. 2, Section 2.2.1), which guided the identification, selection, and organization of literature.

2.1. Materials

2.1.1. Bioenergy pathways in Uganda

This study used the terms "bioenergy pathways" and "bioenergy streams" interchangeably to describe the routes through which biomass is converted into usable energy in solid, liquid, or gaseous forms. These include both traditional systems (e.g., direct combustion of firewood, crop residues, and organic waste) and processed biofuels (e.g., charcoal, briquettes, biogas, biodiesel, and bioethanol). Uganda's energy landscape is dominated by solid biomass, particularly firewood and charcoal, which serve as the primary fuels for households, institutions, and small enterprises. Firewood is harvested mainly for subsistence, while charcoal production is more commercially structured. Modern biomass applications, such as cogeneration, digestion, gasification, and densification, also exist but remain marginal in scale and impact. Accordingly, the analysis in this study focused on four key bioenergy pathways: (i) the firewood stream, (ii) the charcoal production stream, (iii) the organic residue and waste stream (including briquette production and cogeneration from organic residues), and (iv) fuel-grade bioethanol. Although bioethanol is not yet produced commercially in Uganda, it was included hypothetically to facilitate comparison with global trends and to assess its potential relevance for future adoption. Other streams, such as biodiesel, biogas, briquettes, and pellets, were excluded from the core analysis because of their negligible contribution to Uganda's overall energy mix and the limited availability of reliable data.

2.1.2. Socioeconomic sustainability indicators

This study employed the GBEP framework for sustainable bioenergy evaluation, which comprises 24 sustainability indicators evenly distributed across the social, economic, and environmental dimensions (GBEP, 2011). To align with the study's objectives, the eight environment-related indicators were excluded, and the analysis focused on the social and economic dimensions. Eight indicators captured social aspects such as employment, occupational health and safety, mortality and morbidity, time burdens, income, land access, and food security. The other eight indicators assessed economic dimensions, including productivity, value addition, and energy security, diversity, and transition. A summary of the selected sixteen (16) indicators, eight social and eight economic, is presented in Fig. 1. To ensure their effective application, the study operationalized these indicators by adhering to the methodological procedures and data requirements outlined in the GBEP guidelines. This approach ensured consistency with internationally established practices for evaluating bioenergy sustainability.

2.2. Methods

2.2.1. Data collection

The overall literature search protocol is summarized in Fig. 2. The review included both peer-reviewed and grey literature. Scholarly sources were retrieved from indexing databases, including Science Direct and Google Scholar, while grey literature, comprising policy documents, reports, and datasets, was sourced from institutions such as Ministry of Lands, Housing, and Urban Development (MLHUD), Ministry of Energy and Mineral Development (MEMD), Uganda Bureau of Statistics (UBOS), International Labor Organization (ILO), IEA, Energy Regulatory Authority (ERA), and the Food and Agriculture Organization (FAO).

For a systematic retrieval of publications, search terms were constructed, and Boolean operators were used to combine keywords from three thematic clusters. The first cluster focused on socioeconomic sustainability indicators (SSI), which were grouped and summarized as in Fig. 1. The second cluster addressed bioenergy pathways, including firewood, charcoal, bagasse, biomass waste, biogas, bioethanol, and biodiesel (see Section 2.1.1). The third cluster defined the geospatial scope, which was not limited to Uganda but extended to East Africa, SSA, and in some cases to Europe, America, and Asia to allow for broader comparisons and contextual learning. Examples of search strings that were used included: ("Land tenure" OR "Land use" OR "Land acquisitions") AND ("Firewood" OR "Charcoal" OR "Biomass residues" OR "Agriculture residues") AND ("Uganda" OR "SSA" OR "East Africa" OR "EU"). Other search strings were formulated as per the thematic domain that was under consideration. Additional sources were identified through the snowballing technique by screening the reference lists of retrieved literature. Publications were retained for review based on three criteria: (1) relevance to the selected SSI and Ugandan bioenergy streams, (2) availability in English, and (3) open access or accessible summaries with clear and conclusive results when full texts required subscription. There was no temporal boundary set, though priority was for studies published between 2000 and 2023, reflecting the period of active bioenergy policy development in Uganda.

Grey literature, such as government reports, technical documents, and publications from development partners, was indispensable in this study due to the scarcity of peer-reviewed studies (in several dimensions) directly addressing Uganda's bioenergy sector. Recognizing the potential challenges of non-peer-reviewed material, a structured validation strategy was employed. First, a triangulation approach was adopted. Data from grey literature were systematically cross-checked against official statistics and international datasets from credible institutions, thus ensuring that the data used in the study were consistent with authoritative sources, and discrepancies were critically assessed and reconciled before inclusion in the analysis. Secondly, consistency and reliability checks were carried out across time-series datasets. Where inconsistencies were identified between different reports, priority was given to the most recent, comprehensive, and institutionally recognized source. In cases where official government data conflicted with international databases, a careful comparison was made, and both perspectives were discussed to reflect uncertainty and highlight data gaps.

Third, interpretive validation was undertaken by embedding the analysis within Uganda's policy and institutional context. Reports produced by responsible agencies were not only treated as data sources but also evaluated based on their mandates, methodological rigor, and alignment with national reporting systems. For instance, forestry data were validated against the NFA and FAO Forest Resources Assessments, while energy statistics were compared with MEMD, ERA and IEA reports. In total, 185 publications were retrieved, 55 were discarded due to non-alignment with the inclusion criteria, and 130 were reviewed across seven thematic domains, of which 55 % were peer-reviewed journal articles and 45 % grey literature (see Fig. 2 and Fig. 3). By combining multiple sources and verifying consistency with responsible institutions, the study ensured that even non-peer-reviewed data were robust, credible, and fit for purpose. This rigorous validation process enhanced the reliability of the findings and strengthened the study's overall credibility.

2.2.2. *Data analysis and thematic structuring*

The analysis followed the GBEP framework's recommended methodologies for each selected indicator, employing both qualitative interpretation and quantitative techniques. Data were compiled from secondary sources, cleaned, and systematically organized in Microsoft Excel. To ensure comparability across indicators and time periods, the datasets were standardized where possible. Descriptive statistics were used to summarize the performance of indicators, while trend analysis tracked temporal changes in variables such as bioenergy production from firewood and charcoal, as well as bioenergy economic performance. Quantitative outputs were visualized using tables, charts, and graphs. These visualizations were critical for revealing trends, highlighting relationships between variables, and enabling comparisons across social and economic dimensions of sustainability. They also provided a clear foundation for structured discussions of results, particularly in distinguishing between the performance of traditional and modern bioenergy pathways, as well as Uganda's best practices compared to regional and global standards.

In addition to numerical assessments, the analysis incorporated qualitative interpretation of secondary literature, reports, and policy documents to explain the observed patterns. This contextual dimension helped clarify the drivers and implications of the trends, particularly where data limitations constrained purely statistical evaluation, like in the case of excessive woodfuel consumption by the charcoal pathway despite it minor contribution to TPES and GDP compared to the firewood stream. Combining numerical analysis with contextual interpretation ensured that the study results were both evidence-based and grounded in Uganda's broader bioenergy realities. Such an integrative approach strengthened the reliability of findings and their alignment with the GBEP assessment framework for sustainable bioenergy.

For interpretive clarity, indicators were grouped into seven thematic domains rather than presented numerically. These themes, summarized in Fig. 1, include: a) Land Allocation and Tenure (Indicator I); b) National Food Basket (Indicator II); c) Employment, Income, and Professional Development (Indicators III, IV, XII); d) Access to Modern Bioenergy (Indicators V, XIII); e) Bioenergy-Related Hazards (Indicators VI, VII, VIII); f) Financial Contributions (Indicators IX, X, XI); and g) Energy Security and Diversity (Indicators XIV, XV, XVI). This thematic reorganization allowed for a more coherent and non-redundant discussion of interrelated findings.

2.2.3. *Methodological limitations*

The interdisciplinary and multisectoral nature of bioenergy governance and utilization in Uganda presented inherent challenges in sourcing comprehensive and consistent data. Limited access to sectoral statistics, coupled with reliance on grey literature (45 % of reviewed sources), constrained the availability of peer-reviewed empirical research. Although triangulation and validation strategies were applied, the dominance of non-peer-reviewed sources might have introduced sectoral bias or partial representation. Additional limitations arose from restricted database coverage, language barriers, and potential omissions of relevant studies, collectively limiting the breadth of evidence captured. This review, therefore, does not claim to provide a fully exhaustive account of bioenergy in Uganda. Instead, it offers an informative and focused assessment of how bioenergy exploitation affects socioeconomic sustainability, grounded in the best available and validated evidence.

3. Results and discussions

This section presents the study findings and discussions organized in eight sections. The first section examines the literature base by repository, geospatial origin, and distribution across thematic areas and indicators. The remaining seven sections detail results and interpretations following the thematic classifications outlined in Fig. 1 and Section 2.2.2. Results and discussions are integrated to maintain analytical coherence and ensure a logically structured narrative, avoiding potential fragmentation of key insights. Cross-domain linkages between indicators are highlighted, and findings are contextualized against regional and global best practices. Finally, the role of enabling factors, governance, financing, and ICT in shaping the socioeconomic sustainability of bioenergy across domains is discussed.

