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The Synergy of Indigenous Vegetables and Bioenergy for Nutritious Food Sovereignty in Tanzania and Beyond: A Systematic Review

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Abstract

Ensuring food sovereignty amid climate change, energy insecurity, and fragile food systems remains a central challenge for low- and middle-income countries. Indigenous vegetables (IVs) and bioenergy represent two locally grounded yet often separately addressed components of sustainable development. This systematic review synthesises evidence on how synergies between IVs and bioenergy systems jointly advance nutritious food sovereignty in Tanzania and comparable contexts globally. Drawing on 123 peer-reviewed and grey literature sources published between 1990 and 2025, the review demonstrates that IVs provide climate-resilient, nutrient-dense foods essential for dietary diversity, while bioenergy enables energy-efficient processing, preservation, and storage of these foods. When integrated, IVs and bioenergy form a circular bioeconomy in which agricultural residues are valorised into clean energy, post-harvest losses are reduced, nutrient retention is enhanced, and reliance on imported food and fossil fuels declines. The review further shows that such synergies align strongly with national development strategies and global sustainability frameworks, including Tanzania's NMNAP II, FYDP III, and the Sustainable Development Goals (SDGs 2 and 7). The paper concludes that integrating indigenous agri-food systems with decentralised bioenergy is not merely a technical option but a strategic pathway toward equitable, resilient, and sovereign food-energy systems. Future research should focus on socio-technical integration, gender-inclusive governance, and scalable policy frameworks to unlock the full potential of IV-bioenergy synergies.

Keywords

Indigenous Vegetables, Bioenergy, Food Sovereignty, Circular Bioeconomy, Clean Cooking, Tanzania

1. Introduction

Access to nutritious food and reliable energy is fundamental to human well-being. Yet, for many communities, these remain structurally constrained by climate change, market volatility, and dependence on external inputs. In the Global South, sub-Saharan Africa, and Tanzania in particular, food systems are characterised by persistent malnutrition, post-harvest losses, and energy poverty, despite abundant biological resources. Specifically, indigenous vegetables (IVs) and bioenergy represent two critical yet often siloed pillars of sustainable development. This paradox highlights the need for integrated approaches that address food and energy challenges simultaneously rather than in isolation. Access to IVs and bioenergy contributes to the community's sustainable availability of energy and nutritious food. Both IVs and bioenergy sustain biodiversity [1] [2]. Biodiversity refers to the variety of life within ecosystems, which is crucial for ecological resilience, nutrient cycling, and cultural heritage [3]. IVs—locally adapted, nutrient-dense crops—support dietary diversity, biodiversity conservation, and climate adaptation [4] [5]. Bioenergy, derived from biomass resources such as crop residues and non-edible plant parts, offers a renewable alternative to fossil fuels, reducing greenhouse gas emissions and enhancing energy access [6] [7]. The integrated approaches that address food and energy challenges enhance sustainability.

IVs, also known as traditional vegetables, are defined as species that are locally important for the sustainability of economies, human nutrition and health, and social systems, but have not yet attained the same global recognition as major vegetable commodities such as tomato or cabbage [4]. In Tanzania, IVs—such as African eggplant, cowpea leaves, jute mallow (*Corchorus olitorius* L.), amaranth (*Amaranthus spp*.), spider plant (*Cleome gynandra*), African nightshade (*Solanum nigrum*), *Justicia heterocarpa*, *Sesamum angustifolium*, *Ipomea batatas*, *Manihort esculenta*, and *Corchorus trilocularis*—are native crops adapted to local climates and pests; they offer vital food macronutrients (Protein, dietary fibre) and micronutrients (Iron, zinc, calcium, and vitamins A and C) that address health issues [8]-[10]. The availability of nutrients in IVs is influenced by the processing applied to them [11]. These IVs preserve agrobiodiversity by maintaining genetic diversity and supporting pollinators. In Tanzania's local food systems, IVs are collected from private and community land and forests as wild vegetables, but they are also cultivated in home gardens or large farms, intercropped with staples, and sold in informal markets [12] [13]. Globally, IVs underpin traditional agroecosystems but face threats from climate change and from industrial agriculture, which prioritises monocultures of exotic species [14]. Generally, IVs are a critical yet underexplored component of sustainable food systems. These locally adapted crops are rich in essential micronutrients, resilient to climatic stress, and embedded within traditional knowledge systems.

Bioenergy is a type of renewable energy (RE) derived from biological materials (biomass), including crop residues, manure, and non-edible plant parts. According to Asaad *et al.* [6], bioenergy is produced by the oxidation of biomass substrates, which are categorised as first-generation (edible food sources), second-generation (non-edible sources), and third-generation (biomass derived from algae). Bioenergy is a sustainable alternative to fossil fuels when used efficiently. Examples of bioenergy include biogas, bioethanol, and biodiesel. Inefficient utilisation of biomass resources contributes to deforestation and to respiratory diseases caused by the use of firewood in poorly performing cook stoves [15]. In Tanzania, the application of fossil fuels is accompanied by challenges, including pollution, price volatility, and import dependence, that exacerbate energy poverty [16]. The challenges justify seeking and using alternative sources of clean and environmentally friendly energy, including bioenergy.

In addition, a few Tanzanian households use modern energy, especially for cooking [17]. The availability of bioenergy can contribute to increased use of modern energy solutions, such as biogas for clean cook stoves and refrigeration [18]. Moreover, the use of biomass resources to generate bioenergy, for instance, by producing syngas from rice husk, reduces atmospheric carbon dioxide accumulation [19]. Generally, bioenergy—derived from agricultural residues and organic waste—offers a renewable, locally available energy source that can support food processing, preservation, and clean cooking. Yet, policy and research frameworks have largely treated IVs as a nutrition issue and bioenergy as an energy issue, overlooking their interdependence. The interdependence between bioenergy and IVs has the potential to improve the community's food sovereignty.

