



Economic Potential of Producing Bioethanol From Sweet Potatoes for Tropical Regions

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Abstract

This review presents a comprehensive techno-economic evaluation of producing bioethanol from sweet potatoes (*Ipomoea batatas* (L.) Lam.) in tropical regions, highlighting its agronomic, economic, environmental, and policy implications, and introducing a novel dual-role perspective that examines sweet potato simultaneously as a food and fuel crop. Sweet potato, a high-starch, drought-tolerant crop, demonstrates remarkable adaptability to low-input farming and marginal lands, traits which render it a compelling bioethanol feedstock for tropical countries grappling with food-energy nexus challenges. Drawing on a systematic qualitative literature review, the study quantifies potential ethanol yields of 4,500–10,000 L/ha/year under dual-cropping systems, benchmarked against maize, cassava, and sugarcane. A techno-economic model estimates capital expenditures, operating costs, and revenue streams, incorporating co-products like animal feed and CO₂. Financial indicators, including Levelized Cost of Ethanol (\$0.50–\$0.75/L), IRR (12–25%), and payback periods (3–6 years), are analysed under yield, cost, and market volatility scenarios. The study further examines GHG reduction potential (40–60% vs. gasoline), efficient land/water use, and strategies to mitigate food-vs-fuel trade-offs through marginal land use and dual-purpose cropping. Social dimensions such as rural employment and gender inclusivity are explored, especially given women's predominant role in sweet potato cultivation. Policy and market drivers, biofuel mandates, PPPs, and regional trade are evaluated for their enabling roles. The findings advocate for the integration of sweet potato into national bioenergy portfolios as a viable pathway toward SDG-aligned climate mitigation, rural development, and energy security in tropical economies. This research closes a critical knowledge gap and positions sweet potato as a sustainable, underutilised asset in the future of biofuels.

Keywords Sweet potato bioethanol · Techno-economic analysis · Tropical energy crops · Sustainable biofuels · Rural development

Introduction

The conversion of starchy crops to bioethanol is a well-established pathway for advancing renewable liquid fuels in tropical countries. Among candidate feedstocks, sweet potato (*Ipomoea batatas* (L.) Lam.) stands out for

its notable agronomic advantages in warm climates, high starch content, short growing cycles, drought tolerance, and low input requirements, all of which make it particularly suited to biodiesel-producing contexts where conventional feedstocks such as maize or sugarcane may be less viable [1]. In many tropical and subtropical regions, such as parts of Africa, Southeast Asia, and Latin America, sweet potato is already among the most widely cultivated staple root crops, with global production reaching approximately 131 million tonnes per year, with an estimated 98% cultivated in developing countries, underlining its prominence outside the temperate zone [2]. Although China alone contributes around 80% of global output, sweet potato remains widely grown in many smallholder systems across tropical regions, contributing to food security and caloric intake in small-scale farming communities [3, 4].

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Land area harvested in developing countries totalled about 9.1 million hectares, with Asia accounting for roughly 82%, Sub-Saharan Africa about 15%, and Latin America and the Caribbean the remaining 3% [5, 6]. Sweet potato is overwhelmingly produced by China, accounting for roughly 76–80% of global output, but the crop remains a key staple across tropical smallholder systems in sub-Saharan Africa, Southeast Asia, and Latin America. Its persistence outside China highlights its adaptability to warm climates and low-input conditions [7, 8]. This distribution highlights the crop's adaptation to warm climates and its agroecological suitability under low-input conditions.

A growing body of international literature confirms that sweet potato can yield 1,250 to over 8,800 L of ethanol per hectare per year, outperforming field corn and rivaling sugarcane under favourable conditions [1]. Industrially bred cultivars with high dry-matter content have been shown to achieve ethanol yields of 4,500–6,500 L/ha, compared to 2,800–3,800 L/ha from maize, when converted via optimised enzymatic saccharification and fermentation [9]. Recent research conducted in Brazil using high-starch varieties (e.g., BRS Cuia) reported yields of approximately 10,000 L/ha with two cropping cycles per year, using selected yeast strains and high cell inoculum strategies [10].

Despite these promising productivity figures, few comprehensive techno-economic evaluations exist that examine the viability of sweet potato bioethanol under realistic conditions in tropical countries. Many studies focus on laboratory yields or agronomic performance without integrating the detailed cost structure, supply chains, infrastructure requirements, and market frameworks required for implementation at scale. For example, while sugarcane and cassava are well studied in Nigeria, Ghana, and Southeast Asia, sweet potato remains underrepresented in policy and economic literature, despite its potential to alleviate fuel import dependence and foster rural economic development [11–13].

Concurrently, sustainable development goals (SDGs) emphasise the dual benefits of renewable energy and rural poverty alleviation. Sweet potato cultivation and processing could offer such co-benefits, yet also face trade-offs, such as competition with food uses and water or land resource constraints in areas of smallholder agriculture [14]. Furthermore, geographic and varietal diversity in tropical zones (e.g., seasonal rainfall variability, soil types, post-harvest losses) influences feasibility; hence, techno-economic analysis must be context-sensitive. Given these gaps, there is a clear need for a structured economic assessment that integrates agronomic productivity, capital and operating costs, co-product revenues, environmental impact, and policy levers, supported by recent field-level or pilot data in the tropics.

The dual use of sweet potato (SP) as both a food crop and an energy feedstock offers interesting trade-offs that merit

quantitative examination. On the one hand, its deployment as a food contributes directly to human nutrition and food security; on the other, its utilisation as a biofuel feedstock (for ethanol, biogas, biodiesel integration) presents an alternative value-chain that may compete with its role as food or complement it in a circular-economy scenario. Here we compare key quantitative metrics and discuss real-life implications.

From a nutritional perspective, sweet potato roots are rich in carbohydrates, dietary fibre, and micronutrients. In a comprehensive metabolomic analysis of three flesh-colour types, SP roots contained starch in the range ~22.6–69.7 g per 100 g dry weight (DW), total soluble sugars 10.3–40.0 g/100 g DW, and total dietary fibre 7.99–26.0 g/100 g DW [15]. Another recent analysis of Southern African purple-fleshed genotypes reported significant phytonutrient density, underlining the value of SP for human nutrition and income generation [16]. For example, supplementation of orange-fleshed SP is used in some developing-country household programmes to provide provitamin A [17]. Moreover, SP leaves are also valuable: protein content of 16.7–31.1 g/100 g DW was observed across 40 cultivars [18].

In practical terms, if one considers the food role: for a consumption basis, an SP tuber delivering say ~75% moisture, maybe 25% dry matter; within that, suppose ~20% starch and ~4% fibre. For a 100 g fresh weight tuber (~25 g dry matter), this corresponds to ~5 g starch and ~1 g fibre, plus associated micronutrients. The calorific content, mostly from starch and sugars, would be on the order of 80–90 kcal per 100 g fresh, depending on variety and cooking method. (Direct data vary widely by cultivar and processing). Importantly, as a staple, SP provides calories as well as micronutrient value in contexts of food insecurity.

On the bioenergy side, several studies quantify the yield potentials of SP when used as a feedstock for bioethanol or integrated biofuel production. For example, one study reported that dried SP and fresh SP could achieve ~38–45 g/L ethanol concentration under very high gravity (VHG) conditions, with nearly 100% sugar conversion under favourable conditions [19]. A more recent comparative study (2024) found that sweet potato flour produced ethanol up to 5.273% (v/v) after 48 h of fermentation, albeit less than sugarcane juice in that context [20].

In terms of area yields, one integrated study reported an ethanol yield of about 161.4 L per tonne of SP (wet basis) equivalent, corresponding to ~10 598 L/ha in the particular conditions studied [21]. Another study from Brazil using SP variety 'Cuia' achieved a yield of 25.74 g L⁻¹ ethanol per 100 g SP feedstock (i.e., 257.4 L per tonne) when using specific yeast strains [22]. These figures illustrate the potential: if one hectare produces e.g. 10 000 L of ethanol, and if that ethanol is used to displace fossil fuel equivalents, then

for a standard energy content of ethanol ($\sim 21 \text{ MJ L}^{-1}$), one could derive $\sim 210 \text{ GJ}$ per hectare of primary energy. If that hectare of SP would otherwise serve as food production, the trade-off becomes quite apparent.

From a quantitative perspective, several comparative dimensions can be identified. Reported ethanol yields from sweet potato cultivation can reach approximately $10,600 \text{ L ha}^{-1}$ under favourable agronomic and processing conditions. By contrast, when sweet potato is allocated to food production, a typical fresh tuber yield of around 20 t ha^{-1} , depending on cultivar, climate, and management practices, with an assumed dry matter content of 15–20%, corresponds to roughly $3\text{--}4 \text{ t ha}^{-1}$ of dry biomass. This biomass represents a direct source of calories and nutrients for human consumption, highlighting that the allocation of land to biofuel production versus food use entails a fundamental reassignment of land value.

The conversion of sweet potato starch and sugars into ethanol prioritises energy output, whereas food use preserves nutritional value, including carbohydrates, dietary fibre, and micronutrients. For example, if 1 t of sweet potato feedstock yields approximately 160 L of ethanol, equivalent to about 3.36 GJ , then a feedstock input of 10 t ha^{-1} would deliver roughly 33.6 GJ ha^{-1} of fuel energy. In comparison, 1 t of fresh tuber, corresponding to approximately 0.25 t of dry matter, may provide $1,000\text{--}1,500 \text{ kcal kg}^{-1}$ of dry matter, or about $250\text{--}400 \text{ kcal kg}^{-1}$ on a fresh weight basis. This translates to approximately $250,000\text{--}400,000 \text{ kcal}$ per tonne of fresh tubers, equivalent to about $1.0\text{--}1.6 \text{ GJ}$ of food energy. Although the apparent energy yield per hectare is lower when expressed in biofuel-equivalent terms, food use delivers human nutrition rather than transport fuel.