3.1. *Publications used for assessment*

The socioeconomic sustainability assessment of bioenergy in Uganda, structured across seven thematic domains, drew on diverse literature sources. Fig. 3 and Table 7 (Appendix) present the distribution of reviewed publications by theme. "Contribution to Financial Growth" had the highest coverage (48 publications), followed by "Bioenergy-Related Hazards" (40). Conversely, "Access to Modern Bioenergy" and "Employment, Income, and Professional Development" were least represented, with 17 and 18 publications, respectively. As shown in Fig. 3, most literature focused specifically on Uganda and was dominated by grey sources - government reports, policy briefs, and non-indexed publications - underscoring the scarcity of peer-reviewed empirical studies

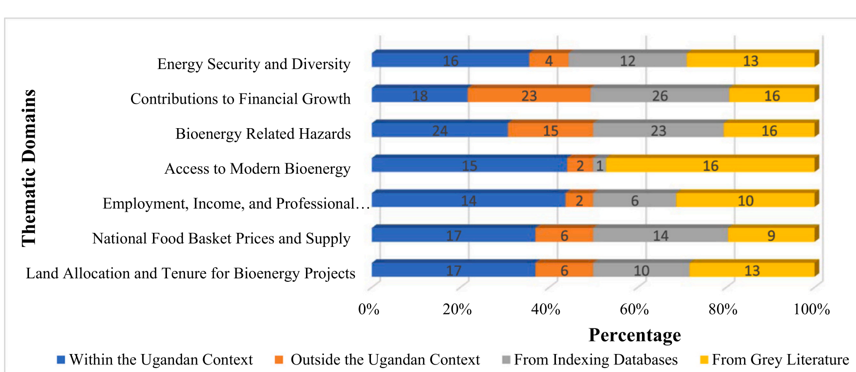

Fig. 3. Distribution of Publications Among Thematic Domains According to Their Repositories and Geospatial Origins.

in this area.

In several cases, key indicators could not be fully assessed due to data gaps. For example, as summarized in Table 7 (Appendix), there was a notable lack of data on Indicator X (Net Energy Balance) for the major bioenergy streams in Uganda. Similarly, data were scarce for Indicator XII (Training and Requalification of the Workforce) and Indicator XVI (Capacity and Flexibility of Use of Bioenergy). Of the 81 Uganda-specific publications reviewed, only 33 came from indexed journals. This heavy reliance on grey literature underscores the need for more rigorous, peer-reviewed empirical research to inform evidence-based bioenergy policy and practice in Uganda. The following sections present the results and discussions following the thematic domains, using the literature that was retrieved, as shown in Fig. 3.

3.2. Land allocation and tenure for bioenergy projects

Uganda's land tenure system and legal framework are comprehensive and robust enough to govern the processes for land acquisition for various uses. This section examines the existing tenure systems, associated legal and institutional frameworks, and potential challenges they may pose to the development of bioenergy projects.

3.2.1. Land tenure systems legal and institutional frameworks in Uganda

Uganda's land tenure system, guided by the 1995 Constitution and the 1998 Land Act, recognizes four primary land tenure systems: freehold, leasehold, customary, and mailo (Pedersen et al., 2012; Walker et al., 2023; Katusiime et al., 2023; GoU, 1995; MLHUD, 2010). Freehold and leasehold are forms of private ownership with formal registration, while customary tenure, covering 68 % of Uganda's land, is communal and restricts transfers outside the community (Walker et al., 2023; Andrew et al., 2023; Awino, 2024). Mailo tenure is unique, with registered landowners holding full rights but overlapping with occupant usage rights, often requiring consent for ownership transfers (Pedersen et al., 2012; Andrew et al., 2023). Freehold and leasehold together cover 22 % of land, mailo 10 %, and customary 68 % (Table 1).

Land governance in Uganda is further underpinned by an elaborate web of legal instruments, institutional framework, and international treaties (Table 8 and Table 9, Appendix). Despite this seemingly robust architecture, Uganda continues to experience various land conflicts, including boundary conflicts, ethnic land tensions, clashes between agriculturalists and pastoralists, landowner-occupant disagreements, and encroachment on protected areas (Muhindo, 2018). Historical injustices, overlapping claims, tenure ambiguities, weak dispute resolution mechanisms, and judicial delays contribute to these persistent conflicts (Nakayi and Twesiime-Kirya, 2017). In this context, rolling out land-intensive bioenergy projects risks exacerbating an already fragile situation.

Although literature is scarce about the bioenergy-land tenure nexus in Uganda, broader evidence suggests that large-scale land acquisitions (LSLAs), often required for commercial bioenergy projects, are challenging under Uganda's tenure systems (DiCarlo and Sims, 2023; Anseeuw et al., 2012; Martiniello, 2023; Neville and Dauvergne, 2012). LSLAs typically involve land appropriation[1] by political authorities, transforming customary tenure into formalized property. These processes often bypass affected communities, lack transparency, and offer inadequate or no compensation, leading to displacement, dispossession, and social conflict (Martiniello, 2023; Chilombo et al., 2019; Boamah, 2014). Land appropriation is often preferred over direct purchase due to the complexity of customary and mailo tenures, marked by overlapping claims, conflicting maps, and procedural ambiguities. Uganda's own LSLA experiences underscore these risks. Projects such as Amuru Sugar Works, Hoima Sugar Limited, and Atiak Sugar Works have triggered severe disputes, evictions, and community unrest due to inadequate compensation and a lack of resettlement support (Martiniello, 2023; Nakayi, 2015; Bahati et al., 2022). These cases illustrate that, despite Uganda's comprehensive legal and institutional frameworks, the practical realities of land acquisition for potential bioenergy development remain fraught with conflicts and uncertainty.

Table 1
Land coverage by tenure system in Uganda.

	Freehold	Mailo	Leasehold	Customary
National Coverage, %	18	10	4	68

Adapted from (Walker et al., 2023).

A critical observation emerging from this is that legal frameworks alone are insufficient to secure land for bioenergy investments. Tenure ambiguities, particularly under customary and mailo systems, complicate land acquisition and increase the likelihood of disputes. Transparent, inclusive, and well-regulated processes are crucial for mitigating conflict, minimizing financial risk, and ensuring the sustainable and equitable implementation of projects. The results further highlight how Uganda's complex tenure arrangements, particularly customary and mailo systems, pose major challenges for scaling bioenergy projects. These findings mirror broader African experiences, where overlapping rights and weak enforcement frameworks undermine the security of land investments (Deininger et al., 2011a; German et al., 2013). International evidence shows that without addressing tenure ambiguities, land-based renewable energy projects risk sparking community resistance, escalating conflicts, and ultimately stalling development (White et al., 2012; Cotula et al., 2009).

Regional best practices suggest that governance reforms can mitigate these risks. For example, Mozambique and Tanzania have introduced participatory land-use planning processes that integrate local communities into decision-making for large-scale energy projects, thereby improving transparency and legitimacy (Wily, 2011). Similarly, Ethiopia's certification of communal land rights has reduced disputes and improved compensation processes, providing lessons that Uganda could strengthen or adapt to its customary tenure systems (Deininger et al., 2011b). Technology also plays a critical role. Digital cadastral mapping and blockchain-based land registries, piloted in countries such as Ghana and Rwanda, have improved land records, reduced overlapping claims, and enhanced trust in land transactions (M. Zein and Twinomurinzi, 2023; Saari et al., 2022). Applying such innovations in Uganda could help streamline land identification and reduce disputes linked to bioenergy investments. Financing arrangements further shape outcomes. Evidence from Kenya and South Africa shows that international financing institutions increasingly condition bioenergy and renewable energy investments on adherence to environmental and social safeguards, including transparent land acquisition and fair compensation (Eberhard and Naude, 2017; International Finance Corporation, 2012). Uganda can leverage such financing frameworks to enforce higher standards, provided governance systems align with global safeguards.

Uganda's land tenure complexities present significant risks for bioenergy development, but these challenges are not insurmountable. By drawing on regional and global best practices in governance, deploying

[1] Land appropriation is when authorities seize land (especially customary land) from local people for development projects without paying adequate compensation for lost crops, property, and livelihood. Where compensation is done, its often to those with power and influence in society (DiCarlo and Sims, 2023).

technology for transparent land administration, and leveraging financing that enforces social safeguards, Uganda can transform land tenure from a barrier into a foundation for sustainable bioenergy expansion. Currently, the land tenure context in Uganda exacerbates other pressures. Customary and mailo tenure systems, which cover most of the country's land, also tend to limit structured land allocation for either food or energy crops and can constrain household access to biomass resources. Consequently, energy crop development is limited in areas where land rights are unclear, while food-driven land conversion continues to erode the biomass base needed for traditional bioenergy. The next section explores the bioenergy-food nexus in Uganda and its impact on the socioeconomic sustainability realities in the country.

3.3. National food basket prices and supply

Globally, bioenergy production has often been linked to concerns about food security, particularly in low-income, agrarian economies. In Uganda, however, the main driver of biomass pressure is agricultural expansion, rather than bioenergy production itself (Holm-Nielsen et al., 2022; Shoaib and Ariaratnam, 2016; Jha and Schmidt, 2021; Jagger and Kittner, 2017). Extensive horizontal land clearance aimed at increasing food production degrades forests and woodlands that supply traditional firewood, charcoal, and crop residues (Ema, 2017; Matondi et al., 2011; FAO et al., 2018). Household-level consequences are evident. Rural households must travel longer distances for firewood, and increasingly rely on dung and unprocessed crop residues, which are less efficient and more polluting (Jagger and Kittner, 2017; Egeru et al., 2014). Firewood, once freely available, has become a commodified resource, compounding household energy poverty and undermining the sustainability of bioenergy systems (MEMD, 2023; MEMD, 2013; Arnold et al., 2003).

On the other hand, Uganda's food, bananas, cassava, maize, sweet potatoes, and beans (UBOS, 2023a), are not generally used for fuel-grade production, and ethanol from bananas remains limited to beverage use (Ema, 2017). Despite this separation of food and fuel systems, food insecurity remains high: between 2015 and 2021, severe food insecurity affected 21.5 - 25.6 % of the population (FAO, 2024b). As of July 2024, 7.9 million Ugandans faced insufficient food consumption, and 28.9 % of children under five were chronically malnourished (Mpuuga, 2023; FAO, 2023). This raises a key policy question: could future expansion of cultivated bioenergy crops worsen food insecurity, even if the current overlap is minimal? Perspectives vary. Some scholars argue that biofuels have not significantly driven food price increases (Brinkman et al., 2020), while others warn that scaling biofuels may strain agricultural systems already under pressure (Jha and Schmidt, 2021; Arndt et al., 2010). Past experiences support this caution.