Food sovereignty is the right to autonomously define agricultural and food policies, as well as production and consumption patterns, in a socially fair and environmentally friendly way, which allows citizens and inhabitants of an area access to sustainable food and promotes the development of the area in which they live without depending on external inputs [20]. Food sovereignty emphasises local control over food production, distribution, and consumption. The food in this context must be nutritious. For Tanzania and beyond, this means prioritising the production, distribution, and consumption of locally grown or wild crops for food, while processing the crop produce using locally generated, sustainable energy. Advantages of this prioritisation include the following: reducing reliance on imported, nutrient-poor foods [20]; empowering smallholders through agroecology and seed sovereignty [21]; and aligning with national and international policies that promote traditional crops and renewable energy [22]. Instances of the alignment of national and international policies and other initiatives, which promotes traditional crops and renewable energy involve: the Energy Policy (2015), Tanzania's National Multisectoral Nutrition Action Plan; Tanzania Clean Cooking Strategy (2023-2033); Africa Agenda 2063, and Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger) and SDG 7 (Affordable and Clean Energy). Ensuring community food sovereignty benefits humanity; therefore, there is a need to support initiatives that advance food sovereignty.

This review advances the argument that nutritious food sovereignty is strongest when IVs and bioenergy are conceptualised as a coupled system. Food sovereignty emphasises the right of communities to define their own food and agricultural systems in culturally appropriate, environmentally sustainable, and socially just ways. Furthermore, nutritious food sovereignty is the right of a community to describe its own food and energy systems, operationalised by the ensured availability of culturally appropriate, micronutrient-dense foods and reliable energy, derived from agroecological systems controlled and managed by local producers. Within this framework, IVs supply the biological foundation of nutrition, while bioenergy provides the enabling energy infrastructure that determines how food is processed, preserved, accessed, and consumed.

Despite growing literature on IVs and bioenergy individually, systematic synthesis of their synergistic pathways remains limited. For instance, existing reviews examine indigenous vegetables primarily through a nutritional or agro-ecological lens, and bioenergy largely through energy access or emissions reduction. This review advances a systems-based perspective that explicitly integrates the two domains. Therefore, this systematic review addresses this gap by asking: How can indigenous vegetables and bioenergy synergise to support nutritious food sovereignty in Tanzania and globally?

A novelty of this systematic review lies in conceptualising indigenous vegetables and bioenergy as mutually reinforcing components of a circular food–energy system that underpins nutritious food sovereignty. By synthesising evidence across nutrition, energy, climate resilience, and policy domains, the review moves beyond sectoral silos and offers a unified analytical framework relevant to sustainability transitions. This integrative contribution responds directly to calls within the energy and sustainability literature for cross-sectoral approaches that link energy systems to food security and social equity outcomes.

2. Methodology

This study employed a systematic literature review in accordance with the SPAR-4-SLR principles [23]. Peer-reviewed articles, theses, and policy reports were sourced from Scopus, PubMed, JSTOR, Google Scholar, and institutional repositories. A total of 123 sources met the inclusion criteria and were synthesised using thematic analysis. Application of SPAR-4-SLR principles ensured transparency, replicability, and analytical rigour. The review integrated peer-reviewed articles, theses, policy documents, and reports from academic databases.

2.1. Inclusion and Scope

The review ensured the relevance and quality of the information sources by applying specific inclusion and exclusion criteria. The information was based on the researcher's studies and grey literature sources.

The inclusion criteria for sources of information were the following:

1) Focused on Tanzania, Sub-Saharan Africa and the global south, where the global north was considered for only comparison or similarity reasons regarding the IVs and bioenergy and nutritional food sovereignty.

2) Addressed indigenous vegetables, bioenergy, nutrition, or food sovereignty

3) Provided empirical or analytical insights relevant to sustainable food-energy systems.

The exclusion criteria ruled out:

1) Studies unrelated to the core themes.

2) Research lacking precise data or findings, such as editorials or opinion pieces.

3) Sources older than 1990, unless foundational to the topic.

Using the above criteria, several documents, including articles, book sections, theses, and reports, were initially selected.

2.2. Search Strategy with Search Means, Database and Search Steps to Apply

The retrieval of research information on indigenous/traditional vegetable-bioenergy synergy to support nutritious food sovereignty in Tanzania and other countries involved a comprehensive search of academic and grey literature. The literature comprises peer-reviewed articles, book sections, theses, and reports published over the past three and a half decades (1990-2025). The items were included to reflect both historical context and recent developments in sustainable food policy, which consider nutritious food sovereignty supported by IVs and bioenergy utilisation. Additionally, only academic and grey literature written in English was considered.

We used databases such as PubMed, Scopus, Journal Storage (JSTOR), and Google Scholar, as well as repositories such as the Sokoine University of Agriculture Institutional Repository (SUAIRE), to locate relevant literature. Additionally, the electronic resources subscribed to by Sokoine University of Agriculture (SUA) were used. Access to these electronic resources was done through the SUA library website (https://www.lib.sua.ac.tz/subscribed-e-resources). Furthermore, we considered reports from governmental, non-governmental, and international organisations. The reports include those from the Tanzania Food and Nutrition Centre (TFNC) (https://www.tfnc.go.tz/), Tanzania National Bureau of Statistics (NBS), Research on Poverty Alleviation (REPOA), Energy and Water Utilities Regulatory Authority (EWURA), Renewable Energy Policy Network for the 21st Century (REN21) (https://www.ren21.net/), Food and Agriculture Organization (FAO), and World Bioenergy Association (WBA).