In regions where food security remains a dominant concern, particularly in parts of Africa and Asia, diverting sweet potato from food to fuel may impose significant nutritional and social opportunity costs. This concern is reinforced by the documented metabolomic richness of diverse sweet potato cultivars, including the presence of multiple essential amino acids and a wide range of organic acids, which underscores the crop's dietary value and role in nutritional resilience [23].

From a value chain and economic perspective, integrated processing studies combining bioethanol and biodiesel production from sweet potato have shown that higher ethanol purity can enhance downstream biodiesel yield and product quality, with reported biodiesel yields ranging from 63 to 83 wt% and purity levels between 50 and 94 wt% [21]. In food markets, however, economic value is increasingly associated with cultivar differentiation, particularly micro-nutrient-rich varieties such as orange-fleshed sweet potato, which command premium prices in health-oriented and value-added markets.

Finally, sustainability considerations suggest that sweet potato offers agronomic advantages, including tolerance to marginal soils, a relatively short growth cycle, and the potential for multiple harvests per year. These characteristics support its suitability for intensified land use and, under appropriate governance and land-use planning, may allow bioenergy production without directly displacing staple cereal crops [24]. In the African context, sweet potato varieties adapted for drought or low-fertility soils (such as those used in nutrition programmes) may yield at lower than optimal levels compared with industrial biofuel-crop conditions. Suppose a local SP yield is $15 \text{ t fresh ha}^{-1}$; if 60% of that dry matter is starch convertible to ethanol with an overall conversion efficiency of 300 L t^{-1} fresh (roughly midpoint of cited values), then ethanol yield would be $\sim 4\,500 \text{ L/ha}$. That means $\sim 4.5 \text{ GJ/ha}$ energy, which is modest compared to some dedicated energy crops (but still meaningful). If instead used as food for human consumption, $15 \text{ t} \times \sim 0.25 \text{ t dry/t fresh} = \sim 3.75 \text{ t dry matter}$; at $\sim 1.0\text{--}1.3 \text{ GJ per tonne dry}$, that is $\sim 3.75\text{--}4.9 \text{ GJ}$ of food-energy. While numerically comparable, the difference is that one is food and one is fuel. Decisions on land allocation need to consider food security, nutritional outcomes, and energy policy. Moreover, if biofuel production uses by-products (leaf, residual biomass) without fully displacing food supply, then a circular strategy may be feasible.

In summary, from a quantitative viewpoint, sweet potato holds potential as both a food and an energy crop; each use either delivers human nutrition or bioenergy. The opportunity cost of diverting SP from food to biofuel varies depending on yield, conversion efficiency, cultivar, and socio-economic context. For countries like South Africa or Malawi, where food security coexists with renewable-energy ambitions, a hybrid strategy may be advisable: prioritise orange- or purple-fleshed cultivars for high nutritional value in food markets, while allocating marginal lands or residual biomass to biofuel feedstock. Research should further quantify local yield responses, conversion efficiencies under local conditions, and socio-economic trade-offs (land-use, food vs. fuel, nutritional impact).

The primary focus of this review is to evaluate the bioethanol production potential of sweet potato (*Ipomoea batatas*) within the broader context of food security and rural income generation in tropical regions. The research does not isolate these dimensions as independent themes but rather treats them as interdependent outcomes of a unified agricultural–energy system. Specifically, the review aims to (i) quantify the technical and economic feasibility of sweet potato as a feedstock for bioethanol under tropical production conditions; (ii) compare its performance with other major starch-based feedstocks such as cassava, maize, and

sugarcane; and (iii) interpret the results in terms of potential implications for food availability, smallholder income, and sustainable rural development.

While the analysis centres on the techno-economic viability of bioethanol, it simultaneously recognises that *I. batatas* serves as a strategic crop that can balance energy production with nutritional and livelihood benefits. Hence, rather than promoting a strict “food versus fuel” dichotomy, the review investigates pathways through which sweet potato can contribute to both national renewable energy targets and community-level food resilience. This framing positions the research within a multidisciplinary scope, linking bioenergy economics with agricultural sustainability and social development, while keeping bioethanol production as its central quantitative and analytical focus.

This paper also aims to evaluate the economic potential of producing bioethanol from sweet potatoes in a tropical country by combining agronomic yield data, process simulation models, market price analysis, and policy context. Specifically, it will quantify expected ethanol yield per hectare, based on sweet potato varieties adapted to tropical climates and dual cropping cycles; estimate capital and operating costs for ethanol production, including land, inputs, processing facilities, enzymes, labour and logistics; analyse revenue streams, including bioethanol sales, possible co-products (e.g., animal feed or residual pulp), and avoided imports; conduct sensitivity and scenario analysis, exploring how variations in yield, feedstock price, enzyme cost, and market price affect profitability; and explore policy and sustainability trade-offs, such as land allocation between food and fuel, greenhouse-gas (GHG) mitigation potential, and rural development outcomes.

Based on the above objectives, the following research questions (RQs) will guide the review:

What is the realistic ethanol yield (L/ha/year) from sweet potato cultivars under tropical conditions, accounting for two cropping cycles and high starch varieties?

What are the detailed cost components (capital, operating, logistics) and revenue projections for a sweet potato-to-ethanol biorefinery at pilot or small commercial scale?

How sensitive are profitability metrics, such as internal rate of return (IRR), levelized cost of ethanol (LCOE), and payback period, to key variables such as yield variability, feedstock price, enzyme cost, and ethanol market price?

What are the socio-economic and environmental implications, particularly in terms of food vs. fuel trade-offs, rural income generation, and potential GHG emissions reductions associated with scaling sweet potato ethanol in tropical contexts?

By integrating agro-technical data with economic modelling and policy analysis, this review addresses a critical research gap in the biofuels literature. It offers a contextualised techno-economic evaluation rarely applied to sweet potato in tropical regions and thus contributes to more diversified renewable energy feedstock portfolios. The findings can inform national biofuel strategies, especially in countries where sweet potato is already cultivated or could be scaled up without displacing staple food production. Moreover, the analysis supports SDG-aligned policy dialogues on clean energy, sustainable agriculture, and rural development.

The novelty of this review lies in its integrated assessment of *Ipomoea batatas* as both a food and fuel crop, situating sweet potato within the dual frameworks of nutritional security and renewable energy generation. Unlike previous techno-economic studies that treat starch crops purely as biofuel feedstocks, this work explicitly quantifies sweet potato's ethanol yield potential while recognising its vital role in rural diets and food systems. By linking varietal specificity, particularly high-starch cultivars such as *BRS Cuia*, *KSP36*, and *W-42*, to both agronomic and economic outcomes, the paper advances a nuanced understanding of how cultivar selection can optimise energy output without compromising food availability. This dual-lens analysis of sweet potato's biophysical performance and socio-economic utility constitutes a novel contribution to the bioenergy and agricultural sustainability literature, providing a replicable model for evaluating other multipurpose crops in tropical contexts.

Methodology

This review employs a qualitative, literature-driven techno-economic assessment, reinforced by comparative analysis and structured interpretation of published data, to evaluate the potential of producing bioethanol from *Ipomoea batatas* in tropical contexts. Such mixed-method frameworks are widely adopted in emerging bioenergy research to integrate agronomic, economic, and policy dimensions under region-specific conditions [25, 26]. The assessment focuses on tropical regions dominated by smallholder agriculture, limited infrastructure, and climatic variability [27, 28], following a five-stage analytical structure adapted from established frameworks [29, 30].

Research Framework

A systematic literature review was conducted covering peer-reviewed journal articles and institutional reports to extract both quantitative and qualitative data on sweet potato yields, starch conversion efficiencies, cost structures, and value-chain characteristics. This review established the

empirical foundation for subsequent techno-economic modelling and comparative analysis.

Sweet potato was then benchmarked against alternative bioethanol feedstocks, including *Zea mays*, *Manihot esculenta*, and *Saccharum officinarum*, using key performance metrics such as crop yield (t ha^{-1}), ethanol productivity (L ha^{-1}), water and nutrient inputs, and land suitability within tropical agroecological zones. This comparative evaluation situates sweet potato within the broader bioethanol landscape and enables assessment of its relative competitiveness under comparable production conditions.

A spreadsheet-based techno-economic model, implemented using Microsoft Excel and complemented where appropriate by Python-based calculations, was developed to estimate key financial indicators, including the Levelized Cost of Ethanol (LCOE), Internal Rate of Return (IRR), Payback Period (PP), and breakeven thresholds. Model parameters were derived from the literature, with a base-case scenario assuming an ethanol yield of $5,000 \text{ L ha}^{-1}$, a feedstock price of $\text{USD } 50 \text{ t}^{-1}$, and a market price of $\text{USD } 0.65 \text{ L}^{-1}$. Alternative scenarios were evaluated across enzymatic, conventional, and hybrid processing routes to capture process-specific cost and performance variability [20, 31–34].

To account for uncertainty and parameter variability under realistic tropical conditions, sensitivity and scenario analyses were performed by systematically varying key inputs, including ethanol yield ($3,000\text{--}9,000 \text{ L ha}^{-1}$), feedstock price ($\text{USD } 30\text{--}80 \text{ t}^{-1}$), enzyme cost ($\text{USD } 0.04\text{--}0.10 \text{ L}^{-1}$), and ethanol market price ($\text{USD } 0.50\text{--}0.90 \text{ L}^{-1}$). These analyses were used to identify financial viability thresholds and assess risk exposure across a range of plausible operating conditions [20, 34, 35].

In addition to the quantitative assessment, a qualitative policy and sustainability appraisal was undertaken, examining national biofuel strategies, agricultural policies, and sustainability frameworks in countries such as Brazil, Thailand, South Africa, Nigeria, and the Philippines. Policy instruments, including blending mandates, land-tenure provisions, and rural development incentives, were analysed to contextualise the techno-economic findings within broader sustainable development objectives, particularly those aligned with SDGs 2, 7, 8, and 13. Qualitative literature survey.