Policy and management implications emerge at the intersection of food, energy, and tenure. Large-scale energy crop expansion could compete with food production, particularly where tenure ambiguities discourage formal agreements and investor participation. Regional experiences illustrate these risks: in Tanzania and South Africa, biofuel programs were suspended after conflicts over land-use and rising food prices (Jha and Schmidt, 2021; Mawejje, 2016). In Eastern Uganda, sugarcane expansion displaced food crops on 81 % of arable land, underscoring the importance of inclusive land management and clear tenure arrangements (Mwanika et al., 2020). Similar effects have been reported elsewhere (Mwavu et al., 2018; Nabalegwa et al., 2022). Conversely, structured out-grower schemes, where governance mechanisms are transparent and smallholders are integrated, can enhance household welfare. Madina et al. (Madina et al., 2025). and Kaahwa et al. (Kaahwa et al., 2023). reported improved food security and asset ownership among households participating in sugarcane out-grower programs. Differentiated outcomes from such empirical studies compound the need for further research to clarify the causal mechanisms and mediating factors influencing bioenergy-food relationships in Uganda. Advocates of cultivated energy crops point to feedstocks like Jatropha curcas, a non-edible oilseed with minimal food competition, and sugarcane for bioethanol. Yet, both require land, water, and labor that could otherwise support food production (Arndt et al., 2010)

Importantly, Uganda's bioenergy potential goes beyond cultivated crops. Significant biomass residues are generated across the agri-food value chain. Okello et al. (Okello et al., 2013). estimated that biomass residues could yield up to 260 PJ/year, while more recent estimates based on data from UBOS (UBOS, 2023a; UBOS, 2020a) place this potential at 737.7 PJ/year, equivalent to 90 % of national biomass energy needs. Such residue-based approaches align with Uganda's 2023 National Energy Policy, which emphasizes waste-based bioenergy solutions, investments in biomass residue utilization, and establishing regulatory frameworks for modern waste-based technologies (MEMD, 2023). Global experiences show that food-bioenergy outcomes are shaped by governance, technology, and financing. Transparent institutions can clarify land rights, mediate conflicts, and enforce safeguards against displacement. Modern technologies, such as efficient residue conversion or biogas systems, can maximize energy yield without competing with food production. Access to finance enables smallholders to participate in modern bioenergy systems, ensuring inclusive benefits. Without these enabling conditions, investments risk exacerbating tenure-related tensions and food insecurity (FAO, 2023; Caspeta et al., 2013).

In summary, Uganda illustrates a context-specific food-bioenergy dynamic. Agricultural expansion threatens biomass availability, while bioenergy itself has not yet displaced staple food production. However, tenure ambiguities, highlighted Section 3.2, shape how energy and food systems interact, influencing both household access to resources and investor confidence. Managed appropriately, residue-based bioenergy and inclusive crop schemes offer pathways to enhance energy security without undermining food systems. Integrating strong governance, tenure-sensitive planning, and technological innovation is essential to ensure a sustainable bioenergy transition that safeguards both energy and food security.

3.4. Employment, income, and professional development

Bioenergy in Uganda offers substantial opportunities to enhance livelihoods, particularly in rural areas where dependence on biomass is high and formal employment opportunities are limited (IEA, 2023b; IEA, 2024b; IEA, 2023c; Kaygusuz, 2011). However, similar to the challenges seen in land tenure and food security, the sector's employment potential is shaped by informality, uneven value distribution, and gendered labor roles. This section evaluates bioenergy's economic impact in Uganda through three key indicators: (a) employment in the bioenergy sector, (b) income dynamics, and (c) workforce training and requalification. These indicators help assess labor welfare and earning potential across various bioenergy streams (GBEP, 2011).

Employment in Uganda's bioenergy sector spans firewood, charcoal, briquettes, improved cookstoves, and modern biomass enterprises such as cogeneration (Khundi et al., 2011; MEMD, 2023; Ainembabazi et al., 2013; Price, 2017). Formal employment is concentrated in modern bioenergy enterprises, cogeneration plants, briquette production, improved cookstove manufacturing, and related product marketing and distribution, while the majority of labor occurs informally, in firewood and charcoal supply chains (Price, 2017). Informal sector jobs are typically precarious, poorly remunerated, and undocumented, echoing the tenure-related vulnerabilities discussed earlier (FAO and ILO, 2022; UBOS, 2021b; UBOS, 2021a). Without formal recognition, the incomes of those working in biomass remain undervalued in national accounts, obscuring the sector's true economic contribution. Firewood collection which is undertaken by 66.2 % of more than 9 million households (UBOS, 2021a) is primarily unpaid family labor performed mostly by women and children (UBOS, 2021b; UBOS, 2018). This reliance on unremunerated work highlights the intersection between energy access, gender inequality, and food security. Time spent on firewood collection reduces women's opportunities for paid employment, food production, and children's opportunities for education, reinforcing cycles of poverty and vulnerability. Moreover, the subsistence nature of firewood use means it is excluded from GDP estimated under the current ILO and UBOS frameworks (ILO, 2014). This methodological exclusion parallels the undervaluation of customary land under Uganda's tenure system; both represent economic "blind spots" that marginalize rural livelihoods in official statistics.

Modern bioenergy pathways, such as briquette production, cogeneration plants, and improved cookstove manufacturing, offer a more sustainable and potentially formalized source of employment. Yet, reliable data on wages, workforce qualifications, or requalification programs remain scarce. This mirrors the data gaps observed in food-bioenergy interactions, where the lack of granular evidence hinders informed policymaking. Without such evidence, it is challenging to design policies that strike a balance between employment creation and environmental sustainability, as well as food security.

A cross-cutting concern across land tenure, food security, and employment is the uneven distribution of risks and benefits. Ambiguous land rights heighten the risk of dispossession from large-scale bioenergy projects, while food security debates highlight potential competition between energy crops and staple production. In employment, these risks appear as informality, engendered labor exclusion, and environmental externalities that erode long-term livelihoods. At the same time, opportunities also span these domains: with effective management, bioenergy could formalize jobs, diversify rural incomes, and valorize agricultural residues to ease land and food pressures. Uganda's bioenergy sector thus holds significant employment and income potential but remains constrained by informality, gender inequality, and limited data. Addressing these overlaps requires integrated policies, particularly labor market formalization, workforce training, and inclusive governance, to shift the sector from precarious livelihoods toward equitable and sustainable rural development.

3.5. Access to modern bioenergy

Although bioenergy dominates Uganda's energy mix, its capacity to enable widespread access to clean cooking solutions and modern energy services, such as electricity and mechanical power, remains limited. Additionally, the extent to which bioenergy displaced traditional biomass and fossil fuels is not well-documented, highlighting a need for deeper analysis. Nevertheless, the ensuing subsections comprehensively examine these critical facets, offering an in-depth analysis of their implications and outcomes. Therefore, this section assesses two key indicators of bioenergy's role in Uganda: (a) its contribution to expanding access to modern energy services, and (b) its effectiveness in reducing reliance on fossil fuels and traditional biomass.

3.5.1. Bioenergy used to expand access to modern energy services

Bioenergy has enormous potential to support improved cooking and expand access to clean cooking. However, Uganda's reliance on bioenergy remains overwhelmingly traditional, with 94 % of households depending on firewood and charcoal for cooking, yet only 10 % use improved systems (UBOS, 2024). Clean cooking access, previously estimated at 6 % (Joshua et al., 2024; IEA, 2023c), has dropped to just 3.8 % (UBOS, 2024). This underscores the limited penetration of modern bioenergy technologies, despite their potential to expand access to clean cooking and electricity. A significant barrier lies in the blurred classification of improved biomass stoves. While many are promoted as "clean," their performance varies, making it difficult to assess their real contribution to the clean cooking transition. This gap underscores the need for research to quantify the share of clean cookstoves within the broader category of improved biomass stoves. At the same time, the low penetration of bioenergy to increasing access to clean cooking compounds other socioeconomic challenges of IAP, time-poverty (Section 3.6), and precarious employment in the bioenergy sector (Section 3.4)

In electricity generation, bioenergy is the second-largest source after hydropower, with 93 % of its potential still untapped (MEMD, 2023; ERA, 2024; ERA, 2023). It contributed 112 MW to Uganda's national grid by 2021, roughly 4 % of total generation and only 7 % of national biomass-based power potential (MEMD, 2023; IEA, 2023c; ERA, 2024).

Table 2 illustrates the growing role of bioenergy in Uganda's power sector over the past decade, as more producers are increasingly attracted to the sector, with factories like Kakira, Kinyara, and Sugar & Allied already exporting surplus electricity after meeting internal needs. These investments highlight the untapped role of industrial residues in Uganda's energy mix. However, this progress contrasts sharply with rural household realities, where reliance on traditional biomass is increasing, compounding energy poverty. This mismatch reflects structural barriers: weak financing for household technologies, limited institutional capacity for stove dissemination, and governance challenges that mirror those seen in land tenure and food security (see Sections 3.2 and 3.3). Therefore, significantly increasing the role of bioenergy in accessing clean cooking and power generation will directly contribute to addressing the current socioeconomic challenges of IAP, time poverty, and inefficient resource utilization in the bioenergy sector.

3.5.2. Change in consumption of fossil fuels and traditional use of biomass

The potential for bioenergy to displace fossil fuels is mixed. As shown in Fig. 4, fossil fuel consumption has been growing steadily between 2017 and 2021 (save for the lockdown period due to COVID-19), reaching 2.3 billion cubic meters (BCM), with petrol and diesel accounting for over 93 % of demand (UBOS, 2023a). These fuels remain the backbone of transport, costing Uganda $1.26 billion annually and comprising nearly 14 % of imports. By contrast, fossil-fueled electricity generation has declined sharply, from 26.4 MW in 2017 to just 7.8 MW in 2021, while biomass-based generation has grown from 78 MW to 112 MW over the same period, as shown in Fig. 4. Yet, this shift is driven more by hydropower expansion and fiscal constraints than deliberate fossil fuel substitution with bioenergy (ERA, 2024). Similarly, there is little evidence of bioethanol and biodiesel displacing imported petroleum products, despite local potential in crops like sugarcane and oilseeds.

Regional and international best practices demonstrate viable pathways for Uganda. In Kenya, advanced gasifier stove programs have reduced charcoal reliance when paired with subsidies and private investment (Bailis et al., 2020; Gitau et al., 2019). India's biogas programme links agricultural residues to decentralized energy systems, enhancing rural energy access and employment (Ministry of New and Renewable Energy MNRE, 2025). Brazil's RENOVABIO policy, through

Table 2
Electric power generation (MW) from biomass-fired power plants.