We retrieved the information using the following search terms, combined with keywords: "indigenous vegetable seed," "traditional vegetable," "bioenergy," "biofuel," "food sovereignty," and "nutrition in Tanzania and other countries". Additionally, the Boolean operators (AND, OR) were employed to refine searches, ensuring that articles addressed the synergetic relationship between IVs and bioenergy toward nutritious food sovereignty in Tanzania and other countries. The following are the combinations of keywords using the Boolean operators: "indigenous OR traditional vegetable seeds AND bioenergy," "synergy of indigenous vegetable AND bioenergy," "traditional vegetable AND bioenergy for nutrition," and "indigenous vegetable seeds AND bioenergy for food sovereignty." All sources of the information, for the review, were subjected to above mentioned search terms from17th December 2024 to 10th March 2025. Articles were selected based on their relevance to the topic, methodological rigour, and contribution to understanding the synergy between IVs and bioenergy for the pursuit of nutritious food sovereignty. The authors of this review article conducted the review based on their expertise in food nutrition and renewable energy. Both authors have been engaged in food security projects. No disagreement occurred during the reviewing sessions.

2.3. Study Screening Steps

Screening the studies in both academia and grey literature was done in two steps: 1) Title and Abstract Screening for eliminating irrelevant articles *i.e.*, the article or report that does not contain any relevant keywords for example vegetable, and bioenergy, food sovereignty, food nutrition; 2) Full-Text Screening for reviewing the remaining articles or reports for relevance and quality where last two paragraph of introduction section, and the sections of methodology, results and discussion, and conclusion and recommendation have to include relevant information related to the indigenous vegetable, bioenergy, nutrition and food sovereignty.

2.4. Selected Study Quality Assessment

Following a quality appraisal using an adapted CASP checklist to ensure the reliability of findings and a full-text review, a few documents initially selected were included in the final analysis, as stipulated by CASP-2018. Studies were assessed based on the clarity of research questions, appropriateness of the study design, robustness of data collection and analysis, and relevance to the Tanzanian and other countries' contexts. During synthesis, we prioritised high-quality studies, especially those with comprehensive analyses or longitudinal data, as these provide a more reliable basis for formulating intervention and policy recommendations.

A descriptive analysis of sources of information was conducted, based on the Year-Wise distribution of the types of literature considered and the frequency of data source applications. Furthermore, a 4th-order polynomial trend curve was generated to show the accumulation of literature within the scope of this study.

2.5. Analytical Framework

Data were extracted and thematically synthesised using analytical frameworks similar to those reported by Pollock *et al.* [24] and Schmidt *et al.* [25]. The framework was applied across three interlinked domains: 1) Nutritional and agro-ecological roles of indigenous vegetables, 2) Productive uses of bioenergy in food systems, and 3) Synergistic IV-bioenergy pathways enabling nutritious food sovereignty. This framework enabled the identification of reinforcing feedback across nutrition, energy, environment, and policy systems [26].

2.6. Limitations

As a review article, this study is limited by its reliance on secondary data, which may not fully capture all local-level distinctions or the most recent on-the-ground developments. Furthermore, the focus on peer-reviewed, high-quality sources may inadvertently exclude informal knowledge or recent innovations that have not yet been documented in the academic literature. However, this review seeks to provide a comprehensive analysis by triangulating sources [27] and combining academic, governmental, and international perspectives.

3. Results

The results include findings from the descriptive analysis of information sources and the thematic synthesis of the extracted data. They are presented in the following subsections.

3.1. Information Sources Descriptive Analysis Results

Using the inclusion and exclusion criteria shown in Sub-section 2.1 of this article, 350 documents, including articles, book sections, theses, and reports, were initially selected. Following a quality appraisal using an adapted CASP checklist to ensure the reliability of findings and a full-text review, 123 documents were included in the final analysis. The descriptive analysis of the information sources used to prepare this article is presented in terms of item distributions by year of publication and item type in **Figure 1** and **Figure 2**, respectively. Also, the frequencies of using the data source during data extraction are presented in **Table 1**.

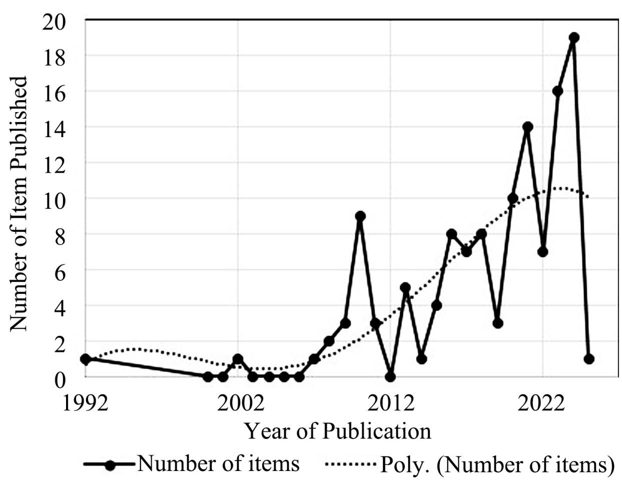

Figure 1. Combined published items distribution from 1992 to 2025.

Table 1. Frequency of data sources used to address the objective of this article.

	Data Source	Frequency
1)	15th International Congress on Agricultural Mechanisation and Energy in Agriculture	
2)	Agrarian South: Journal of Political Economy: A triannual Journal of Agrarian South Network and CARES	
3)	Agroecology and Sustainable Food Systems	
4)	Ambio	
5)	Applied Energy	
6)	Association of Official Seed Analysts	
7)	Bioengineering	
8)	Biomass	
9)	Biomass and Bioenergy	
10)	Biomass, Biofuels, Biochemicals	
11)	Bioresource Technology	
12)	Critical Reviews in Food Science and Nutrition	
13)	Development in Practice	
14)	Development Policy Review	
15)	Diversity and Distributions	
16)	E3S Web of Conferences	
17)	Ecology and Society	
18)	Ecology of Food and Nutrition	
19)	Emerald Open Research	
20)	Energies	
21)	Energy Research & Social Science	
22)	Environment, Development and Sustainability	
23)	Environmental and Resource Economics	
24)	EPJ Web of Conferences	
25)	Food Reviews International	1
26)	Food Science & Nutrition	
27)	Food Security	
28)	Frontiers in Nutrition	
29)	Emerald Publishing Limited	
30)	Genealogy	
31)	Global Change Biology	
32)	Global Environmental Change	
33)	Grasas y Aceites	
34)	International Journal of Development Issues	
35)	International Journal of Green Energy	
36)	International Journal of Health Services	
37)	International Journal of Information Management	
38)	Journal of African Economies	
39)	Journal of Agribusiness in Developing and Emerging Economies	
40)	Journal of Ethnopharmacology	
41)	Journal of Food Science	
42)	Journal of Latin American Geography	
43)	Journal of the Taiwan Institute of Chemical Engineers	
44)	Kybernetes	
45)	Library Review	
46)	Management of Environmental Quality: An International Journal	
47)	Oilseeds and fats, Crops and Lipids (OCL)	
48)	Population and Environment	
49)	Solid-Gaseous Biofuels Production	