The literature review incorporated journal papers, FAO, IEA, IFAD, and CSIR publications, as well as technical and case study reports. Data extraction focused on five domains:

1. Agronomic parameters (yield, dry-matter and starch content, irrigation demand);
2. Conversion efficiency (enzymatic saccharification and fermentation rates);
3. Cost structure (CAPEX, OPEX, logistics, labour, and utilities);

4. Revenue streams (ethanol market prices, co-products, and carbon credits); and.
5. Country-specific enablers (land availability, smallholder participation, infrastructure, and regulatory frameworks).

Data were collated from Scopus, Web of Science, PubMed, Google Scholar, and agricultural databases (FAOSTAT, IRRI, CGIAR), focusing on literature from 2010 to 2024 in tropical regions (Africa, Southeast Asia, Latin America). Results were synthesised into an evidence matrix for cross-comparison by geography, technology, and scale.

Comparative Feedstock Context

For analytical benchmarking, sweet potato was compared with maize, cassava, and sugarcane, considering ethanol yield, input intensity, land use, and food-fuel trade-offs. This contextualisation clarifies sweet potato's agro-economic viability relative to prevailing feedstocks under tropical farming systems.

Model outputs included cost indicators (LCOE USD/L), IRR, PP, and break-even yield/price scenarios. The simulations also tested hybrid enzymatic and conventional process variants to capture technology-related uncertainty [20, 31–34].

Sensitivity testing revealed the influence of yield variability, enzyme pricing, capital costs, and ethanol price volatility on profitability. Thresholds below $4,000 \text{ L/ha}$ or market prices under $\$0.55/\text{L}$ were found to compromise IRR under most conditions, emphasizing the importance of co-product valorisation and policy incentives [20, 34, 35].

The techno-economic findings were interpreted against the policy environment of tropical nations. Attention was given to blending mandates (e.g., E10–E27), fiscal incentives, and social dimensions such as rural employment and gender inclusion. This ensures the economic model aligns with national energy transition and rural development goals.

This review is based on secondary data and assumes representative averages for yields, input costs, and market prices. Local micro-variations and pilot-scale operational complexities are beyond its scope. Nevertheless, triangulation across diverse data sources and robust sensitivity analysis enhance the credibility of conclusions.

Bioethanol Landscape in Tropical Countries

Current Bioethanol Feedstocks: Sugarcane, Cassava, Maize

In tropical nations, the bioethanol sector is primarily dominated by three staple feedstocks: sugarcane, cassava, and maize. Each of these crops presents distinct advantages and

limitations concerning agronomic adaptability, conversion efficiency, environmental sustainability, and socio-economic trade-offs.

Sugarcane is historically the leading bioethanol crop in countries such as Brazil and India, owing to its high biomass yield and superior sugar content. It offers one of the lowest production costs per litre of ethanol (\$0.20–\$0.30 in optimal systems) and exhibits a favourable energy balance [36]. However, sugarcane's reliance on intensive irrigation (up to 2,000 mm per cropping cycle) and agrochemical inputs has raised concerns regarding groundwater depletion, eutrophication, and soil degradation [37]. Moreover, its large-scale monoculture model often marginalises smallholders [37, 38].

Cassava, widely grown across Southeast Asia and Sub-Saharan Africa, offers moderate ethanol yields (1,800–3,000 L/ha) and high starch content [39]. While more drought-tolerant than sugarcane, cassava's ethanol conversion requires substantial enzymatic hydrolysis and generates waste by-products needing careful disposal [40]. Environmental concerns revolve around its susceptibility to pests, periodic food insecurity due to crop diversion, and yield vulnerability to rainfall variability [41, 42].

Maize, though widely utilised in North America and parts of Asia, is less ideal in tropical regions. It provides lower ethanol yield per hectare (2,500–3,800 L/ha) and competes directly with staple food demand, particularly in import-reliant tropical countries [28, 43]. Its input-heavy cultivation further exacerbates land and water pressures. Moreira, M. M. et al. [44] illustrate the intricate relationships among bioenergy, food production, food security, environmental considerations, and economic development. They highlight how these factors can be effectively managed to achieve favourable results in maize cultivation by leveraging existing technologies.

In contrast, sweet potato, as highlighted in the manuscript, offers a compelling case for tropical deployment. It demonstrates superior adaptability to marginal lands, low input requirements, and shorter growing cycles. Ethanol yields from high-starch varieties can reach 6,500–10,000 L/ha under dual cropping systems, outperforming both maize and cassava, and approaching the range of sugarcane under optimal management [9, 10, 28]. Despite these advantages, sweet potato remains underutilised in national biofuel strategies due to underinvestment in processing infrastructure and a lack of inclusion in energy policy dialogues.

Role of Bioethanol in the National Energy Mix

In several tropical countries, bioethanol has emerged as a strategic component of the energy transition, offering a

pathway to reduce fossil fuel dependency, improve rural economies, and mitigate GHG emissions.

Brazil represents the most advanced example of a successful bioethanol economy. Ethanol from sugarcane constitutes nearly 50% of transport fuel use, facilitated by a mature blend mandate (E27), flexible-fuel vehicles (FFVs), and a robust agribusiness infrastructure [45, 46]. Brazil's Proálcool program, initiated in the 1970s, catalysed technological and institutional support for bioethanol expansion, including subsidies, tax incentives, and public-private research consortia [47].

Thailand has pursued an ambitious ethanol expansion strategy under its Alternative Energy Development Plan (AEDP). Cassava and sugarcane molasses serve as the primary feedstocks, with ethanol blends (E10, E20, E85) actively promoted through vehicle standards and producer incentives. The country's focus on farmer integration and small-scale distilleries offers a template for decentralised ethanol models, suitable for replication in similar agro ecological contexts [48–50].

The Philippines, although smaller in production capacity, has leveraged its Biofuels Act (2006) to mandate 10% ethanol blending. The program has spurred rural employment but remains constrained by domestic feedstock supply, necessitating imports. Recent trials involving sweet potato and nipa palm ethanol underscore a growing interest in diversifying the feedstock base for enhanced sustainability [51, 52].

These case studies highlight the importance of clear mandates, feedstock diversification, infrastructure investment, and smallholder inclusion in national ethanol programs.

Energy Security and Rural Development Nexus

The intersection of energy security and rural development constitutes a central rationale for promoting bioethanol in tropical economies. Sweet potato-based ethanol systems offer a potentially effective mechanism for aligning national energy policy objectives with local socio-economic development, particularly in agrarian regions characterised by smallholder dominance and underemployment.

The bioethanol value chain, encompassing cultivation, aggregation, transportation, processing, and distribution, is inherently labour-intensive and capable of generating substantial employment. Sweet potato cultivation is typically undertaken on small plots and requires significant manual input, making it well-suited to rural employment strategies. In Brazil, the ethanol sector is estimated to support approximately 1.5 million jobs, and analogous labour-intensive models could be adapted to sweet potato-based systems in African and Southeast Asian contexts, subject to appropriate institutional and market frameworks [28, 53].

Land-use considerations further strengthen the case for sweet potato relative to alternative bioethanol feedstocks. Unlike sugarcane, which often requires large contiguous landholdings and estate-scale production, sweet potato performs well under smallholder systems and can be integrated into intercropping arrangements. Its ability to grow on marginal or degraded lands offers opportunities to reduce pressure on prime agricultural land and limit deforestation. Nevertheless, the diversion of land or produce from food to fuel applications necessitates robust land governance mechanisms and food security safeguards to ensure that vulnerable populations are not adversely affected.

In addition to direct employment effects, sweet potato-based bioethanol systems can enhance rural incomes through multiple co-benefits. These include the utilisation of processing residues for animal feed, biogas production from waste streams, and employment opportunities associated with decentralised or community-scale distillation facilities. Evidence from pilot initiatives in countries such as Mozambique and Uganda indicates that sweet potato ethanol value chains can increase rural household incomes by approximately 20–30% through structured feedstock procurement contracts and incentives for off-season cultivation [54]. Furthermore, the incorporation of bioethanol into local energy systems, such as ethanol cookstoves or microgrid generators, can enhance energy access in off-grid communities, amplifying the developmental impact.

A shift toward sweet potato-based bioethanol, as proposed in the manuscript, presents an opportunity to address multiple policy imperatives: climate mitigation, rural empowerment, and fossil fuel substitution. While traditional feedstocks like sugarcane and cassava continue to dominate, their environmental and socio-economic limitations underscore the need for a more diversified and context-sensitive approach. The bioethanol landscape in tropical countries is poised for transformation if sweet potato's agronomic potential is matched with targeted investments, inclusive policies, and sustainable land use planning.

Table 1 synthesises key insights into the bioethanol landscape in tropical countries, structured under three thematic domains: feedstock characteristics, roles in national energy strategies, and developmental linkages. It contrasts the agronomic and economic profiles of dominant feedstocks, sugarcane, cassava, maize, and sweet potato, highlighting yield potentials, input requirements, and sustainability constraints. It further summarises national bioethanol integration strategies from Brazil, Thailand, and the Philippines, illustrating the influence of policy frameworks and institutional support. Finally, it outlines the nexus between bioethanol production and rural development, focusing on employment creation, land-use

implications, income generation, and decentralised energy access. Table 1 supports a comparative assessment of sweet potato's suitability for inclusive, sustainable bioethanol expansion in tropical contexts.

Agronomic and Technical Suitability

Sweet Potato Varietals for Ethanol

Sweet potato (*Ipomoea batatas*) exhibits substantial genetic and varietal diversity, enabling its adaptation across a wide range of agroecological zones typical of tropical climates. For bioethanol production, varietals with high dry matter and starch content, short growing cycles, and dual-cropping potential are preferred. Among these, Brazilian and Chinese cultivars such as BRS Cuia, Jinshu No. 8, and Xushu 18 have demonstrated superior ethanol yields, with BRS Cuia reaching up to 10,000 L of ethanol per hectare per year under optimal conditions and bi-cropping systems [9, 10].