	2016	2017	2018	2019	2020	2021
Kakira Sugar Works Ltd	50	50	51.1	51.1	51.1	51.1
Sugar & Allied Uganda Ltd		11.9	11.9	11.9	11.9	11.9
Kinyara Sugar Works Ltd	14.5	14.5	14.5	14.5	14.5	14.5
Sugar Corporation of Uganda Ltd			9.5	9.5	9.5	9.5
Mayuge Sugar Ltd			9.2	9.2	9.2	9.2
Pamoja – Tiribogo			0.032	0.032	0.032	0.032
Pamoja – Ssekanyonyi			0.011	0.011	0.011	0.011
Kalangala Infrastructure Services		1.6	1	1	1	1
Nyamasagani 1						15
Bukasa Island Offgrid					0.1	0.1
Total	**64.5**	**78.0**	**97.3**	**97.3**	**97.4**	**112.3**

Adapted from UBOS (2023b).

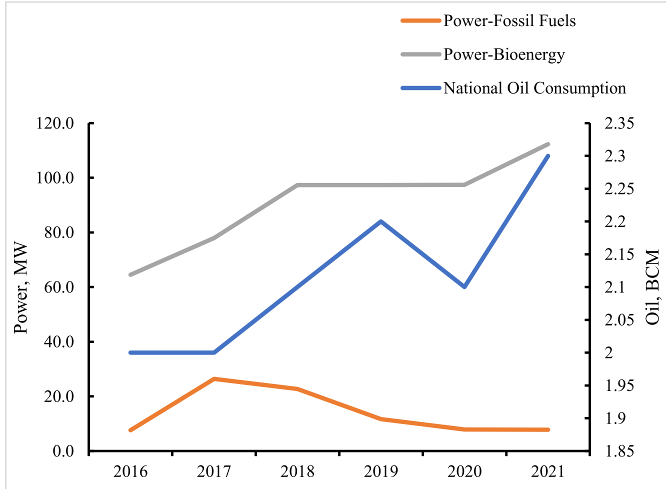

Fig. 4. Power Production from Biomass and Oil Versus Oil Consumption in Uganda, 2016 – 2021 (Data Source: (UBOS, 2023b) and (ERA, 2024)).

mandatory blending and decarbonization credits, shows how coordinated governance and financing can enable biofuels to displace fossil fuels (Ribeiro and da Cunha, 2022). These examples highlight that Uganda's barriers are surmountable with coherent policy and institutional support.

The challenges here overlap with earlier indicators. Land tenure issues (Section 3.2) limit large-scale investments in bagasse-based cogeneration. Agricultural expansion for food (Section 3.3) decreases biomass-rich ecosystems, reducing feedstocks for both traditional and modern energy sources. Without transitioning to modern bioenergy systems, informal employment will persist in the sector (Section 3.4) further hampers professionalization and technological progress. Without addressing these systemic barriers, bioenergy may reinforce energy poverty instead of facilitating transitions, thereby exacerbating socioeconomic sustainability challenges, including those outlined in the next section.

3.6. Bioenergy-related hazards in Uganda

Bioenergy-related hazards in Uganda fall into three domains, aligning with Indicators VI, VII, and VIII (see Fig. 1): (a) firewood collection time-poverty, (b) indoor cooking in poorly ventilated environments, and (c) occupational risks across bioenergy production chains. These hazards highlight the hidden social and health costs of reliance on traditional biomass and underscore the importance of transitioning to modern energy systems.

3.6.1. Firewood Collection and Time Poverty

Firewood remains Uganda's dominant cooking fuel, collected by 66.2 % of households, mainly by women and children (UBOS, 2021a; Chyngwa and Silva; Mariangela, 2024). Declining forest resources, compounded by agricultural expansion (see Section 3.3), force rural households to travel longer distances, exposing them to gender-based violence, inter-communal conflicts, wildlife encounters, and physical exhaustion, sometimes with fatal consequences (Joshua et al., 2024; Dastan et al., 2017; Bamwesigye et al., 2020; Egeru et al., 2014; Chyngwa and Silva; Mosa, 2016). This time-poverty has direct consequences for education, food production, income-generating activities, and women's empowerment. Evidence from global meta-analysis suggests improved biomass stoves and clean fuels could reduce fuel collection time by an equivalent of 23 - 29 days annually, equivalent to income gains of around 5 % per day (Simkovich et al., 2019). Yet, despite decades of promotion, only 3.8 % of the population, roughly half a million out of nine million households in Uganda, had access to clean cooking solutions by 2024 (UBOS, 2024). Barriers include high upfront costs of clean stoves, weak distribution infrastructure, and resistance rooted in cultural norms (Joshua et al., 2024; IEA, 2023c; Price, 2017; Rehfuess et al., 2014). The persistence of firewood dependence links directly to land tenure (Section 3.2), as tenure ambiguities undermine investments in sustainable woodlots, and of employment (Section 3.4), as reliance on unpaid family labor masks the true economic value of firewood supply.

3.6.2. IAP and health burdens

Traditional cooking practices also impose severe health hazards. Inefficient combustion of wood, charcoal, in poorly ventilated spaces, produces high levels of particulate matter (PM2.5), carbon monoxide, and other pollutants (Nakora et al., 2020; Axel et al., 2022; Fullerton et al., 2008; Wafula et al., 2023; Kansiime et al., 2022). These exposures disproportionately affect women and children, causing respiratory infections, chronic obstructive pulmonary disease (COPD), cardiovascular illness, and premature death (Axel et al., 2022; WHO, 2024). In 2017, air pollution was linked to 13,000 deaths in Uganda, over 10,000 tied directly to traditional bioenergy use (ATCMASK, 2024). Infant and under-five mortality are strongly associated with IAP, accounting for 8.2 % of infant deaths and 2.9 % of child mortality (Woolley et al., 2020; GVEP, 2024). As biomass stocks decline due to deforestation and land conversion (Section 3.2), households often resort to burning low-quality biomass, worsening exposure risks (Khundi et al., 2011; Jagger and Shively, 2014). Yet, there is a striking dearth of Uganda-specific epidemiological studies, limiting policymakers' ability to quantify health co-benefits of clean energy investments.

These findings align with regional experiences. Rwanda, for example, integrated improved cookstoves into its climate strategy using community distribution and results-based financing, which resulted in a significant reduction in IAP (Uwizeyimana et al., 2024). Such models demonstrate how targeted programs can address health, energy, and climate simultaneously, an approach Uganda has yet to mainstream.

3.6.3. Occupational hazards in the bioenergy sector

Bioenergy supply chains also carry occupational health and safety risks. Charcoal producers, transporters, and vendors, who form a supply chain employing over 340,000 Ugandans (MEMD, 2023), often work without protective equipment, exposing them to injuries, burns, and toxic emissions (Atusingwize et al., 2019; Tebyetekerwa et al., 2017; Dhananjayan and Ravichandran, 2018). In Liberia, charcoal producers reported frequent exposure to pyrolysis gases and other toxic compounds, underscoring risks likely mirrored in Uganda (Alfaro and Jones, 2018). Uganda's weak labor protection exacerbates these vulnerabilities: only 16 % of workers are covered for occupational injuries, 2.6 %

receive any form of social protection, and labor rights compliance stands at a mere 1.3 % (ILO, 2024). This precarity is heightened by the informal nature of most bioenergy employment (see Section 3.4), where unskilled workers, women, and children are concentrated in low-paying and high-risk roles. Furthermore, occupational risks intersect with access to modern bioenergy (Section 3.5): without professionalizing biomass supply chains, workers remain trapped in hazardous, informal markets rather than transitioning to safer, formalized roles in clean energy industries.

Across these domains, bioenergy hazards illustrate how Uganda's dependence on traditional biomass undermines well-being. Firewood collection reproduces gender inequities and time poverty; IAP fuels a preventable health crisis; and occupational hazards threaten labor safety and livelihoods. These risks are not isolated but intersect with other sustainability indicators. Land tenure insecurities perpetuate reliance on unsustainable firewood harvesting. Agricultural expansion, driven by food demand, reduces the biomass base, increasing collection burdens and IAP exposure. Informal employment in the bioenergy sector both sustains and masks occupational risks, while the slow uptake of modern bioenergy technologies limits hazard reduction. International experiences show that hazards can be mitigated. India's biogas programs demonstrate how agricultural residues can substitute traditional fuels while creating safer rural employment (Ministry of New and Renewable Energy MNRE, 2025). Kenya's ethanol stove initiatives have reduced women's exposure to firewood hazards (Gitau et al., 2019; Bailis et al., 2020). These models highlight pathways Uganda could adapt: combining clean energy access with labor protections, integrating hazard reduction into energy and health policy, and targeting women's empowerment through inclusive financing.

Bioenergy in Uganda generates substantial hidden costs in the form of health, safety, and time-use hazards. Without systemic reform, these burdens risk entrenching energy poverty and gender inequities. Addressing them requires coordinated policy interventions that integrate land, food, employment, and energy dimensions. Priorities include accelerating clean cooking access, investing in hazard-free technologies, strengthening occupational safety frameworks, and generating Uganda-specific health and labor data. In doing so, Uganda can align hazard reduction with broader sustainable development goals.

3.7. *Contribution to financial growth*

Under this theme, the financial growth contribution of Uganda's bioenergy sector is examined through three interrelated indicators: (a) productivity, (b) net energy balance (NEB), and (c) gross value added (GVA). These dimensions provide insights into the sector's efficiency, energy performance, and macroeconomic impact. Together, they illustrate the sector's competitiveness, its cost implications for energy access, and its potential role in national economic development. To assess this domain, an input-output framework is applied to analyze various bioenergy streams within the country.