Continued

50) Sustainability 51) The European Journal of Development Research 52) The Journal of Development Studies 53) Women's Food Matters 54) World Journal of Engineering 55) Norwegian University of Life Sciences 56) Stockholm Environment Institute 57) Food and Agriculture Organisation (FAO) 58) Journal of Academics Stand against Poverty 59) Proceedings of the 2nd SUA Scientific Conference-2021 60) International Journal of Consumer Studies, 61) Energy and Water Utilities Regulatory Authority EWURA), 62) Research on Poverty Alleviation (REPOA)	
1) African Journal of Food, Agriculture, Nutrition and Development 2) Agronomy 3) British Food Journal 4) Economic Botany 5) Energy & Environment 6) International Journal of Energy Sector Management 7) International Journal of Social Economics 8) Journal of Ethnobiology and Ethnomedicine 9) Nutrition & Food Science 10) Science of The Total Environment 11) Waste Management Bulletin 12) Renewable Energy Policy Network for the 21st Century (REN21) 13) Tanzania Food Nutrition Centre 14) Tanzania National Bureau of Statistics (NBS)	2
1) Renewable and Sustainable Energy Reviews 2) World Bioenergy Association (WBA).	3
1) Environmental Research Letters 2) Heliyon 3) IOP Conference Series: Earth and Environmental Science 4) Outlook on Agriculture	4
1) Sokoine University of Agriculture (SUA)	11

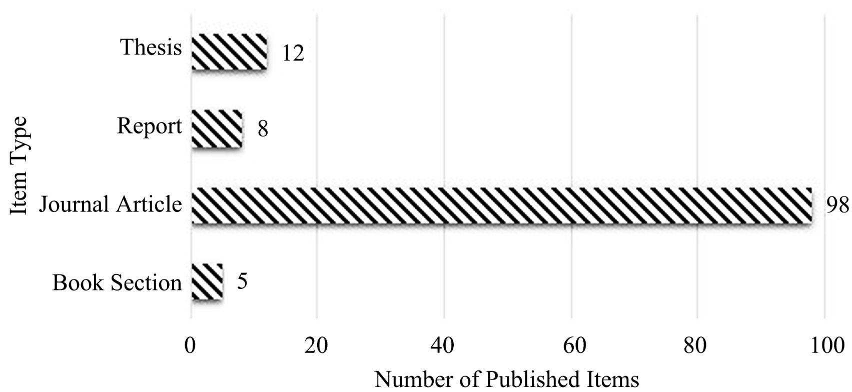

Figure 2. Total number of published items for each type of source.

3.1.1. Year-Wise Distribution of the Type of Literature Considered

The distribution of published items by year of publication is as follows: 2024-2002 for journal articles; 2024-2017 for book sections or book chapters; 2024-2013 for reports; and 2024-2008 for theses. Figure 1 shows the ranges of the combined published item distributions from 1992 to 2025. From Figure 1, a 4th-order polynomial trend curve shows that publications on IVs and biomass energy research increased from 2007 to 2024. The increase might have been caused by greater attention paid to meeting the SDGs through initiatives worldwide.

Figure 2 shows that most of the information used in this article was collected from the journal articles. Most journal articles were based on the original research, as shown in the reference section. Little information was collected from the book sections.

Additionally, the synthesis of the 123 items included in this study is presented in the subsequent subsections. The synthesis focused on addressing the research question of how IVs and bioenergy can synergise to support the attainment of food sovereignty that is nutritious in Tanzania and other countries.

3.1.2. Data Sources Application Frequency

The items, *i.e.*, articles, theses, book sections, and reports synthesised were obtained from different journals and the websites of reputable organisations, including national and international agencies and organisations. Major publishers where most of the data were collected include Springer Nature Switzerland, Elsevier, Emerald Publishing Limited, Wiley, and Springer International Publishing (Table 1). SUA has the highest frequency [17] among all data sources shown in Table 1. SUA focuses on agriculture and allied disciplines; therefore, it is justifiable as a leading source of information on IVs and biomass energy. The diverse information sources ensure the relevance of the findings.

3.2. Thematic Synthesis of Extracted Data

The synthesis revealed and confirmed three converging domains: 1) nutritional and agro-ecological roles of indigenous vegetables, 2) productive uses of bioenergy in food systems, and 3) Synergistic indigenous vegetables-bioenergy pathways enabling nutritious food sovereignty. Additionally, the synthesis provided insight into addressing the research question of 'How can indigenous vegetables and bioenergy synergise to support nutritious food sovereignty in Tanzania and globally?' Furthermore, the research question is addressed through the findings presented in the subsequent subsections and the following sections.