These varieties typically exhibit dry matter content between 25% and 35%, translating into starch concentrations of 15% to 25%, depending on soil fertility, irrigation, and maturity duration. Rapid-maturing varieties, reaching harvest within 90–120 days, enable multiple harvests per year, a critical attribute in equatorial regions with bimodal rainfall patterns (e.g., Uganda, Ghana, and parts of Indonesia) [55–57].

Table 2 summarises the representative *Ipomoea batatas* cultivars considered in the present analysis, classified by their primary use (industrial, table, or dual-purpose). The techno-economic model used yield and composition parameters consistent with high-starch industrial varieties such as 'KSP36', 'W-42', and 'Cuia', which exhibit dry-matter contents above 30% and starch levels exceeding 22% of dry mass. These cultivars are widely employed in African, Asian, and Latin American ethanol feasibility studies and provide the most realistic basis for assessing large-scale conversion efficiency. Table varieties such as 'Beauregard' and purple-fleshed landraces were referenced only for comparative nutritional assessment in the food-versus-fuel discussion, not for the core economic calculations.

Yield and starch data employed in the techno-economic analysis are derived primarily from high-starch industrial cultivars, KSP36 (Kenya), W-42 (China), and BRS Cuia (Brazil), which exhibit dry matter content above 30% and starch levels exceeding 22% of dry mass. These varieties formed the empirical basis for the ethanol yield and conversion efficiency values presented in Tables 3, 4 and 5. Comparative references to Beauregard and Kakamega varieties are used solely for nutritional and dual-purpose discussions.

Table 1 Key dimensions of the bioethanol landscape in tropical countries

Theme	Aspect	Key Points
Current Bioethanol Feedstocks	Sugarcane	High ethanol yield (up to 8,000 L/ha); low cost per litre; water- and input-intensive; favours large-scale plantations; sustainability concerns (groundwater depletion, soil degradation).
	Cassava	Moderate yields (1,800–3,000 L/ha); drought tolerant; enzyme-dependent processing; pest-prone; competes with food uses during shortages.
	Maize	Low ethanol yield (2,500–3,800 L/ha); input-intensive; less suited to tropical climates; high food-versus-fuel conflict.
	Sweet Potato	High yields (up to 10,000 L/ha with dual cropping); thrives in low-input, marginal land; underutilised; well-suited for smallholder systems.
Role of Bioethanol in National Energy Mix	Brazil	E27 blend mandate; large-scale sugarcane ethanol; public–private R&D; flexible-fuel vehicles; strong institutional support.
	Thailand	Cassava and molasses-based ethanol; national blend levels (E10–E85); incentives for decentralised production; farmer participation programs.
	Philippines	10% blending mandate; feedstock supply shortages; growing interest in alternative feed-stocks (e.g., sweet potato, nipa palm).
Energy Security and Rural Development Nexus	Employment Generation	Labour-intensive production chain; smallholder-friendly; examples from Brazil and African pilot projects.
	Land Use Impacts	Sweet potato is suitable for marginal and intercropped land; reduces land pressure; requires food-fuel trade-off policies.
	Rural Incomes	Contracts for feedstock supply and processing jobs; co-products like animal feed and bio-gas add value; potential for 20–30% income increase in pilot regions.
	Decentralised Energy Access	Ethanol-fuelled cookstoves and microgrids could enhance rural energy security and reduce biomass dependence.

Table 2 Representative sweet potato (*Ipomoea batatas*) varieties considered in the bioethanol analysis

Variety/Type	Origin/Region	Type Classification	Average Dry Matter (%) FW)	Starch Content (% DM)	Typical Yield (t ha ⁻¹)	Ethanol Yield (L t ⁻¹ FW)	Remarks/Relevance to Review
KSP36	Kenya/East Africa	High-starch industrial cultivar	32–36	22–26	25–35	220–250	Preferred in African bioethanol trials due to high starch-to-sugar ratio and moderate fibre
W-42 (White-fleshed)	China/SE Asia	Industrial starch variety	30–35	24–28	30–40	250–300	Common in Chinese ethanol plants; excellent fermentation yield; low β -carotene
Beauregard	USA/Global	Table variety (orange-fleshed)	25–28	18–20	20–25	150–180	Nutritionally rich (high β -carotene); used for food but suitable for small-scale ethanol
Kakamega/Resisto	East & Southern Africa	Dual-purpose variety	27–30	20–22	20–30	180–220	Balanced nutritional and starch profile; adaptable to smallholder systems
Cuia	Brazil	Industrial starch-rich cultivar	33–38	25–30	35–45	250–280	Used in Brazilian ethanol pilot studies; high fermentation efficiency
Purple-fleshed landraces (various)	Southern Africa/Asia	Anthocyanin-rich table types	25–32	18–22	20–25	160–190	Lower ethanol yield but value-added potential for nutraceutical co-products

Socio-economic Implications of Varietal Adoption

The adoption of specific sweet potato varieties has profound implications for rural livelihoods, employment generation, and the inclusion of smallholder farmers in bioethanol value chains. Industrial high-starch cultivars such as BRS Cuia, KSP36, or W-42 can catalyse new agro-industrial linkages, particularly when cultivated under contract-farming or cooperative frameworks. These varieties, favoured for ethanol conversion efficiency, stimulate rural employment across seed propagation, planting, harvesting, and local

processing. In regions such as East Africa and Northeast Brazil, pilot projects involving high-starch sweet potato ethanol have demonstrated 20–30% increases in seasonal income for participating smallholders, alongside the creation of decentralised processing jobs, especially for women and youth engaged in tuber handling and fermentation units.

Conversely, dual-purpose and table varieties such as Beauregard, Kakamega, or purple-fleshed landraces provide a more inclusive route for livelihood enhancement because they integrate food security with energy production. Farmers can allocate part of their harvest to household

Table 3 Comparative assessment of the agronomic viability of sweet potato as an ethanol feedstock compared to other dominant tropical crops

Parameter	Sweet Potato	Cassava	Sugarcane
Yield (t/ha/year)	20–40 (<i>up to 60 under irrigation</i>)	15–35	60–100
Dry Matter (%)	25–35	35–40	18–23 (juice)
Starch Content (%)	15–25	25–30	~15 (sucrose equivalent)
Ethanol Yield (L/ha/year)	4,500–10,000	2,800–4,000	5,000–8,500
Cropping Cycle	3–4 months	10–12 months	12–18 months
Water Requirement	Low–Moderate	Moderate	High
Input Requirement	Low	Moderate	High

Table 4 Empirically computed starch content and ethanol yield of sweet potato

Parameter	Low-End	Typical Range	High-End
Starch Content (% dry matter)	15%	20–25%	28%
Ethanol Yield (L/tonne fresh tubers)	90–150 L/t	180–250 L/t	280–300 L/t
Ethanol Yield (L/ha/year)*	~3,000	4,500–6,500	10,000+

*Assuming average yield of 20–40 t/ha and two cropping cycles

consumption while selling surplus or lower-grade tubers to bioethanol facilities. This reduces the “food-versus-fuel” tension and supports livelihood diversification. Adoption of such mixed systems has proven effective in community-led biofuel cooperatives in Uganda and the Philippines, where farmers supplied both nutritional and industrial markets without compromising staple food access.

At a broader scale, varietal choice influences the structure of rural employment. Industrial cultivars encourage aggregation and mechanisation, suited for semi-commercial estates or clusters, whereas dual-purpose and local landraces sustain labour-intensive, smallholder-oriented systems that distribute income more equitably. Policies promoting the coexistence of both streams, industrial for high-yield ethanol production and dual-purpose for community resilience, can therefore maximise social benefit. Tailored extension services, seed distribution networks, and micro-credit access remain essential to ensure that smallholders, particularly women who dominate sweet potato cultivation in many tropical regions, can effectively participate in and benefit from emerging bioethanol markets.

Varietal Resilience Under Drought and Low-input Farming Systems

Sweet potato exhibits exceptional environmental adaptability, with varietal resilience playing a decisive role in sustaining productivity under drought and nutrient-limited

conditions typical of tropical smallholder landscapes. High-starch industrial cultivars such as *KSP36*, *W-42*, and *BRS Cuia* demonstrate moderate drought tolerance when managed under controlled irrigation or mulch-based moisture retention systems, maintaining 70–85% of their yield potential during seasonal dry spells. Their robust root architecture, capable of deep soil penetration (up to 1.5 m in friable soils), enables efficient subsoil moisture extraction, conferring significant resilience to transient water stress.

Conversely, dual-purpose and landrace varieties such as *Kakamega*, *Resisto*, and purple-fleshed genotypes are particularly well adapted to low-input systems. These cultivars evolved under subsistence farming regimes with minimal fertiliser use, exhibiting superior nutrient-use efficiency and tolerance to acidic or degraded soils. Field observations in Malawi, Uganda, and southern China indicate that such varieties maintain acceptable tuber yields (15–25 t ha⁻¹) even under nitrogen application rates below 40 kg ha⁻¹, conditions under which maize or cassava would typically underperform.

Environmental resilience among these varieties also contributes to reduced greenhouse-gas emissions and lower resource footprints. Their compatibility with organic fertilisation and intercropping systems enhances soil structure and microbial diversity, while their short growth cycles limit erosion and nutrient depletion. Consequently, varietal selection should consider not only ethanol yield but also ecological stability, with priority given to genotypes that sustain productivity under marginal water and nutrient conditions. Integrating such resilient varieties into bioethanol programs strengthens both climate adaptation and the long-term sustainability of rural agro-ecosystems.

Agricultural Requirements

Sweet potato is widely recognised for its low input demand compared to conventional energy crops such as sugarcane or maize. Fertiliser use is minimal, with recommended applications of 40–90 kg/ha NPK mixtures, and in many smallholder systems, it thrives under organic or manure-based fertilisation. The crop’s ability to fix and efficiently utilise soil nutrients under low-input regimes makes it highly suited for resource-poor environments [8].