3.7.1. *Productivity*

Among Uganda's bioenergy streams, the charcoal pathway exhibits the lowest productivity, primarily due to significant losses throughout its supply chain, especially at the production stage. Most charcoal is produced using traditional earth kilns, locally known as *Kinyankole* and *Kasisira*, which operate at a conversion efficiency of just 10 – 15 % (MEMD, 2023; Namaalwa et al., 2009), with 8 kg of woodfuel required to produce 1 kg of charcoal. Downstream, traditional charcoal stoves (ISO Tier 1, ~38 % efficiency) further exacerbate the inefficiencies (Nathan, 2024). Additionally, transportation and handling losses (10 - 15 %) reduce productivity as a significant amount of charcoal degrades into unusable dust (Tanui et al., 2018). The firewood stream exhibits a different profile, with the losses mainly at the utilization stage due to the widespread use of traditional three-stone stoves (ISO Tier 0, ~15 % efficiency) (Nathan, 2024). Although improved firewood cookstoves exist in Uganda, their use is limited, mainly to institutional and commercial settings (IEA, 2023c). Therefore, this study takes the overall productivity of the firewood stream as 15 %. Fig. 5 depicts the volume of wood used for firewood, its energy content, and the useful energy derived between 1990 and 2015.

A more promising bioenergy stream is the biomass-fired steam power generation, which is making growing contributions to Uganda's electricity supply. Over the past six years, the sector's contribution has nearly doubled, as shown in Table 2. Although detailed cost data on biomass-generated electricity in Uganda is limited, estimates place production costs between US$0.08 and 0.15 per kWh (Martinez-Hernandez et al., 2021; USDE, 2016). Assuming full capacity operation of all biomass power plants listed in Table 2, the annual production costs and income from electricity sales are estimated at US$1 million and US$26 million, respectively.

Comparing the energy in wood for charcoal production with the useful energy from charcoal shows that charcoal supply chain productivity remained consistently low, oscillating around 7.7 % as shown in Table 3. Fig. 5 illustrates the growing disparity between the energy content of wood inputs and the useful energy obtained from charcoal and firewood. While useful energy output did not show a significant increase, the energy content of the harvested wood seems to exhibit exponential growth. The underlying causes for these trends are not clear from the literature; however, they point to the fact that an increase in energy demand is met by a disproportionately high woodfuel extraction, accompanied by excessive energy losses.

Consequently, about 92 % of the initial energy is consistently lost due to the continued reliance on inefficient kilns and stoves in addition to the handling losses. The unchecked expansion in wood harvesting, combined with stagnant productivity, highlights an urgent need for interventions that reduce energy losses and improve conversion efficiency in both the charcoal and firewood streams. Previous studies support these findings (Dastan et al., 2017; MEMD, 2023; Nabukalu and Gieré, 2019; Bamwesigye et al., 2020).

Therefore, the charcoal stream remains the least productive, with a productivity value of approximately 0.08, followed by firewood at 0.15. In contrast, biomass-based electricity generation demonstrates the highest productivity at 26. These findings reveal the stark differences in efficiency and economic potential across Uganda's bioenergy streams and underscore the importance of targeted interventions to enhance productivity, reduce losses, and maximize the benefits of bioenergy.

3.7.2. *Net energy balance*

This study was unable to estimate the net energy balance (NEB) for Uganda's bioenergy streams due to the absence of reliable data on energy inputs required for biofuel production. This limitation is particularly acute for traditional biofuels, such as firewood, charcoal, agricultural residues, and organic waste, which account for the majority of Uganda's energy consumption. Compounding this data gap is the minimal adoption of modern biofuels in the country, further constraining the feasibility of NEB assessments. To provide insight, the study reviewed NEB estimates from comparable contexts across SSA.

For instance, Ayamga et al. (2015) reported a positive NEB of 1718.7 MJ and an output-input energy ratio of 1.31 for second-generation bioethanol derived from crop residues in Ghana. In Ethiopia, Gabisa et al. (2019) also found a favorable NEB for bioethanol production from sugarcane molasses. Likewise, in Tanzania, Eshton et al. (2013) documented a significant energy gain of 19.2 GJ per tonne of Jatropha-based biodiesel. Beyond Africa, studies have yielded similar findings. In the United States, Illukpitiya et al. (2017). reported a positive NEB for bioethanol derived from native warm-season grasses. In Europe, Van Meerbeek et al. (2019) confirmed NEB gains from lignocellulosic biomass. Other relevant studies include those by Maranduba et al. (2016)., Portugal-Pereira et al. (2015)., Pleanjai and Gheewala (2009) on biodiesel, as well as Coral Medina et al. (2018)., Guerrero and Muñoz (2018), Saga et al. (2010), Shelar et al. (2023)., and Tan et al. (2010) on

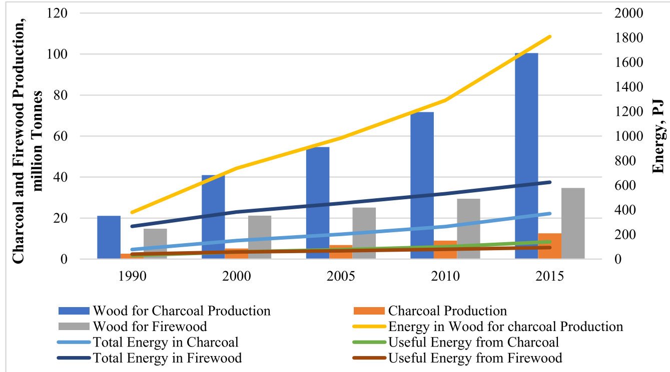

Fig. 5. Energy Production and Wood Resource Extraction along the Firewood and Charcoal Streams in Uganda.

Table 3
Bioenergy production from firewood and charcoal pathways in Uganda.

Year	Wood for Charcoal Production (million tonnes)	Charcoal Production (million tonnes)	Wood for Firewood (million tonnes)	Energy in Wood for Charcoal Production (PJ)	Useful Energy from Charcoal (PJ)	Productivity of Charcoal Stream
1990	21.09	2.64	14.78	379.62	29.54	7.78
2000	40.99	5.12	21.23	737.82	57.30	7.77
2005	54.65	6.83	25.16	983.7	76.43	7.77
2010	71.70	8.96	29.48	1290.6	100.27	7.77
2015	100.48	12.56	34.70	1808.64	140.56	7.77

Adapted from UBOS (2020b).

bioethanol.

Despite this body of literature, the energy performance of modern biofuels remains a subject of debate. For example, Barr et al. (2021) highlighted stark contradictions in foundational studies: Pimentel and Patzek (2005) argued that both first- and second-generation biofuels suffer from energy deficits ranging from 29 % to 118 %, while Shapouri et al. (2002) reported a positive energy return on investment. Barr et al. contend that the discrepancy arises from differing methodologies, with Pimentel and Patzek accounting more comprehensively for total energy inputs. Similarly, Randelli (2009) observed that the NEB of first-generation biofuels is generally lower than that of second-generation alternatives, though regional variations remain substantial. Notably, Ayamga et al. (2015) found second-generation bioethanol to be more expensive than its first-generation counterpart, adding economic complexity to the energy balance debate.

Overall, the literature reveals considerable variability in NEB values, even for the same bioenergy streams, highlighting the highly context-specific nature of such assessments, as was previously observed by Randelli (2009). These inconsistencies underscore the urgent need for standardized, region-specific methodologies to assess the NEB of biofuels in comparison to fossil fuels. Although some consensus has emerged suggesting that biofuels generally have lower NEB values than fossil fuels (Barr et al., 2021; Pimentel and Patzek, 2005; Shapouri et al., 2002; Randelli, 2009; Patel et al., 2020), the evidence remains context-dependent and, in many cases, inconclusive. Crucially, while much of the existing literature focuses on liquid biofuels, there is a glaring lack of empirical NEB studies on traditional biomass fuels, particularly firewood and charcoal. Given that these fuels remain the dominant energy sources in Uganda and much of SSA, gaining a clearer understanding of their energy efficiency is essential for designing effective and sustainable energy strategies.

3.7.3. Gross value added

The economic contribution of bioenergy in Uganda, measured through GVA, was assessed using data from the Forest Accounts Report by UBOS (UBOS, 2020b). These estimates were cross-validated with figures from the UBOS (UBOS, 2023a) Statistical Abstract, and key trends are subsequently presented and discussed. Fig. 6 shows the historical trends in wood resource use for charcoal and firewood from 1990 to 2015. Over the past 25 years, the amount of wood used for charcoal production has increased almost fivefold, from 21 million tonnes to over 100 million tonnes, equivalent to an average annual increase of 5.3 million tonnes. Firewood consumption also rose, albeit more modestly, with an average annual increase of 1.3 million tonnes. The dominance of wood use in the charcoal stream contrasts with broader energy trends: charcoal accounts for only 5.6 % of Uganda's TPES, while firewood contributes over 78.7 %, and consistently outpaces charcoal in terms of economic returns (MEMD, 2023).

Since 1990, charcoal's GVA has remained less than half that of firewood. This disparity underscores charcoal's lower economic efficiency and higher environmental costs. The UBOS (UBOS, 2020b) Forest Account Report critically analyzed this unexpected trend and attributed it to the nature of the charcoal value chain, which often relies on wood harvested without incurring extraction costs, largely due to informal or illegal sourcing. If wood used for charcoal production were priced even at the level of the lowest-valued industrial wood, the charcoal sector would likely lose its competitive edge relative to other fuel alternatives. Furthermore, value addition in the charcoal sector primarily affects market prices rather than resource rent. Because charcoal producers face minimal wood acquisition costs, there is little economic incentive to improve efficiency or sustainability across the value chain. This helps explain the disproportionately high resource use for charcoal production, despite its limited economic returns. In contrast, other forestry products exhibit stronger economic viability and resource rent potential. A study by the International Union for the Conservation of Nature (IUCN) and the MWE in 2018 found that forestry products other than charcoal contribute more significantly to Uganda's economy, reinforcing the conclusion that charcoal provides lower economic returns while imposing higher environmental costs (IUCN, 2018).