3.2.1. Indigenous Vegetables as Pillars of Nutrition and Resilience

The digestion of the extracted data revealed that the IVs contribute to nutrition security, climate resilience, agricultural sustainability and food sovereignty. The evidence consistently shows that IVs contribute disproportionately to micronutrient intake, dietary diversity, and climate resilience. As detailed in the subsequent sub-section, species such as *Amaranthus spp.*, *Solanum nigrum*, and *Cor-*

chorus olitorius provide iron, zinc, calcium, and vitamins essential for addressing child stunting and hidden hunger. Their adaptability to marginal environments and low input requirements positions them as strategic crops under climate variability. Beyond nutrition, IVs sustain agrobiodiversity, informal seed systems, and women-led knowledge networks—core elements of food sovereignty. However, their full nutritional value is often undermined by inefficient post-harvest processing and preservation methods. The contribution of IVs is explained in detail as follows:

1) Nutrition security

The findings show that IVs have rich nutrient profiles, such as *Solanum nigrum*, *Amaranthus spp.*, and *Corchorus oliforius* found in Tanzania and Ghana, which are high in protein (15.5% - 22.8%), essential amino acids, minerals (calcium, iron, zinc), and α-linolenic acid. These nutrients address deficiencies common in sub-Saharan Africa [28] [29]. Also, condensed tannins in traditionally processed vegetables, such as drumstick and amaranth, exhibit antioxidant and antidiabetic properties, thereby enhancing dietary health [29]. The nutritional values of IVs have led to efforts to promote knowledge sharing about their use. For example, in Tanzania, knowledge-sharing through social networks and school-based programs was argued to improve awareness of IVs and support food security [30]. However, a decline in IV use was reported in South Africa. This underscores the need for campaigns to preserve indigenous knowledge and promote IVs' cooking and preservation techniques [31].

2) Climate resilience

Climate resilience can be seen in the adaptability and biodiversity hotspot management techniques used to address climate change issues. In terms of adaptability, IVs such as Cleome gynandra and Cucumis metuliferus thrive in diverse climates, including during dry seasons, ensuring year-round availability [32] [33]. Additionally, low-water-use crops, including traditional leafy vegetables, are promoted in South Africa to address water scarcity [34]. Furthermore, biodiversity hotspots in Tanzania, such as Arusha and Morogoro, as well as in Ethiopia, host high vegetable diversity, which is critical for adapting to climate change [33].

3) Agricultural sustainability and practices

Agricultural sustainability depends on various factors, including the availability of reliable inputs like seeds. IVs supports biodiversity conservation and sustainable seed systems. Home gardens in Tanzania and Zimbabwe conserve traditional germplasm, with 52% - 81% of households relying on local seed sharing [32] [35]. Additionally, strengthening informal seed systems, compared to formal ones, ensures access to climate-resilient varieties, including those of IVs [36].

The IVs' traditional preservation methods, e.g., sun-drying, reduce post-harvest losses quantitatively but may also increase losses in quality and nutrient bioavailability. Regarding the issue of IV quality loss, Bighaghire *et al.* [37] proposed optimising preservation methods to retain the vital nutrients of processed IVs using an improved traditional method. IVs were reported to reduce dependence on external inputs and align with agro-ecological practices, as the seeds are readily available [38] [39].

4) Preservation of IVs for nutritious food sovereignty

In Tanzania and globally, supporting smallholder farming rather than industrial-scale models preserves IV cultivation and aligns with food sovereignty principles [40]. Some countries have recognised the potential of IVs to support food sovereignty. They have formulated strategies to promote a wide range of valuable IV varieties. For instance, Ecuador amended its constitution to adopt food sovereignty, emphasising local production and traditional foods, including IVs, thereby reducing reliance on imports of agricultural inputs [20]. Also, traditional preservation methods for IVs, such as fermentation, mitigate losses. This has been noted in Haiti, where traditional foods are being promoted through policies aimed at reducing waste and enhancing nutrition [41].

Furthermore, fostering food sovereignty is enhanced through agroecology practices. The practices protect biodiversity and traditional knowledge while ensuring resilient food systems [42]. For instance, indigenous communities in Peru and Brazil maintain food sovereignty through diversified crops like maize and IVs' home gardens, using agro-ecological practices [43] [44]. Women, often custodians of traditional preservation techniques, play critical roles in reducing losses and maintaining dietary diversity [42]. Besides, they dominate seed conservation and decision-making in home gardens, but gender-transformative approaches are needed for equitable benefits [35] [45].

3.2.2. Bioenergy as an Enabler of Nutritious Food Systems

Bioenergy systems—particularly biogas, briquettes, and gasification—enable productive use of energy across the food value chain. Agricultural residues, including IV waste, cassava peels, and cereal husks, represent a substantial untapped energy resource in Tanzania.

The literature demonstrates that decentralised bioenergy does the following: powers drying, milling, refrigeration, and storage; reduces post-harvest losses by up to 20%; replaces biomass combustion in inefficient stoves, lowering indoor air pollution, and produces by-products (e.g., biochar) that enhance soil fertility. Thus, bioenergy directly influences not only energy access but also food quality, safety, and availability.

Tanzania and other tropical countries have abundant biomass for bioenergy generation. There are various biomass sources in Tanzania, including agricultural residues such as maize, sugarcane, and cassava, as well as vegetable wastes. Agricultural wastes (e.g., cassava peels, maize stalks, bagasse) offer untapped biomass energy potential (~135 PJ/year) that could support decentralised energy solutions[40]. Conversion of these residues into bioenergy through processes such as anaerobic digestion, gasification, or briquetting provides a reliable energy source for food drying, milling, preservation, and storage, thereby reducing post-harvest losses, especially in humid areas [46] [47]. Cassava waste yields bioethanol at 85 g/L and biogas at 15 - 23 MJ/kg of volatile solids, providing energy for small-scale vegetable processing [48]. Biogas from livestock manure and vegetable waste supports energy-intensive processes such as drying, oil extraction, and storage, improving the shelf life of IVs [49]. Furthermore, small-scale biogas plants in rural areas, for example, in Kenya and Bangladesh, use vegetable and crop waste to generate electricity for milling and refrigeration, enhancing food security [50].