Land Suitability Sweet potatoes tolerate a range of soil types, loamy, sandy-loam, or even degraded lateritic soils, provided drainage is adequate. Unlike sugarcane, which demands deep tillage and level fields, sweet potatoes require modest land preparation and are amenable to ridge or mound cultivation systems.

Climate Resilience The crop is exceptionally drought-tolerant, capable of producing tubers even under water-stressed

Table 5 Summary of quantitative literature on sweet potato bioethanol production

Parameter	Quantitative Range/ Value	Context or Notes	Source(s)
Ethanol yield per hectare (L ha ⁻¹ yr ⁻¹)	1,250–10,000 L ha ⁻¹	Range across tropical cultivars; higher end under dual cropping and enzyme optimisation	[1, 9, 10, 28, 35]
Ethanol yield per tonne of fresh tuber (L t ⁻¹)	90–300 L t ⁻¹	Depends on starch content (15–28% DM) and process efficiency	[9, 10, 20]
Crop yield (t ha ⁻¹)	20–40 t ha ⁻¹ (up to 60 t ha ⁻¹ with irrigation)	Tropical average; varies by soil, cultivar, and fertilisation regime	[8, 55–57]
Dry matter content (% fresh weight)	25–35%	Determines starch availability for conversion	[8, 9]
Starch content (% dry matter)	15–25%	High-starch industrial varieties used for ethanol	[9, 10]
Conversion efficiency (starch to ethanol)	70–90% of theoretical	Enhanced with Simultaneous Saccharification and Fermentation (SSF)	[9, 70, 71]
Fermentation time (h)	48–72 h	Typical batch/SSF systems using <i>S. cerevisiae</i>	[9, 70, 72, 73]
Enzyme requirement (α -amylase + glucoamylase)	0.05–0.10 USD L ⁻¹ ethanol	Major operational cost; cost reduction via in-house enzyme production	[35, 81]
Feedstock cost (USD t ⁻¹ fresh)	40–80 USD t ⁻¹	Regional variation; accounts for 40–60% of production cost	[5, 8, 35]
Levelized Cost of Ethanol (LCOE)	0.50–0.75 USD L ⁻¹	Base case before co-product credits; competitive with cassava or maize ethanol	[34, 35, 86, 87]
Internal Rate of Return (IRR)	12–25%	Under high-yield (>6,000 L ha ⁻¹) and stable ethanol price (>0.60 USD L ⁻¹)	[35, 54]
Payback period (years)	3–6 years	Small to medium-scale facilities with co-product valorisation	[1, 35]
GHG reduction vs. gasoline	40–60%	Lifecycle reduction under low-input cultivation and renewable heat use	[1, 14, 35]
Water requirement	Low – Moderate (~500–700 mm per cycle)	Much less than sugarcane (~2,000 mm per cycle)	[36, 37]
Cropping cycle duration (days)	90–120 days	Enables dual-cropping in tropical climates	[56–58]
Capital expenditure (CAPEX)	4–8 million USD (20–50 kL day ⁻¹ plant)	Dependent on technology and localisation	[34, 35, 80]
Operating expenditure (OPEX)	0.30–0.55 USD L ⁻¹	Includes feedstock, enzyme, labour, and utilities	[81, 82]

conditions. It performs optimally in temperature ranges between 20 and 30 °C and has a moderate tolerance to heat extremes (> 35 °C). Moreover, unlike cassava, which is prone to mosaic viruses or sugarcane vulnerable to red rot, sweet potato demonstrates moderate resistance to pest outbreaks and root rot, particularly when local landraces are crossed with industrial cultivars [58, 59].

Pest and Disease Management Common pests include the sweet potato weevil (*Cylas spp.*), but improved cultivars combined with crop rotation and resistant clones reduce the incidence. Moreover, minimal pesticide use enhances its compatibility with sustainable and organic production frameworks.

Comparative Yields

The comparative assessment in Table 3 illustrates the agro-economic viability of sweet potato as an ethanol feedstock compared to other dominant tropical crops.

While sugarcane provides higher biomass, its intensive resource demands and long maturity period make it unsuitable for many tropical smallholder systems. Cassava, though

rich in starch, requires longer growing seasons and careful pest management. Sweet potato, with its high ethanol potential per unit time, low water use, and flexible cropping windows, offers a strategically superior choice in agroclimatic zones with constrained infrastructure and land availability.

Harvesting and Storage Logistics

Sweet potato presents both opportunities and challenges in post-harvest logistics. Harvesting is typically manual, which is labour-intensive but beneficial for employment in smallholder contexts. Mechanised harvesting solutions exist (e.g., rotary diggers), but they require soil-specific calibration and may not be cost-effective for fragmented land holdings.

Post-harvest, the tubers exhibit high perishability, with enzymatic degradation and microbial spoilage beginning within 7–10 days under ambient tropical conditions. This presents logistical challenges for ethanol production, especially where biorefineries are not in proximity to production areas.

Mitigation strategies include field-to-plant transport within 24–48 h to prevent starch degradation, on-site pre-processing (e.g., drying, grating, ensiling) to convert the

biomass into storable intermediate forms, modified Atmosphere Storage (MAS) and temperature control (15–18 °C) where feasible, especially in industrial-scale settings and use of cooperatives or farmer clusters for aggregating and scheduling deliveries to minimise post-harvest losses [60–62].

Despite the perishability, the short crop cycle and possibility of staggered planting across adjacent plots facilitate continuous feedstock availability, which aligns well with the steady-state requirements of ethanol plants.

Figure 1 presents a visual synthesis of the technical and agronomic parameters that support the viability of sweet potato as a bioethanol feedstock in tropical countries. It highlights the characteristics of high-starch, short-cycle varieties suited to dual-cropping systems; outlines input and resilience attributes such as low fertiliser dependency, drought tolerance, and pest resistance; and compares yields with cassava and sugarcane in terms of biomass and starch content. Additionally, it notes critical post-harvest handling issues, such as perishability and manual harvesting constraints, that influence processing efficiency and value chain integration. The figure provides a concise reference to support strategic evaluation of feedstock suitability in bioethanol planning frameworks.

In summary, sweet potato demonstrates compelling agronomic and technical suitability as a bioethanol feedstock for tropical countries. Its high starch yield, dual-season cropping, minimal input demand, and adaptability to degraded soils make it ideal for sustainable bioenergy systems in regions where sugarcane and cassava may falter. However,

logistics planning, particularly regarding harvest timing and tuber perishability, remains critical for successful commercial-scale deployment. With proper varietal selection and decentralised processing infrastructure, sweet potato can play a transformative role in tropical biofuel economies.

Bioethanol Conversion Process

The transformation of sweet potato into bioethanol follows a biochemical conversion route characterised by four major stages: pre-treatment, saccharification, fermentation, and distillation. Each phase influences overall conversion efficiency, yield, and production cost.

Pre-treatment

Pre-treatment of sweet potato tubers is essential to prepare the feedstock for efficient enzymatic hydrolysis. This involves washing and peeling [63] to remove soil and microbial contaminants, size reduction [64] through chipping or grating to increase surface area and reduce diffusion resistance, thermal gelatinisation [9, 64], usually by steam or hot water (at 80–90 °C), to disrupt the semi-crystalline structure of starch granules and make them accessible to enzymes.

Notably, sweet potato has a relatively low lignin and cellulose content, unlike lignocellulosic feedstocks, which eliminates the need for harsh chemical or physicochemical pre-treatment processes, such as acid hydrolysis or steam explosion. This feature reduces energy and reagent costs while simplifying downstream processing.

Saccharification

This enzymatic step converts gelatinised starch into fermentable sugars. It typically involves Liquefaction using α -amylase enzymes at ~85–90 °C to break down long-chain polysaccharides into dextrins [65], Saccharification using glucoamylase or amyloglucosidase at 55–60 °C to hydrolyse dextrins into glucose monomers [66, 67]. Advanced saccharification strategies incorporate Simultaneous Saccharification and Fermentation (SSF) to streamline process steps, reduce contamination risk, and improve sugar-to-ethanol conversion rates, and enzyme cocktail optimisation to accommodate the specific starch structure and inhibitory compounds in different sweet potato varieties [68, 69].

Fermentation

The glucose-rich hydrolysate is fermented by yeast, most commonly *Saccharomyces cerevisiae*, to produce ethanol and CO₂. Industrial-scale fermentations operate under the

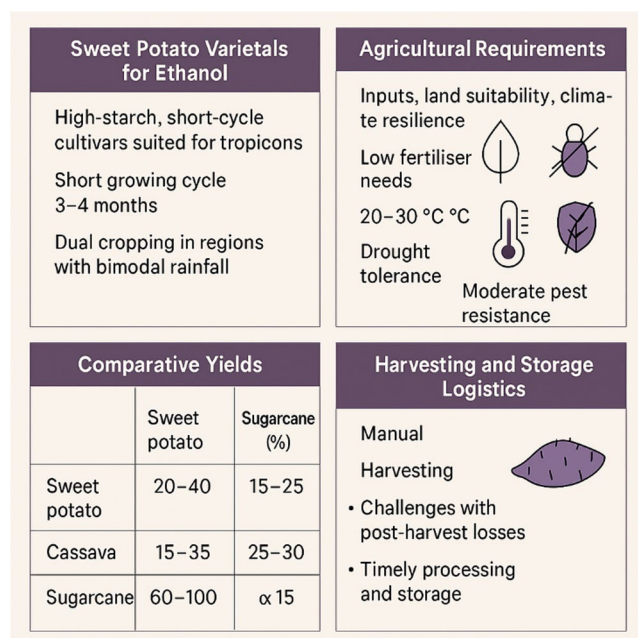


Fig. 1 Agronomic and technical suitability of sweet potatoes for bioethanol production in tropical regions

parameters: Temperature: 30–35 °C, pH: 4.5–5.5, and Fermentation time: 48–72 h [9, 70, 71].