Given this context, promoting firewood-based clean cooking technologies presents a more sustainable and economically rational strategy for addressing household energy needs. However, for this energy transition to succeed, coordinated efforts to overcome the social stigma associated with firewood use, particularly in urban areas, will be

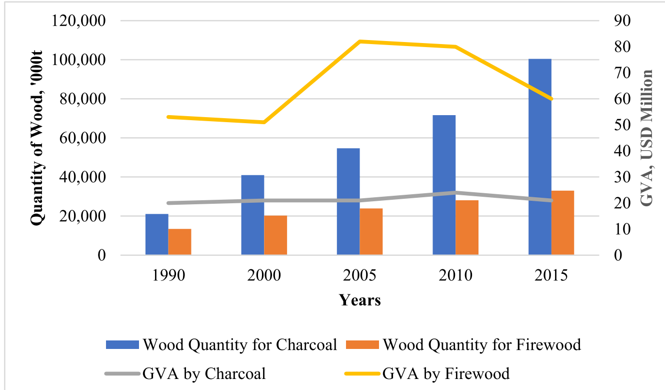

Fig. 6. Woody Biomass Extraction and GVA for Firewood and Charcoal in Uganda (Data from (UBOS, 2023a) and (UBOS, 2020b)).

essential through public sensitization, development of robust market structures for improved firewood stoves, and sustained investment in technological research and innovation. Elsewhere, the biomass-electricity stream demonstrates steady growth, with GVA rising from US$18 million in 2016 to US$32 million in 2021, though its GDP share remains under 0.1 % (Table 4). With 93 % of its potential untapped (Twinomuhangi et al., 2022), this subsector offers significant opportunities if anchored in reliable financing, technology transfer, and supportive regulation.

Experiences from other countries illustrate that financial growth and sustainability are not mutually exclusive. In Ghana, bioethanol from residues shows that productive agricultural-bioenergy linkages can generate strong economic returns (Larsen et al., 2020; Kemausuor et al., 2013; Präger et al., 2019). Kenya's ethanol stove programs, backed by subsidies and private investment, have simultaneously reduced household charcoal demand and created new business opportunities (Karanja and Gasparatos, 2019; Bailis et al., 2020). Rwanda's integration of improved cookstoves into climate strategies through results-based financing demonstrates how governance frameworks can mobilize resources and scale up adoption (Uwizeyimana et al., 2024). Globally, Brazil's ethanol blending program and India's decentralized biogas systems showcase how clear policy frameworks, technological innovation, and financing structures can turn bioenergy into an economic growth driver (Ministry of New and Renewable Energy MNRE, 2025; Ribeiro and da Cunha, 2022). Importantly, these examples reveal strong parallels with Uganda's challenges: weak tenure systems, inefficient traditional pathways, and health hazards limit productivity and economic returns.

Uganda's bioenergy sector shows mixed contributions to financial growth. Traditional fuels, especially charcoal, are inefficient and economically fragile, while emerging technologies such as biomass electricity offer high productivity and GVA potential. However, weak tenure governance and persistent hazards, ranging from time poverty to health burdens, undermine the sector's ability to support growth. International and regional experiences indicate that with secure tenure, efficient technologies, and supportive financing, bioenergy can contribute significantly to both livelihoods and national economies. Linking financial growth with the earlier-discussed indicators on land tenure and hazards underscores that sustainable bioenergy in Uganda will not be achieved through technology alone, it requires coordinated governance reforms, inclusive financing mechanisms, and policies that balance efficiency, equity, and sustainability.

3.8. *Energy security and diversity*

Energy security in Uganda is both multidimensional and context-specific, shaped by the dominance of traditional biomass, limited diversification, and underutilized renewable potential. Modern definitions of energy security emphasize four key dimensions: availability, acceptability, affordability, and accessibility (Esfahani et al., 2021; Cherp and Jewell, 2014). The IEA (IEA, 2025) defines energy security as the uninterrupted availability of energy at an affordable cost, underscoring the vital role of accessibility in an increasingly energy-dependent world. Disruptions or shortages can have serious consequences for social welfare, environmental sustainability, and economic growth (Strojny et al., 2023).

3.8.1. *Energy diversity*

This indicator assesses the role of bioenergy in diversifying Uganda's TPES. Following GBEP (GBEP, 2011) guidelines, the Herfindahl Index (HI) is used to quantify energy diversity. The HI is calculated by summing the squares of the fractional shares of each energy source in TPES. The index ranges from 0 to 1, where 1 indicates a monopolistic supply structure and lower values reflect a more balanced and diverse energy mix. To evaluate bioenergy's impact, HI was computed under four different scenarios: with and without various bioenergy sources, redistributing their shares to the most probable alternative supply. They included: (1) the current energy mix, (2) the removal of firewood (replaced by residues and waste), (3) the substitution of charcoal with firewood, and (4) the replacement of biofuels with electricity and petroleum products.

The results reveal that Uganda's TPES in 2021 was 22 Mtoe, with bioenergy contributing 89 %, followed by petroleum (9 %) and electricity (2 %) (IEA, 2023c). Within bioenergy, firewood accounts for 78.7 %, charcoal 5.6 %, and residues and waste 4.7 % (Fig. 7). The HI calculations, presented in Table 5, confirm a highly monopolized structure with HI values ranging between 0.52 and 0.73 under different substitution scenarios. This indicates significant vulnerability to supply shocks, as the removal of firewood or charcoal further reduces energy diversity, for example, scenarios 2 and 3. Such heavy dependence on

Table 4
Electric energy sales to UETCL and GVA by biomass-fired power plants.

	2016	2017	2018	2019	2020	2021
Electric Energy from Biomass (GWh)	177.5	149.8	206.4	196.8	188.2	266.5
GVA (USD million)	18	16	23	23	24	32
Contribution to GDP (%)	0.062	0.050	0.067	0.062	0.061	0.074

Date from MEMD (2023), IEA (2023c), ERA (2023).

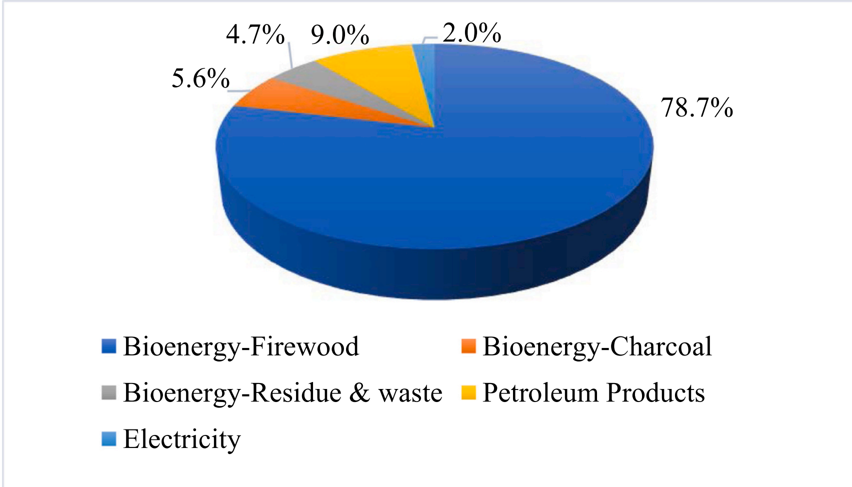

Fig. 7. The Composition of TPES for Uganda.

Table 5
Contribution of bioenergy to energy diversity.

TPES	Scenarios			
	The current Scenario	Without Firewood	Without Charcoal	Without Bioenergy
Bioenergy-Firewood	0.787	0	0.843	0
Bioenergy-Charcoal	0.056	0.056	0	0
Bioenergy-Residue & waste	0.047	0.834	0.047	0
Petroleum Products	0.09	0.09	0.09	0.393
Electricity	0.02	0.02	0.02	0.607
HI	**0.633**	**0.707**	**0.721**	**0.523**

Data source: IEA (2024a).

traditional biomass mirrors earlier findings on hazards (Section 3.6), where unsustainable fuelwood collection and reliance on charcoal create health burdens and time poverty. It also reinforces concerns raised in land tenure (Section 3.2), since insecure access to forest resources undermines sustainable feedstock supply. Moreover, the predominance of informal labor in this subsector (Section 3.4) constrains opportunities for technological upgrading and formalization.

International experience underscores how diversification strategies can enhance resilience. For example, Brazil's *RenovaBio* program mandates biofuel blending and establishes decarbonization credits, significantly diversifying its energy mix and reducing fossil fuel dependence (De Oliveira and Coelho, 2017; Salles-Filho et al., 2017). In Ghana, the Renewable Energy Act of 2011 created a legal framework for biofuels and biomass energy, stimulating private investment and enabling the substitution of charcoal with modern fuels (International Comparative Legal Guides (ICLG), 2024). These examples demonstrate that Uganda's current monopolistic energy structure could be addressed through coordinated policies, incentives, and integration of modern bioenergy alongside other renewables.

3.8.2. *Infrastructure and logistics of distribution of bioenergy*

Energy systems - including oil, gas, biofuels, and electricity - require robust infrastructure and distribution networks to ensure accessibility. However, these systems can face vulnerabilities that pose risks to energy security. If disruptions can be swiftly addressed or easily substituted, their impact remains minimal. In contrast, "critical" infrastructure, such as pipelines, ports, and rail networks, poses a greater risk due to the complexity and time required for repairs or limited alternative arrangements. Road-based distribution systems are generally more resilient, offering flexible routes and quicker response options (GBEP, 2011).

This indicator assessed the extent to which bioenergy in Uganda depends on "critical" distribution infrastructure and the capacity and number of transport routes involved. As outlined in Sections 3.5.1 and 3.6.1, most bioenergy, especially firewood, is sourced locally and distributed primarily through road networks, bicycles, and manual collection (Khundi et al., 2011; MEMD, 2023; Nabukalu and Gieré, 2019; Bamwesigye et al., 2020; Mwampamba et al., 2013). While this reduces reliance on "critical" infrastructure such as pipelines or ports, it also reflects a low-technology, fragmented system. For rural households, this distribution model reinforces firewood dependence, exposing women and children to hazards during collection.

Global best practices highlight how infrastructure investment can reshape energy access. In India, the large-scale national biogas and manure management programme has built decentralized systems linking households and communities to cleaner energy sources (Ministry of New and Renewable Energy MNRE, 2025; Srivastava et al., 2016; Raipurkar, 2024; Raha et al., 2014). Similarly, China's widespread deployment of household biogas digesters under clean development mechanism (CDM) projects demonstrates how community-level infrastructure can both improve energy access and reduce emissions (Hou et al., 2017; Chen et al., 2017). For Uganda, such decentralized systems could alleviate transport pressures, reduce forest dependence, and foster rural employment.