Moreover, improved cooking technologies like microgasifiers and improved cookstoves (ICS) reduce firewood use. In Tanzania and Asia, technologies that enable waste-to-energy (e.g., rice husk gasification, citrus seed biodiesel) provide clean energy for food preservation while reducing reliance on fossil fuels, thereby enhancing the circular economy [51] [52]. The reduction frees firewood for food processing and lowers indoor pollution. Also, residues from ICS, such as biochar, enhance soil fertility for vegetable cultivation [53] [54]. Furthermore, sorghum biomass in semi-arid regions (e.g., Brazil and Africa) is densified into briquettes with heating values comparable to those of wood, which can be used to dry leafy vegetables [55].

The systems that combine drought-resistant crops such as sorghum with bioenergy production ensure year-round energy for food processing. Surplus biomass from agroforestry can power small-scale combined heat and power (CHP) plants [56].

3.3. Synergy: From Parallel Systems to a Circular Bioeconomy

The finding of this review is that the intersection of IVs and bioenergy creates a circular bioeconomy. In this system, IV residues and other agricultural wastes are converted into bioenergy; bioenergy supports energy-efficient processing that preserves nutrients; reduced losses and improved shelf life enhance food availability; reliance on imported food and fossil fuels declines, and environmental externalities are minimised.

Energy-efficient cooking and preservation technologies emerge as a critical nexus where nutrition and energy outcomes converge. When supported by coherent policies and gender-inclusive governance, these synergies translate into tangible gains in food sovereignty.

Biοenergy enables better utilisation of indigenous crops, including IVs, through energy-efficient cooking and storage technologies, ensuring nutrient retention and reducing waste. The findings regarding the synergy of IVs and the productive use of bioenergy are based on the above-mentioned fact. The subsequent subsections present a synthesis of the extracted data on the synergy between IVs and the productive use of bioenergy for nutritious food sovereignty in Tanzania and other countries.

1) Energy-efficient cooking technologies

The availability of efficient technologies facilitates the use of IVs and bioenergy synergy to process nutritious food. For instance, improved cook stoves and the integration of bioenergy reduce reliance on traditional fuels. The modern cook stoves (e.g., micro-gasifiers, pellet stoves) exemplify the integration advantage. They are powered by bioenergy (biogas, biodiesel, and briquettes) and reduce firewood consumption by 15% - 37%, lowering indoor pollution and preserving heat-sensitive nutrients in IVs [54]; [57]. Pellet cookstoves and other modern biomass systems (e.g., biogas cookstoves) enable faster, cleaner cooking while maintaining micronutrient integrity in IVs [57]. Also, rice husk gasification produces syngas for thermal drying [51], reducing post-harvest losses and preserving nutrient-rich IVs. Bioenergy sources, such as crop residues (e.g., cassava peels) and indigenous fruit/vegetable wastes, when converted efficiently into biogas or biodiesel, provide clean cooking energy without competing with food security [58] [59]. Moreover, biodiesel produced from castor and jatropha meets the required standards, offering RE for food processing without threatening food sovereignty [58]. Integration of bioenergy and solar energy systems is vital for the reliable energy supply needed for food processing. It improves the system's capacity factor. The abundance of biomass (including IV waste) and sunlight, especially in Tanzania, makes the system reliable for dehydrating vegetables and retaining vitamins and antioxidants better than open-air sun drying [60]. Furthermore, Tanzania's NMNAP II and Five-Year Development Plan (FYDP III) advocate RE in agriculture, but implementation requires public-private partnerships [61] [62].

2) Preservation and storage innovations

Decentralised biogas plants coupled with biogas generator power refrigeration units. The units extend shelf life and reduce post-harvest losses of various crops, including IVs. Reducing losses can reduce spoilage by up to 20% [46]. Also, solar drying and biogas-powered refrigeration extend shelf life, reducing post-harvest losses by up to 20%. For example, solar dryers retain nutrients better than traditional sun-drying methods. Drying vegetables using available, low-cost integrated solar technology offers an opportunity to increase the value of the seasonal surplus [63].

3) Circular bioeconomy and waste valorisation

The synergy of IVs and bioenergy powers the circular bioeconomy by utilising agro-residues. Cassava peels, maize stalks, fruit seeds, and IV wastes are converted into bioenergy (e.g., biodiesel, biogas) using various technologies. This creates a closed-loop system for waste-to-energy in food processing [64] [65]. For example, citrus seed biodiesel (with a 93% yield) powers machinery for vegetable milling and packaging [52]. Circular bioeconomy models repurpose non-edible fruit seeds into bioenergy, supporting local economies without displacing food crops. Furthermore, Carbon Credit markets incentivise bioenergy adoption, linking environmental and nutritional goals. This was noted in a study conducted in Bangladesh to assess the viability of utilising agricultural biomass-based energy to meet Bangladesh's energy demands [66]. In the context of climate resilience, RE from biomass reduces greenhouse gas emissions and supports climate-smart agriculture [67]; agroforestry-bioenergy systems (e.g., sorghum and biogas in Brazil) enhance resilience to droughts while supporting food processing [55]. These lead to

SDG alignment, with reduced greenhouse gas emissions (through waste-to-energy) and advances in SDGs 2 and 7 noted [59].

4) Enhancing food sovereignty

Some smallholder farmers in Tanzania adopt agro-ecological practices to grow nutrient-dense IVs (e.g., amaranth, spider plant). The practice can be supported by bioenergy for irrigation and food processing [68]. Agro-ecological practices enhance the use of locally available resources in farming. This phenomenon reduces reliance on imported farming inputs, thereby supporting food sovereignty. Policies in Ecuador and Haiti prioritised traditional crops and decentralised energy systems, thereby reducing reliance on imported foods [20] [41]. Haiti's food sovereignty policy prioritises smallholders and traditional foods, in contrast to Nigeria's fragmented approaches. Effective policies require infrastructure for preservation and bioenergy adoption [69]. Also, Walters [70] emphasises that overreliance on imported seeds threatens food security, but promoting indigenous varieties enhances local adaptability. Furthermore, agro-ecological practices prioritise the cultivation of IVs, aligning with food sovereignty principles [42].