Recent advances include high cell density fermentation using immobilised yeast or selected strains (e.g., *S. cerevisiae* var. *bayanus*, *Kluyveromyces marxianus*) to increase ethanol productivity, inhibitor-tolerant yeasts to handle stress conditions arising from by-products in non-sterile environments, and continuous or fed-batch fermentation to reduce downtime and improve reactor efficiency [70, 72–74].

Distillation

The fermentation broth typically contains 8–12% (v/v) ethanol. Ethanol is separated through a two-stage distillation process: primary distillation to concentrate ethanol to 85–90% and azeotropic distillation or molecular sieving (e.g., pervaporation or adsorption using zeolites) to obtain fuel-grade ethanol (> 99.5%). In energy-constrained settings, multi-effect distillation or solar-assisted distillation is explored to reduce the process energy footprint [9].

Technology Options

Traditional systems are typically decentralised, small-scale units found in rural or village settings. They rely on batch-based cooking and fermentation, manual operations with limited process control, and open fermentation tanks and rudimentary distillation units. These systems are cost-accessible and employable in smallholder regions but suffer from low ethanol recovery (typically < 20% of theoretical yield), high energy consumption per litre of ethanol, and poor hygiene and contamination risks [75–77].

Advanced biorefineries, on the other hand, incorporate integrated enzymatic hydrolysis and fermentation systems (e.g., SSF or SHF), process automation and closed fermenters for contamination control, waste heat recovery, co-product valorisation, and CIP (clean-in-place) protocols, and in some cases, biogas digesters to treat stillage and generate process heat or electricity [78].

Such systems demonstrate high conversion efficiency (70–90% of theoretical), better scalability, and improved compliance with fuel standards [78, 79]. However, they demand high initial capital and a reliable feedstock supply, making them suitable for industrial clusters or cooperative-based aggregation models.

Yield Estimates

Conversion yields vary based on varietal starch content, process efficiency, and technology employed. Table 4 depicts the outcomes of empirical studies.

Advanced Brazilian trials e.g. [10], using BRS Cuia reported yields up to 10,000 L/ha/year, under dual cropping, enzyme optimisation, and yeast selection protocols. These results position sweet potato competitively against maize (2,800–3,800 L/ha) and approaching sugarcane (6,000–9,000 L/ha) in tropical climates.

In summary, the process of converting starch from sweet potatoes into ethanol provides a technically sound and cost-effective method for producing bioethanol, especially in tropical regions. The biochemical composition of sweet potatoes enables high efficiency in saccharification, and their suitability for both traditional and advanced processing systems allows for flexible implementation. As enzyme formulations and fermentation strains improve, and as decentralised pre-processing technologies (such as mobile distilleries or on-farm drying units) become more affordable, the scalability of sweet potato ethanol biorefineries in developing tropical countries looks increasingly promising.

Economic Analysis

Table 5 provides a concise quantitative synthesis of the key agronomic, technical, and economic parameters from the literature used in the review for economic analysis, to quickly appraise comparative values and data ranges that underpin the techno-economic model.

Table 6 presents the set of technical, financial, and policy assumptions employed in the techno-economic analysis of bioethanol production from *Ipomoea batatas*. The parameters reflect realistic ranges reported in contemporary literature and international energy-economic datasets, normalised to 2024 cost levels. Feedstock and process variables (e.g., crop yield, starch fraction, conversion efficiency, enzyme cost, and fermentation time) represent mean operational conditions achievable under tropical or subtropical climates. Financial assumptions, including capital and operating costs, discount and inflation rates, and fiscal terms, were selected to represent medium-scale distillery operations typical of emerging-market biofuel projects. Policy-linked variables such as ethanol blending mandates, carbon credit valuation, and lifecycle greenhouse-gas reductions were included to capture the macro-economic environment influencing project viability. Collectively, these assumptions provide the analytical foundation for computing the Levelized Cost of Ethanol (LCOE), Internal Rate of Return (IRR), Payback Period (PP), and related sensitivity analyses discussed in the following sections.

A full cost accounting of sweet potato bioethanol production spans from agricultural production through to distribution. These costs vary across geographies but can be generalised into four principal categories.

Table 6 Key assumptions used in the techno-economic analysis of sweet potato bioethanol production

Category	Parameter/Variable	Assumed Value/Range	Basis/Justification	Reference(s)
Feedstock Parameters	Crop yield	20–40 t ha ⁻¹ (fresh weight)	Representative yield under tropical smallholder and semi-mechanised systems	[8, 55–57]
	Dry-matter content	25–35%	Typical range for <i>Ipomoea batatas</i> industrial cultivars	[8–10]
	Starch fraction of dry matter	15–25%	Used for theoretical ethanol conversion estimation	[9, 10]
Process Parameters	Feedstock cost	USD 40–80 t ⁻¹ (fresh)	Farm-gate cost including harvesting and logistics	[5, 35]
	Conversion efficiency (starch to ethanol)	70–90%	Literature average under SSF process using <i>S. cerevisiae</i>	[9, 70, 71]
	Fermentation duration	48–72 h	Batch/SSF operation typical for tropical distilleries	[70, 72, 73]
	Enzyme consumption	0.05–0.10 USD L ⁻¹ ethanol	Based on industrial enzyme cost share (α -amylase + glucoamylase)	[35, 81]
Financial Parameters	Process water requirement	5–6 L water L ⁻¹ ethanol	Inclusive of fermentation, cooling and cleaning	[36, 37]
	Ethanol market price	0.55–0.85 USD L ⁻¹	Regional fuel-grade ethanol prices (2023–2024)	[34, 35, 86, 87]
	Exchange rate	1 USD = 18.0 ZAR (base case)	Average 2024–2025 rate for South Africa	[Treasury data]
	Capital expenditure (CAPEX)	USD 4–8 million (20–50 kL day ⁻¹ plant)	Scale-dependent investment estimate	[34, 35, 80]
	Operating expenditure (OPEX)	0.30–0.55 USD L ⁻¹	Includes feedstock, enzyme, utilities, labour	[81, 82]
	Plant lifetime	15 years	Conventional lifespan for small–medium distilleries	[80, 81]
	Discount rate	8–12% p.a.	Reflects risk-adjusted cost of capital in developing markets	[83, 84]
	Inflation/escalation rate	3% p.a.	Based on IMF and South African Reserve Bank averages	[83, 84]
	Tax rate	28%	Standard corporate tax in South Africa	[Treasury data]
	Loan-to-equity ratio	70 : 30	Typical structure for biofuel investment projects	[35, 80]
Policy & Environmental Factors	Payback period target	≤ 6 years	Acceptable threshold for project viability	[1, 35]
	Ethanol blending mandate	E10 – E27 (country dependent)	Current policy range in tropical developing nations	[89]
	Carbon credit value	25 USD t ⁻¹ CO ₂ e	Conservative carbon price used for co-benefit estimation	[89, 90]
	GHG reduction vs. gasoline	40–60%	Based on lifecycle analyses of starch-based ethanol	[1, 14, 35]

Feedstock Production Cost

Feedstock cost remains the single largest contributor to bioethanol production costs, often accounting for 40–60% of total expenses [35]. For sweet potato, this includes land lease or ownership (variable by country and tenure system), labour and mechanisation (ploughing, planting, weeding, harvesting), input costs: fertilisers (minimal), organic compost, pest management, irrigation and water management (if necessary, in drier zones), post-harvest logistics: on-farm handling, transportation to processing site. Current literature suggests average production costs range from \$40–\$80 per tonne of fresh tubers, depending on yield, region, and scale [5, 8].

Capital Cost of Biorefinery

Initial capital investment includes land acquisition and civil construction, processing equipment (pre-treatment,

enzymatic reactors, fermentation tanks, distillation columns, dehydration units), utilities such as boilers, effluent treatment, and power systems, storage tanks and ethanol handling infrastructure.

For a small-to-medium scale biorefinery (e.g., 20,000–50,000 L/day), capital expenditure (CAPEX) is typically \$4–8 million USD, depending on localisation, technology complexity, and construction standards [34, 35, 80].

Operating Costs

Operating cost has several components, such as enzymes where α -amylase and glucoamylase are cost-intensive (~\$0.05–\$0.10/L of ethanol), yeast which has recurring cost unless high-cell density cultures are maintained, utilities such as energy (steam, electricity), water, and cooling systems, both skilled and unskilled labour, maintenance and downtime such as periodic repairs, yield loss and power

system breakdown due to various system faults and lighting, and waste treatment and environmental compliance. OPEX typically ranges between \$0.30–\$0.55 per litre of ethanol produced, subject to regional utility rates and automation levels [81].

Distribution and Marketing

Final ethanol handling, transportation, and marketing involve storage at terminal depots, blending infrastructure (with gasoline or local fuels), regulatory certification and quality assurance and retail and wholesale distribution networks. Depending on location, these costs contribute an additional \$0.05–\$0.10/L [82].

Primary revenue is from ethanol sold to blending markets under national mandates (e.g., E10–E27), off-grid energy markets: rural generators, cookstoves and industrial and institutional clients (pharmaceutical, sanitisation sectors). Average market prices vary: \$0.50–\$0.90/L, depending on policy incentives, import parity, and carbon credit systems [83, 84].

Several co-products enhance profitability such as animal feed, a fibrous pulp and fermentation residue can be pelletised or used directly as high-protein feed (~\$100–\$150/tonne), residual starch or industrial pulp, useful in food or adhesive industries and captured CO₂ from fermentation, can be purified and sold to beverage or agricultural markets (~\$50–\$100/tonne in specialised facilities) [54, 85]. These co-products can contribute 15–30% of the total revenue stream, depending on processing integration.

To calculate the break-even price, we assume that the ethanol price is the price at which total cost = total revenue. Typically, \$0.45–\$0.65/L for small systems with > 5,000 L/ha yield. Lower for systems that valorise co-products and benefit from subsidies [35, 86].