3.8.3. *Capacity and flexibility of use of bioenergy*

Another key dimension of energy security is evaluating (a) the Capacity Utilization Ratio, the ratio of actual bioenergy use to its available production capacity for each major energy stream, and (b) the Flexible Capacity Ratio, the share of bioenergy systems capable of switching between bioenergy and alternative fuels. The former measures production buffer, while the latter assesses adaptability and resilience. The analysis focused on firewood, charcoal, and biomass-based electricity.

Uganda's woody biomass utilization ratio exceeds 100 %, with an annual demand of 65 million tonnes compared to a sustainable supply of 27 million tonnes. This supply deficit has grown 22-fold since 2000, underscoring unsustainable extraction patterns. Conversely, biomass-based electricity, mainly from bagasse, remains underutilized, with only 1120 GWh of a potential 14,454 GWh exploited. Flexibility is also low, since most cookstoves and biomass systems are fuel-specific and lack switching capacity. Lessons from Rwanda's clean cooking strategy are instructive. The government's ReCiC program, which supports Tier-3 + stove producers and introduces results-based financing, has expanded consumer access and diversified energy use (Nyaga et al., 2021). By contrast, Uganda's low penetration of clean cooking (3.8 % of households in 2024) reflects weak financing, fragmented supply chains, and inadequate policy enforcement. Bridging this gap requires targeted subsidies, consumer finance mechanisms, and stronger institutional coordination.

The findings reveal a paradox: Uganda is richly endowed with renewable energy potential, over 4500 MW of hydropower, 5000 MW of solar, 800 MW of peat, and 1.65 GW of biomass cogeneration (see Table 6), yet the country remains locked in an unsustainable energy structure dominated by traditional bioenergy. Lessons from global best practices suggest three key enablers for overcoming this paradox. First, governance is critical; clear and coherent policy frameworks, such as those adopted in Ghana and Brazil, can guide diversification, regulate technology standards, and integrate bioenergy into broader energy planning. For Uganda, this requires addressing land tenure complexities (Section 3.2) to secure sustainable feedstock supplies.

Second, technology adoption is essential; modern bioenergy systems, including biogas digesters, pellets, and efficient cookstoves, can reduce indoor air pollution hazards (Section 3.6) while simultaneously strengthening employment opportunities in both rural and urban areas (Section 3.4). Third, financing mechanisms play a central role; results-based financing, targeted subsidies, and international climate funds such as the Green Climate Fund are needed to accelerate uptake. Rwanda's innovative clean cooking financing models illustrate how such mechanisms can be localized. In sum, Uganda's bioenergy-driven total primary energy supply presents both risks and opportunities. Without diversification, energy insecurity, environmental degradation, and public health burdens will likely intensify. However, by leveraging stronger governance, technological innovation, and inclusive financing, anchored in regional and international best practices, Uganda can transition toward a more secure, diversified, and sustainable energy future.

3.9. Synthesis and implications

The assessment of Uganda's bioenergy sector using the GBEP socioeconomic sustainability indicators underscores the complexity of balancing energy access, livelihoods, and sustainability in a context shaped by limited resources and governance challenges. A cross-domain synthesis reveals several critical insights with implications for policy, practice, and future research. First, the results point to urgent policy and governance implications. Traditional bioenergy pathways, particularly firewood and charcoal, remain the backbone of Uganda's household energy access and rural employment, but they are simultaneously linked to negative outcomes such as gendered time burdens, occupational health risks, food insecurity, and environmental degradation. These impacts intersect with land tenure challenges, where insecure or contested rights over woodlots, farmlands, and communal resources exacerbate disputes, constrain sustainable biomass management, and intensify the food–energy–land trade-offs. Effective governance, therefore, requires not only energy-sector reforms but also cross-sectoral coordination with land administration, forestry management, and rural development institutions. Strengthening regulatory frameworks for charcoal production, clarifying land rights, and mainstreaming gender equity into energy policy are essential steps toward a more sustainable and just bioenergy system.

The findings also reveal the centrality of financing mechanisms in shaping Uganda's bioenergy transition. Despite significant potential from residues, biogas, and bioenergy-based electricity, investments in modern bioenergy technologies remain minimal. This underinvestment reflects both limited domestic capital and inadequate international financing flows, which are often concentrated in other renewables such as solar and hydropower. Without targeted financing instruments, such as concessional credit for biomass enterprises, public–private partnerships, and results-based financing for clean cooking technologies, the transition from traditional to modern bioenergy will remain slow. Strengthened governance structures are equally important for ensuring that financing is effectively deployed and monitored, minimizing risks of elite capture, misallocation, or unsustainable practices.

Third, the study makes a unique contribution to the literature by being the first to apply the GBEP socioeconomic indicators comprehensively to Uganda's bioenergy sector. Beyond assessing individual indicators, the analysis demonstrates how outcomes are interconnected across domains: for instance, efforts to expand bioenergy-based employment must be matched with safeguards for gender equity; improvements in energy security can be undermined if they exacerbate land conflicts or food insecurity; and financing mechanisms that unlock new technologies must be anchored in governance systems that ensure equitable benefits. This integrative perspective demonstrates the value of using the GBEP framework in developing-country contexts, even where empirical data are limited, by systematically drawing insights from both peer-reviewed and grey literature.

Finally, the synthesis highlights a forward-looking research agenda that addresses Uganda's most pressing evidence gaps as summarized in Table 10 (appendix). Three priorities emerge. First, empirical field studies are urgently needed to quantify household-level impacts of bioenergy transitions, including cookstove performance, time use, and health outcomes. Second, quantitative analyses of the food–energy–land nexus should be advanced to capture trade-offs between biomass energy expansion, agricultural productivity, and tenure security, particularly in rural communities where customary and statutory land systems overlap. Third, cross-country comparative studies within Africa are necessary to benchmark Uganda's experiences against regional peers, extract transferable best practices, and identify policy innovations that balance energy access with land and livelihood security.

Therefore, the sustainability of Uganda's bioenergy sector cannot be reduced to technical efficiency or fuel substitution alone. It hinges on the interconnected domains of governance, financing, land tenure, gender equity, food security, and employment. By weaving these dimensions together, this study not only provides actionable insights for policymakers but also advances scholarly understanding of how indicator-based frameworks such as GBEP can be operationalized in data-scarce, developing-country contexts. At the same time, it charts a forward-looking agenda for research and practice aimed at ensuring that Uganda's bioenergy transition contributes meaningfully to sustainable development.

Table 6
Uganda's potential and exploited energy resources.

	Potential	Exploited
Hydro	4500 MW	822 MW
Solar	5000 MW	54 MW
Peat	800 MW	none
Biomass Cogeneration	1650 MW	112 MW
Biomass Stock (Sustainable annual yield)	50 million tons	Over exploited
Wind	No official Estimates	None
Geothermal	450 MW	None
Oil (Recoverable)	1.4 billion barrels	None
Gas	700 billion ft^3	None

4. Limitations of the study

In addition to the methodological limitations outlined in Section 2.2.3, this study was limited in its coverage of Uganda's bioenergy sector. The analysis primarily focused on three dominant bioenergy streams: firewood, charcoal, and organic residues/waste, particularly bagasse. While the study acknowledges the existence of other bioenergy streams, such as biomass digestion, gasification, and densification, these pathways were not included in the assessment. Their exclusion may have affected the comprehensiveness and generalizability of the findings. Furthermore, inconsistencies observed across data sources, especially within grey literature, posed additional limitations. In cases where such inconsistencies in data could not be independently verified, such datasets were excluded from the analysis to maintain analytical rigor and accuracy. This inevitably resulted in a partial assessment of some indicators, highlighting the need for more robust, coordinated, and verifiable data systems in Uganda's bioenergy sector.

Second, while the study applied the GBEP framework to structure the analysis, indicator comparability across contexts remains a challenge. Many of the indicators were originally designed for countries with more robust statistical systems and better-documented bioenergy sectors. Applying them in Uganda required adaptation and interpretation, which may introduce measurement bias or reduce precision. For example, proxy indicators were occasionally used where primary data were missing, potentially affecting the depth of the analysis. This limitation highlights the need to contextualize global frameworks to local realities and invest in methodological innovations that better capture the informal and traditional dimensions of bioenergy in sub-Saharan Africa.

A further key limitation concerns the incomplete application of the GBEP indicators due to data gaps. For instance, Indicator X (Net Energy Balance) could not be assessed across Uganda's bioenergy streams, restricting evaluation of energy efficiency and trade-offs. Similarly, Indicator XII (Training and Requalification of the Workforce) and Indicator XVI (Capacity and Flexibility of Use of Bioenergy) lacked sufficient evidence, narrowing the analysis of workforce transitions and system resilience. While these gaps do not undermine the validity and analytical depth of the indicators whose data were available, and the overall study, they reduce the general comprehensiveness and reflect broader weaknesses in Uganda's energy data systems. Addressing these limitations requires more systematic national surveys, empirical field research, and stronger institutional coordination.

5. Conclusions

This study demonstrates that bioenergy remains the backbone of Uganda's energy system, accounting for nearly 90 % of total primary energy supply. Firewood and charcoal dominate, providing livelihoods and supporting rural economies, but they are increasingly unsustainable, with woody biomass demand exceeding the sustainable annual yield by more than 14 million tonnes. Their continued reliance also perpetuates health risks from IAP and exacerbates gender inequities linked to the burden of fuel collection.

At the same time, the results highlight significant opportunities for transition. Agricultural residues, organic waste, and biomass cogeneration remain largely untapped, with only 7 % of the country's estimated 1.65 GW biomass electricity potential currently exploited. Clean cooking access is just 3.8 %, yet the adoption of efficient biomass stoves, LPG, ethanol, and electric cooking technologies offers clear pathways to reduce environmental degradation, strengthen energy security, and improve public health outcomes.