5) Nutrient retention, health and dietary diversity

Energy-efficient cooking (e.g., cooking with gasifiers) preserves iron, vitamin A, and folate in leafy greens, *i.e.*, in indigenous vegetable dishes. Consuming these dishes with the mentioned nutrients helped address Tanzania's 35% child stunting rate [71]. In Kenya, the coupled interventions of production and nutrition education increased Women's Dietary Diversity Scores (WDDS) by 21% while enhancing access to nutrient-dense IVs [71]. Chicory (*Cichorium intybus*) and Sintrong (*Crassocephalum repidiodes*) are IVs found in India, Indonesia, Italy and Bulgaria. Research on these IVs has demonstrated the global potential for their use in managing diabetes and malnutrition [72] [73].

3.4. Challenges Facing Synergetic IVs and Productive Use of Bioenergy

The challenges constraining the synergetic IVs and productive use of bioenergy include the limited information on the bioavailability of IV nutrients and anti-nutrient effects that require further study [28]; inadequate storage, transportation, processing, and preservation facilities that hinder biomass utilisation [63], and minimal investments in integrated solar drying and biogas plants, which are needed in rural Tanzania [63]. Furthermore, the use of modern cooking solutions in Tanzanian households remains limited; investments in pellet stoves, biogas systems, and other clean cooking technologies are critical [61].

4. Discussion

Reviewers' concerns often focus on novelty, policy relevance, and scalability. This review addresses novelty by explicitly conceptualising IVs and bioenergy as an integrated system. Policy relevance is demonstrated through alignment with national strategies and SDGs, while scalability is discussed via decentralised, community-based bioenergy models adaptable across the Global South.

The findings reposition IVs and bioenergy from sectoral interventions to mutually reinforcing components of sustainable food-energy systems. This integration challenges conventional development pathways that prioritise industrial agriculture and centralised energy infrastructure. Importantly, the review highlights that technological potential alone is insufficient. Realising IV–bioenergy synergies depends on: inclusive seed and energy governance; investments in decentralised infrastructure; recognition of women's roles in food-energy systems, and alignment of nutrition, energy, and agricultural policies. Countries that have embedded food sovereignty principles into their policy frameworks demonstrate greater coherence among local production, clean energy, and nutrition outcomes.

The main objective of this article was to synthesise the literature on how IVs and bioenergy can synergise to support nutritious food sovereignty in Tanzania and other countries globally. The focus was on countries with IVs and bioenergy-related resources.

4.1. Indigenous Nutritional Vegetables and Agricultural Values

Nutritional values of post-harvest produce are assessed quantitatively and qualitatively, with macro- and micronutrients expressed in standard units or percentages [28] [74]. The agricultural value of the produce can be expressed in several ways, including identifying opportunities across all components of its value chain.

With this note, the IVs Nutritional and Agricultural Values were evident in terms of nutrition security, climate resilience, agricultural sustainability and food sovereignty. IVs provide essential nutrients to improve dietary health, leading to their promotion; however, awareness of their benefits and their decline in use are reported. The significance of the IVs and their promotion has also been reported by Mbhatsani *et al.* [75]. Besides, various varieties of IVs in Tanzania and other countries thrive in diverse climates, ensuring their availability throughout the year and their critical adaptation to climate change. The resilience of the IVs to climate is valuable, as was argued by Chepkoech *et al.* [5].

Furthermore, IVs' sustainability is guaranteed, provided they are not affected by invasive species, as their seeds are locally available and sometimes shared at minimal cost. However, Mativavarira *et al.* [76] call for strengthening informal seed systems to address IVs' seed availability. Most traditional preservation practices for IVs lead to a loss of product quality; however, improved practices can be developed. IVs must be valued in terms of quantity and quality [77].

Nutritious food sovereignty is supported, among others, through the sensitisation of IVs farming. Some countries have formulated policies and even amended their constitutions to incorporate food sovereignty grounded in local production and traditional foods, including IVs. These initiatives have led to the development of several projects and programmes aimed at boosting the countries' locally based nutritious food sovereignty [78]-[80]. Agro-ecological practices and women's involvement in promoting the IVs are vital for supporting food sovereignty. These matters are insisted on by [81] and Ekomer *et al.* [82].

4.2. Productive Use of Bioenergy and Associated Technologies

Resources in Tanzania are abundant for producing bioenergy equivalent to 135 PJ/year. The trend is similar to that of other tropical countries. The primary sources of bioenergy are agricultural waste, including vegetable waste. Proven conversion processes for biomass into bioenergy (e.g., briquettes, biogas, bioethanol) for productive use, along with their associated technologies, are available. The productive use of bioenergy includes powering systems for post-harvest processing, preservation, and storage, leading to reduced quantity and quality losses and to improved shelf life of produce (e.g., IVs and food).

Examples of productive uses of bioenergy from agricultural waste include generating electricity for refrigeration via systems such as biogas-fueled generators [50]. Also, clean cooking through improved cooking technologies that use bioenergy lowers indoor pollution, reduces fossil fuel dependence, and by-products (e.g., biochar) from improved cook stoves enhance soil structure for vegetable cultivation. Furthermore, biomass resources power small-scale CHP plants. The availability of biomass resources, the conversion technology, and the productive use of bioenergy described in this subsection are similar to those reported by Babu *et al.* [7], Sikiru *et al.* [83], and Tshikovhi and Motaung [84].

4.3. Synergetic Indigenous Vegetables and Bioenergy with Related Challenges

The synergy of efficiently applying improved cooking technologies, including clean energy such as bioenergy, to prepare food involving IVs offers the following: retention of heat-sensitive nutrients in the IVs dish and reduced reliance on environmentally polluting firewood. Also, the synergy enhances reduced post-harvest losses of nutrient-rich IVs and other produce through processing, provides clean energy from agricultural wastes without threatening food sovereignty, and offers the option of integrating bioenergy and other RE systems to improve the capacity factor for processing post-harvest produce and food.