The time required to recover the initial investment is 3–6 years in high-yield, dual-cropping systems. It can be extended to 7–10 years in regions with low yield or poor infrastructure [1].

The Internal Rate of Return (IRR) is also an important parameter in analysing the economic aspects of bioethanol success. IRR is a financial performance indicator sensitive to cash flows. IRRs of 12–25% are typical under favourable techno-economic assumptions: high yields (> 6,000 L/ha), stable ethanol prices (> \$0.60/L), low feedstock costs and efficient conversion systems [35, 54].

Another important metric, the LCOE, reflects the average lifecycle cost of ethanol production. The base case is \$0.50–\$0.75/L. With co-product revenue or subsidies, it may fall below \$0.45/L [86, 87].

Sensitivity assessments evaluate economic robustness under fluctuating parameters. Table 7 presents the sensitivity

analysis of core economic variables influencing the profitability and viability of sweet potato-derived bioethanol systems in tropical countries. It outlines the expected parameter ranges, such as land cost, crop yield, enzyme price, and ethanol market price, and evaluates their impact on financial performance indicators like IRR, break-even thresholds, and risk exposure. The analysis highlights critical thresholds beyond which bioethanol production becomes financially unsustainable, providing valuable insights for investors, policymakers, and development planners in renewable energy and agriculture. A multi-variable scenario simulation (e.g., Monte Carlo analysis) can help identify risk clusters, indicating where interventions (e.g., subsidies, co-product development, yield improvement) are most needed.

Economic viability of sweet potato-based bioethanol production is highly contextual, hinging on agronomic performance, process efficiency, and access to markets. While feedstock and enzyme costs are dominant cost factors, strategic optimisation of co-products, decentralised logistics, and favourable policy environments can reduce the Levelised Cost of Ethanol and improve financial returns. The short cropping cycle and yield elasticity of sweet potato offer opportunities for dynamic business modelling, especially in smallholder-dominant tropical economies.

Environmental and Social Implications

The production of bioethanol from sweet potatoes in tropical regions presents significant environmental and social implications, which must be carefully evaluated to ensure alignment with sustainable development goals (SDGs). Below, these implications are explored under key thematic areas.

GHG Emissions Reduction Potential (Compared to Gasoline)

Sweet potato-based bioethanol has the potential to substantially reduce greenhouse gas (GHG) emissions compared to fossil gasoline. Studies indicate that bioethanol derived from starchy crops can reduce lifecycle GHG emissions by 40–60%, depending on cultivation practices, processing efficiency, and energy sources used in production. Sweet potatoes, with their high starch content and adaptability to low-input farming, further enhance this benefit by minimising synthetic fertiliser use and reducing associated emissions. However, the net reduction depends on avoiding deforestation for crop expansion and optimising supply chains to lower transportation emissions.

Table 7 Sensitivity of key economic parameters in sweet potato-based bioethanol production

Parameter	Range	Impact on Profitability	References
Land Cost	\$100–\$600/ha	High influence in peri-urban zones; manageable in marginal/rural lands.	[88–93]
Yield	3,000–9,000	Critical threshold: <4,000 L/ha leads to negative IRR under most scenarios.	[92,
Variability	L/ha		94–96]
Enzyme Price	\$0.04–\$0.10/L	High sensitivity due to proportional use; bulk procurement or in-house enzyme production can reduce impact.	[97–99]
Ethanol Market Price	\$0.50–\$0.90/L	Directly tied to IRR and break-even, public blending mandates stabilise prices and reduce volatility.	[100–102]

Water and Land Use Considerations

Water use: Sweet potatoes are relatively drought-tolerant compared to other biofuel feedstocks like sugarcane, making them suitable for regions with limited water resources. However, irrigation demands must be managed to prevent water scarcity, especially in areas prone to seasonal droughts.

Land use: Sweet potatoes can be cultivated on marginal or degraded lands, reducing pressure on prime agricultural land. This minimises competition with food crops and mitigates deforestation risks. Their short growing cycles and high yield potential per hectare also improve land-use efficiency.

Food vs. Fuel Debate

The “food vs. fuel” debate is a critical concern, particularly in regions where sweet potatoes are a staple food. To address this:

Marginal lands: Cultivating sweet potatoes on underutilised or marginal lands can avoid displacing food crops.

Dual-purpose varieties: High-starch varieties bred specifically for bioethanol can coexist with food-grade sweet potatoes, ensuring food security while supporting energy production.

Co-products: Utilising residues (e.g., pulp for animal feed) can enhance resource efficiency and provide additional income streams for farmers.

Employment and Gender Impacts in Rural Areas

Employment generation: Bioethanol production can create jobs in farming, processing, and logistics, boosting rural economies. Smallholder farmers may benefit from new market opportunities and value-added activities.

Gender equity Women, who often dominate sweet potato cultivation in tropical smallholder systems, could gain economically through targeted inclusion in processing cooperatives or training programs. However, care must be taken to

ensure equitable access to resources (e.g., land, credit) and prevent increased labour burdens without fair compensation.

Sweet potato-based bioethanol offers promising environmental benefits, including GHG reductions and efficient land/water use, while addressing social challenges through rural employment and gender-inclusive growth. However, its sustainability hinges on policies that prioritise marginal land use, water conservation, and equitable participation. Integrating these considerations into national biofuel strategies can help tropical countries achieve SDGs 2 (Zero Hunger), 7 (Affordable and Clean Energy), 8 (Decent Work), and 13 (Climate Action).

Policy and Market Drivers

The economic viability and scalability of sweet potato-based bioethanol production depend heavily on policy frameworks and market dynamics. Below is an analysis of key drivers and barriers under four critical themes:

Biofuel Mandates and Incentives

Ethanol blending mandates have been implemented in several countries to create stable and predictable demand for biofuels. Brazil has adopted an E27 mandate, while Nigeria and Thailand have established blending targets of E10 and E20, respectively. Similar policy instruments could be introduced in other tropical nations to incentivise the development and market uptake of sweet potato-based ethanol.

Fiscal incentives play a critical role in reducing production costs and lowering investment risk in emerging bioethanol sectors. Measures such as tax exemptions, direct subsidies, and grant schemes targeting smallholder farmers and feedstock suppliers can enhance the financial viability of sweet potato ethanol systems. For instance, India’s ethanol blending programme provides financial support for feedstock procurement and infrastructure development, offering a policy model that could be adapted to tropical contexts.

Market-based climate policy instruments can further strengthen the economics of sweet potato ethanol through the monetisation of greenhouse gas emission reductions.

Participation in carbon credit mechanisms, such as the Clean Development Mechanism or its successor frameworks under international climate agreements, allows bioethanol projects to generate additional revenue streams linked to verified emissions abatement.

Despite these opportunities, policy-related challenges remain significant. Inconsistent policy enforcement, regulatory uncertainty, and abrupt changes in incentive structures in some tropical countries can undermine investor confidence and slow sectoral development, underscoring the importance of stable and transparent governance frameworks.

Regulatory Barriers

Cumbersome licensing and permitting requirements for biorefineries and ethanol distribution infrastructure can lead to significant project delays and increased transaction costs. Streamlining approval processes through coordinated regulatory mechanisms, such as Ghana's one-stop licensing framework for agro-processing investments, is therefore critical to improving project timelines and investor confidence.

Compliance with national fuel quality standards is a prerequisite for market entry and consumer acceptance. Ethanol must meet established specifications, such as ASTM D4806, and ethanol derived from sweet potato feedstocks may require additional testing and certification to demonstrate equivalence with conventional ethanol sources and to secure market acceptance.

Land tenure challenges represent another major regulatory constraint, particularly in smallholder-dominated agricultural systems. In regions such as sub-Saharan Africa, unclear or contested land rights can discourage long-term investments in feedstock cultivation and undermine supply chain stability.

At the same time, regulatory harmonisation across regional economic blocs offers a significant opportunity to reduce trade barriers and expand market access. Aligning biofuel standards, licensing requirements, and sustainability criteria within frameworks such as ECOWAS and ASEAN could facilitate cross-border ethanol trade and enhance the scalability of sweet potato-based bioethanol systems.

Public-Private Partnerships (PPPs) and Investment Climate

Public-private partnerships and a supportive investment climate are central to scaling sweet potato-based bioethanol systems in tropical economies. Experience from Brazil demonstrates that structured partnerships between state-owned energy companies and agricultural producers can play a

decisive role in stabilising feedstock supply and reducing market risk. Similar arrangements could be developed for sweet potato value chains, with government-backed off-take agreements and pricing guarantees used to de-risk private sector participation and encourage investment in biorefinery infrastructure.

The broader investment climate also exerts a strong influence on project viability. Risks associated with currency volatility, limited rural infrastructure, and inadequate storage and transport networks can significantly raise transaction costs and deter long-term investment. Addressing these constraints requires coordinated public intervention, particularly in rural road development and logistics. Multilateral and regional development banks, such as the African Development Bank and the International Finance Corporation, are well positioned to provide concessional financing and low-interest loans to support the establishment of biorefineries and associated infrastructure.

Regional demand dynamics further shape the export potential of sweet potato-based bioethanol. Within the Southern African Development Community, South Africa's biofuels strategy creates opportunities for intra-regional trade, particularly if neighbouring countries can supply competitively priced ethanol. In Southeast Asia, Thailand's E20 blending mandate and Indonesia's rapid expansion of biodiesel production signal sustained regional demand for liquid biofuels, suggesting that sweet potato ethanol could find viable markets within ASEAN economies.

However, international trade in bioethanol remains constrained by both tariff and non-tariff barriers. Import duties, such as the European Union's anti-dumping measures on bioethanol, alongside stringent sustainability certification requirements, can limit access to extra-regional markets and increase compliance costs for producers in developing countries. These constraints indicate that early-stage market strategies should prioritise regional and sub-regional trade, particularly where preferential trade agreements are already in place.