Methodologically, the application of GBEP sustainability indicators has proven useful in systematically assessing the socio-economic dimensions of bioenergy in a developing country context. Nonetheless, persistent challenges such as data scarcity, reliance on grey literature, and fragmented institutional responsibilities remain major barriers to evidence-based policymaking.

In summary, Uganda's bioenergy sector embodies both challenge and promise: entrenched dependence on traditional biomass threatens health, equity, and ecosystems, but modern bioenergy options, if supported by coherent governance, sustained investment in technology, and innovative financing, could transform the sector into a driver of sustainable energy and national development. Looking forward, steering Uganda's bioenergy sector toward sustainability necessitates several policy actions as presented in the next section.

6. Recommendations

6.1. Policy recommendation

Strengthening land and resource governance is crucial for securing a sustainable feedstock supply. Uganda's reliance on firewood (68 %) and charcoal (21 %) of TPES has accelerated forest loss and land-use conflicts. Drawing lessons from community-based forest management in Tanzania and Brazil's biofuel zoning, Uganda can balance bioenergy expansion with food security and forest conservation, while protecting communities reliant on customary tenure systems.

Accelerating the transition to clean cooking technologies is equally critical. Traditional biomass remains a major source of indoor air pollution and contributes to women's time poverty from fuel collection. Uganda can learn from Rwanda's results-based financing for improved cookstoves and Kenya's ethanol-based clean cooking programs, which have reduced charcoal dependence and improved health outcomes. Gender-sensitive subsidies and incentives for private-sector investment would further expand clean cooking access.

Reforming charcoal governance while expanding alternative value chains is also essential. Establishing standards for sustainable production, regulating the charcoal trade, and promoting cleaner alternatives would reduce unsustainable harvesting. Given that firewood provides both higher energy and greater GVA than charcoal, efforts should prioritize improved firewood cookstoves. At the same time, agricultural residues offer an untapped resource. Uganda generates over 737.7 PJ of residues annually, yet most remain unused. Harnessing this for biogas, pellets, and cogeneration could displace wood fuels, reduce waste, and create rural jobs. Comparable initiatives in India and Brazil illustrate how residues can support electrification and agro-industrial productivity.

Finally, Uganda's fragmented bioenergy governance and persistent data gaps hinder effective planning. Lessons from Ghana's Renewable Energy Directorate and Brazil's EMBRAPA Bioenergia highlight the value of consolidated data, coordination, and cross-sectoral planning. Strengthening institutions and establishing systematic monitoring will be essential for evidence-based policymaking and sustainable growth.

6.2. Recommendations for future research

Bioenergy Systems Modeling and Scenario Analysis: Sustainability assessments can be significantly strengthened through advanced modeling capable of forecasting trends, testing policy scenarios, and analyzing long-term socioeconomic and environmental outcomes. Yet, no significant modeling efforts have been contextualized for Uganda's bioenergy sector, a critical research gap. System dynamics, which captures cross-sectoral interactions and feedback loops, is well-suited to bioenergy complexity. MEMD should spearhead such efforts with academic and research partners.

Testing and Classification of Biomass Cookstoves: Uganda still categorizes all biomass cookstoves as Tier 0 despite widespread adoption of improved technologies. Some could meet Tier 3 or higher standards, but the absence of a testing and certification framework hinders accurate classification. Establishing a national evaluation system would facilitate scaling clean cooking solutions. MEMD, together with UNBS and manufacturers, should lead this initiative.

Bioenergy - Food Production Nexus: Land-use competition between food and bioenergy is intensifying, with agricultural expansion reducing access to firewood and charcoal. Empirical evidence on trade-offs and synergies remains scarce. Joint studies by MAAIF, MEMD, and academic institutions are needed to guide integrated land-use planning that balances energy, food, and environmental priorities.

Bioenergy and Human Capital Development: Limited knowledge exists on employment and labor conditions in Uganda's bioenergy sector. Research should address job creation across value chains, differentiating between formal and informal work, wages, skills, and occupational health. Integrating these variables into UBOS labor surveys would inform workforce planning.

Charcoal Replacement Strategies: Charcoal is highly inefficient, consuming more wood and yielding less economic value than firewood. Transition strategies should include promoting efficient firewood stoves, understanding consumer preferences, fiscal and regulatory incentives for fuel switching, and awareness campaigns to overcome cultural biases. MEMD should lead the development of a comprehensive charcoal transition plan.

Energy Security and Diversification: Heavy reliance on bioenergy for heat and hydropower for electricity exposes Uganda to shocks, including biomass scarcity and climate-driven variability. Strategic diversification into solar, wind, geothermal, oil and gas, and nuclear, guided by scenario modeling, is essential for resilience.

Bioenergy Sector Governance: Despite its dominance, bioenergy governance remains fragmented. Establishing a dedicated MEMD directorate would ensure oversight, sustainable production, research coordination, and strategic planning. Careful institutional design will be key to aligning with national priorities.

Cross-Country Benchmarking: Uganda's bioenergy sustainability performance has not been systematically compared with that of other SSA countries. Conducting structured cross-country assessments would benchmark progress, highlight regional synergies, and guide harmonized policy development under frameworks such as the East African Community renewable energy targets.

CRediT authorship contribution statement

Liberty Kanyamumba: Writing – review & editing, Visualization. **Michael Lubwama:** Writing – review & editing, Supervision, Conceptualization. **Betty Nabuuma:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Robert Kakebe Sekajja:** Writing – review & editing, Writing – original draft, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT and DeepSeek in order to improve its readability, clarity, and language. After using this tool/service, the authors reviewed and edited the content as needed, and take full responsibility for the content of the publication.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table 7
Distribution of publications among indicators and thematics used in this assessment.

No	Thematics	Indicators	Within the Ugandan Context	Outside the Ugandan Context	From Indexing Databases	From Grey Literature	Total
a	Land Allocation and Tenure for Bioenergy Projects	I	*17*	*6*	*10*	*13*	*23*
b	National Food Basket Prices and Supply	II	*18*	*6*	*15*	*9*	*24*
c	Employment, Income, and Professional Development	III	*4*	*0*	*3*	*1*	*18*
		IV	*10*	*2*	*3*	*9*	
		XII	*0*	*0*	*0*	*0*	
d	Access to Modern Bioenergy	V	*13*	*0*	*1*	*12*	*17*
		XIII	*2*	*2*	*0*	*4*	
e	Bioenergy Related Hazards	VI	*15*	*9*	*13*	*11*	*40*
		VII	*7*	*3*	*7*	*3*	
		VIII	*3*	*3*	*4*	*2*	
f	Contributions to Financial Growth	IX	*8*	*5*	*8*	*5*	*48*
		X	*0*	*17*	*17*	*0*	
		XI	*10*	*1*	*1*	*10*	
g	Energy Security and Diversity	XIV	*1*	*2*	*0*	*3*	*19*
		XV	*4*	*2*	*4*	*2*	
		XVI	*11*	*0*	*8*	*8*	
	Total		***81***	***51***	***71***	***59***	***130***

Table 8
International, regional, and national legal instruments used for land regulation and management in Uganda.

International	Regional	National
• UN Charter • UN Declaration • Convention on Elimination of All Forms of Discrimination Against Women (CEDAW) • The Kyoto Protocol • Universal Declaration of Human Rights	• The African Charter • The East African Community	• The 1995 Constitution of Uganda • The Land Act, Cap 227 of Uganda • The Succession Act (Amendment) Decree of 1972 • The Registration of Titles Act Cap 205 • The National Environment Act Cap 153 • The Land Acquisition Act Cap 226

Table 9
National institutional frameworks for regulation and management of acquisition, use, and disputes on land in Uganda.

No	Institution	Contribution to Land Regulation	References
1	MLHUB	Sets policy direction, establishes national standards, and coordinates all land, housing, and urban development issues. It executes policies and spearheads legislation that guarantees sustainable land management, advocates for equitable housing for all, and supports organized urban growth in the country.	(MLHUD, 2024)
2	Uganda Land Commission	It possesses and oversees any land in Uganda vested in or acquired by the Government of Uganda, in line with the provisions of the Constitution, and carries out any additional functions designated by the national legislative body.	(MLHUD, 2024)
3	District Land Board	It holds and distributes land not owned by any individual or entity, facilitates the registration or transfer of land interests, and manages all land-related matters within the district following laws enacted by the legislature.	(MLHUD, 2024)
4	Area Land Committees	Offers advisory services to the boards on land matters, including ascertaining land rights	(MLHUD, 2015)
5	Recorder	Is answerable to the board and responsible for accepting applications for, issuing, and keeping records relating to certificates of occupancy and customary ownership.	
6	Land Dispute Tribunals	They are established per district and comprise a chairperson and two additional members. They resolve disputes concerning leases, grants, repossession, transfer, acquisition, or compensation for land acquired by individuals, the land commission, or other authorities.	(GoU, 2003)

Table 10
Summary of key data deficits.

Indicator	Description	Deficits Identified	Suggested Research Priorities
II	National Food Basket Prices and Supply	Scarce evidence on bioenergy–food production trade-offs and synergies	Conduct integrated food–energy nexus studies using system dynamics and field surveys; develop land-use planning tools to balance food security and bioenergy.
II	National Food Basket Prices and Supply	Outdated, fragmented estimates of residue energy potential	Develop spatially explicit residue potential assessments; apply remote sensing and lifecycle analysis; model supply chain logistics.
III, IV, XII	Employment, Income, and Professional Development	Informal labor data; weak evidence on skills, training, and requalification	Undertake sectoral employment surveys; map skill gaps; design training and requalification programs with MGLSD, UBOS, and MEMD.
V	Bioenergy for Access to Modern Energy	No standardized cookstove performance data; most remain Tier 0	Establish national testing and certification framework; benchmark against ISO tiers; create longitudinal performance datasets.
VI	Unpaid Time for Biomass Collection	Lack of gender-disaggregated labour metrics across value chains	Conduct gender-focused surveys; integrate time-use and labour modules into national surveys; assess occupational health and safety risks.
VII	Mortality and Morbidity burdens from IAP	Limited empirical data on modern bioenergy's health impacts	Conduct Uganda-specific epidemiological studies to quantify health co-benefits of clean energy adoption.

Data Availability

The data that was used was from published sources, available to the public, and was duly referenced

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