Moreover, synergy between IVs and bioenergy facilitates innovations in post-harvest preservation and storage, the circular bioeconomy, and waste valorisation, thereby enhancing food sovereignty, health, and dietary diversity. The facilitated initiatives support the nutritious food sovereignty in Tanzania and other countries. The synergy advances the nations and international agenda, including Tanzania's NMNAP II and FYDP III, as well as SDG 2 and SDG 7. The synergy of indigenous vegetables and bioenergy is demonstrated in the conceptual framework (**Figure 3**). Indigenous vegetables supply nutrient-dense food and biomass residues. These residues are converted into bioenergy, which powers energy-efficient cooking, processing, and storage. The feedback loop reduces losses, enhances nutrition, and supports a circular bioeconomy, reinforcing food sovereignty outcomes.

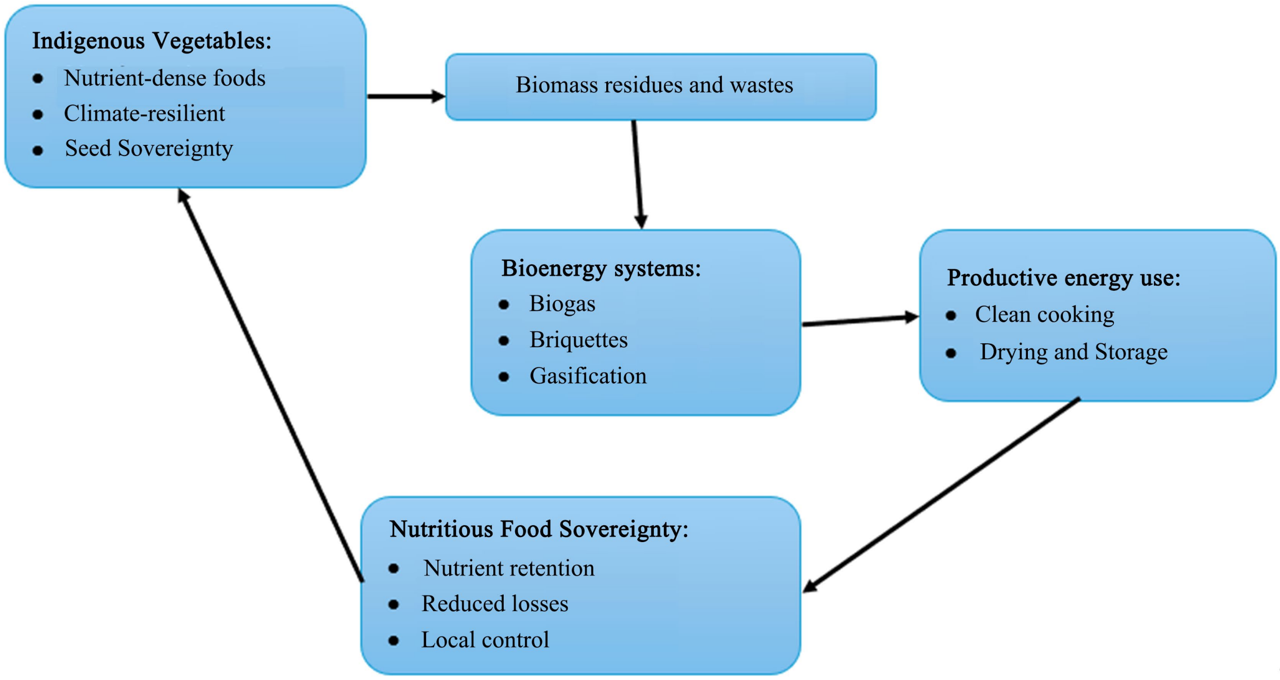

Figure 3. Conceptual framework illustrating the synergy between indigenous vegetables and bioenergy.

The challenges hindering the full potential of the synergy include limited information on the bioavailability of IV nutrients and anti-nutrient effects, scarce and affordable digesters and other infrastructure, and minimal investment in biomass utilisation and the integration of RE systems. Also, the adoption of modern clean-cooking solutions is low in Tanzania. The information presented on challenges is similar to that reported by Byaruhanga and Isgren [85], Diamantis *et al.* [86], Freitas *et al.* [87], Huang [88] and Rajendran *et al.* [89]. One option to address the challenges mentioned is to increase awareness of the merits of synergy among stakeholders, governments, and financial institutions to support concession loans and subsidies in communities below the poverty line.

5. Conclusions

Integrating indigenous vegetables with bioenergy systems enhances nutrient retention, reduces waste, and strengthens food sovereignty. This coupled approach reframes food and energy as interdependent systems essential for sustainable development. This systematic review demonstrates that nutritious food sovereignty is most effectively advanced through integrated indigenous vegetable–bioenergy systems. Indigenous vegetables provide the nutritional and ecological foundation of resilient food systems, while bioenergy supplies the enabling infrastructure to sustainably preserve, process, and valorise these foods.

For Tanzania and similar contexts, prioritising IV-bioenergy synergies offers a scalable pathway toward climate resilience, reduced malnutrition, and energy justice, while aligning with SDGs 2 and 7. The scientific contribution of this review lies in reframing food and energy not as parallel sectors, but as interdependent systems whose integration is essential for sustainable development.

6. Implications and Future Research

Policy: Integrated food-energy policies are required, with explicit support for decentralised bioenergy in agri-food systems.

Practice: Investments in clean cooking, solar-bioenergy hybrids, and community-scale processing are critical.

Research: Future studies should develop socio-technical frameworks linking IV seed systems, bioenergy value chains, gender equity, and climate resilience.

Credit Authorship Contribution Statement

Yusto Mugisha Yustas: Conceptualisation, Methodology, Formal analysis, Writing-Original draft preparation, Writing-Reviewing and Editing.

Hadijah Ally Mbwana: Conceptualisation, Methodology, Writing- Reviewing and Editing, and Supervision

Conflicts of Interest

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

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