As illustrated in Table 8, a combination of policy and market drivers plays a decisive role in shaping the viability of sweet potato bioethanol industries. Effective policy synergy can be achieved by integrating blending mandates, targeted subsidies, and public-private partnership frameworks to reduce investment risk. A regional market focus allows producers to leverage existing demand centres, such as Thailand and South Africa, while minimising exposure to external trade barriers. At the same time, the integration of smallholders into bioethanol value chains can be strengthened by aligning incentives with land tenure reforms and cooperative production models.

Overall, the analysis indicates that unlocking the full potential of sweet potato-based bioethanol in tropical

Table 8 Policy and market drivers for sweet potato bioethanol

Theme	Key Drivers	Challenges	Opportunities/ Strategies	References
Biofuel Mandates & Incentives	- Blending targets (e.g., Nigeria E10, Thailand E20). - Subsidies/tax waivers for feedstock. - Carbon pricing (e.g., CDM credits).	- Inconsistent enforcement in some countries. - High initial subsidy costs.	- Align policies with SDGs (e.g., clean energy targets). - Link incentives to smallholder inclusion.	[100–103]
Regulatory Barriers	- Licensing for biorefineries (e.g., Ghana's one-stop shops). - Fuel quality standards (ASTM D4806).	- Land tenure conflicts in smallholder systems. - Bureaucratic delays.	- Harmonize standards regionally (e.g., ECOWAS, ASEAN). - Fast-track land-use approvals.	[91, 104–106]
Public-Pri- vate Partner- ships (PPPs)	- State-backed off-take agreements (e.g., Brazil's Petrobras model). - Development bank loans (AfDB, IFC).	- Currency volatility risks. - Weak rural infrastructure.	- Replicate the Philippines' \$200 M bioenergy PPPs. - Invest in smallholder cooperatives.	[107–109]
Export Potential	- Regional demand (SADC: 2B liters/year; ASEAN: 8B liters/year). - Trade pacts (AfCFTA tariff cuts).	- EU anti-dumping duties. - Sustainability certification costs.	- Target ASEAN/SADC markets first. - Advocate for bioethanol under AfCFTA.	[99, 100, 110, 111]

countries requires a coordinated and multi-dimensional policy approach. This includes strengthening regulatory frameworks through enforceable blending mandates and well-designed subsidy schemes, reducing administrative bottlenecks by simplifying licensing and land access procedures, leveraging public–private partnerships with agribusinesses and development finance institutions, and targeting regional export corridors characterised by strong and stable biofuel demand.

An economic benchmark against other established bioethanol feedstocks provides perspective on the cost-competitiveness of *Ipomoea batatas* as an energy crop. Table 9 summarises indicative techno-economic metrics for representative bioethanol pathways based on current global and regional data.

From an economic standpoint, sweet-potato-based ethanol is comparable to cassava and maize in production cost and yield potential, while offering distinct advantages in agronomic flexibility and resource efficiency. The Levelized

Cost of Ethanol (LCOE) of 0.50–0.75 USD L⁻¹ reported for sweet potato is marginally higher than that of sugarcane or molasses routes but lower than that of lignocellulosic processes, which currently remain pre-commercial due to high enzyme and pretreatment costs [61, 88].

The relatively short cropping cycle (90–120 days) and ability to thrive on marginal soils make *I. batatas* economically attractive where land and water constraints limit sugarcane or maize. Its moderate capital requirement (4–8 million USD for 20–50 kL day⁻¹ capacity) is lower than for sugarcane distilleries of equivalent output, enhancing financial viability for decentralised or cooperative production models. However, enzyme and feedstock costs remain decisive; combined, they can contribute more than 60% of operating expenditure, echoing findings from cassava-based facilities [112].

When evaluated through Internal Rate of Return (IRR), sweet potato ethanol projects achieve 12–25% under yields above 6,000 L ha⁻¹ and ethanol prices ≥ 0.60 USD L⁻¹,

Table 9 Economic comparison with other bioethanol feedstocks and production routes

Feedstock/Route	Typical Ethanol Yield (L ha ⁻¹ yr ⁻¹)	Levelized Cost of Ethanol (USD L ⁻¹)	Key Cost Drivers/Remarks	Sources
<i>Ipomoea batatas</i> (sweet potato)	4 000–10 000	0.50–0.75	Moderate input cost; starch hydrolysis and enzymes dominate OPEX; suitable for short-cycle tropical cultivation	[9, 10, 34, 35, 80]
<i>Zea mays</i> (maize)	3 500–5 000	0.45–0.70	High fertiliser and irrigation cost; large industrial scale in USA; feedstock accounts for >60% total cost	[89–91]
<i>Manihot esculenta</i> (cassava)	3 000–7 000	0.45–0.68	Low enzyme demand; cheaper rural labour; seasonal yield variability	[92, 113]
<i>Saccharum officinarum</i> (sugarcane)	5 000–8 000	0.40–0.60	High capital intensity; bagasse energy offset; water-intensive; best in humid tropics	[42, 89]
Lignocellulosic biomass (maize stover, switchgrass, bagasse residues)	2 500–4 000	0.80–1.10	High pretreatment and enzyme cost; emerging technology; potential long-term cost decline	[61, 88]
Molasses (sugar-processing by-product)	2 000–3 000	0.35–0.50	Low feedstock cost; limited scalability; dependent on sugar industry	[88, 91]
Oil Palm Trunk (OPT) Sap	9,500–10,300	~0.45–0.65 (est.)	Lignocellulosic sap, seasonal availability, used in Malaysia	[114, 115]

closely paralleling cassava and maize pathways but below the 25–30% observed for high-throughput sugarcane mills [42]. Nevertheless, the lower capital intensity and flexible scale improve accessibility for small- and medium-scale investors.

Environmentally, sweet potato's lifecycle GHG reduction (40–60% vs. gasoline) aligns with starch-based ethanol averages and substantially exceeds that of fossil fuels [89]. In semi-arid regions, its lower irrigation demand ($\sim 500\text{--}700\text{ mm cycle}^{-1}$) offers a decisive water-efficiency edge over sugarcane ($\sim 2\,000\text{ mm cycle}^{-1}$).

Comparing production routes, first-generation (starch/sugar) pathways, sweet potato, cassava, maize, and sugarcane, remain cost-competitive, whereas second-generation lignocellulosic ethanol is economically unfavourable at present but strategically vital for long-term decarbonisation. The transition to such advanced pathways will rely on reductions in enzyme cost (projected 30–40% decline by 2030) and improved biomass logistics [61].

From a policy perspective, sweet potato offers a balance between food security and bioenergy objectives. Unlike maize, it is less integrated into industrial food supply chains, reducing price-volatility risks. Where rural livelihoods are a concern, such as in southern Africa, Southeast Asia, and parts of Latin America, *I. batatas* cultivation for bioethanol can stimulate smallholder income without major land-use competition.

In economic terms, sweet-potato-based ethanol occupies a mid-range cost position: more expensive than molasses or sugarcane ethanol but potentially cheaper than maize or advanced lignocellulosic routes when produced at a moderate scale under tropical conditions. The trade-off lies in enzyme cost and feedstock logistics versus the social and environmental benefits of decentralised, low-input cultivation. With incremental efficiency improvements and favourable policy incentives (e.g., blending mandates, carbon-credit inclusion), *I. batatas* can evolve into a regionally competitive bioethanol feedstock complementing, rather than competing with, traditional crops.

Challenges and Limitations

Despite the promising agronomic and economic potential of sweet potato-based bioethanol in tropical countries, several challenges hinder its widespread adoption and long-term scalability. These limitations span across technical, financial, infrastructural, and institutional domains.

Feedstock Supply Chain Risks

The perishability of sweet potato tubers represents a critical vulnerability in the feedstock supply chain.

Post-harvest degradation begins within 7–10 days under ambient tropical conditions, leading to substantial starch loss and microbial contamination. This necessitates tightly coordinated harvesting and processing schedules or investment in on-site pre-processing infrastructure, such as drying, ensiling, or cold storage, which are often absent in smallholder-dominated landscapes. Fragmented land holdings, lack of cooperatives, and weak rural logistics further compound supply inconsistencies, making it difficult to sustain year-round feedstock availability at an industrial scale.

Advanced bioethanol production technologies, particularly those involving enzymatic hydrolysis, SSF reactors, and molecular sieving distillation, are capital-intensive and require skilled operation and maintenance. In many tropical regions, rural areas lack access to such technologies, and training deficits persist among local technicians. Consequently, many regions remain reliant on low-efficiency traditional distilleries, which suffer from low ethanol recovery, high energy input, and environmental non-compliance.

Establishing even small- to medium-scale biorefineries requires capital investments ranging from \$4–8 million, posing a formidable barrier in low-income countries. Limited access to affordable credit, coupled with currency depreciation and underdeveloped insurance markets, deters private sector engagement. Moreover, ethanol market prices exhibit significant volatility, influenced by global oil prices, policy incentives, and trade dynamics. Without long-term purchase agreements or stabilised blending mandates, investors face substantial revenue uncertainty.

Although sweet potato supports dual cropping in some tropical agroecologies, yields remain subject to seasonal rainfall variability, temperature fluctuations, and pest/disease outbreaks. In regions with pronounced dry seasons or erratic precipitation patterns, yields may fall below economic viability thresholds ($< 4,000\text{ L/ha}$) [96]. Furthermore, asynchronous planting across regions disrupts continuous feedstock supply, unless staggered planting calendars and aggregation models are effectively implemented.

The “food vs. fuel” tension remains salient. In food-insecure regions, diverting sweet potato tubers toward energy applications may exacerbate caloric deficits unless a clear demarcation is made between industrial and food-grade cultivars. Moreover, the expansion of bioethanol cropping onto fertile lands may drive land-use conflicts and social discontent unless policies enforce the use of marginal or degraded lands.

Many tropical countries lack cohesive biofuel strategies that align agricultural, energy, and environmental policies. Weak enforcement of blending mandates, absence of

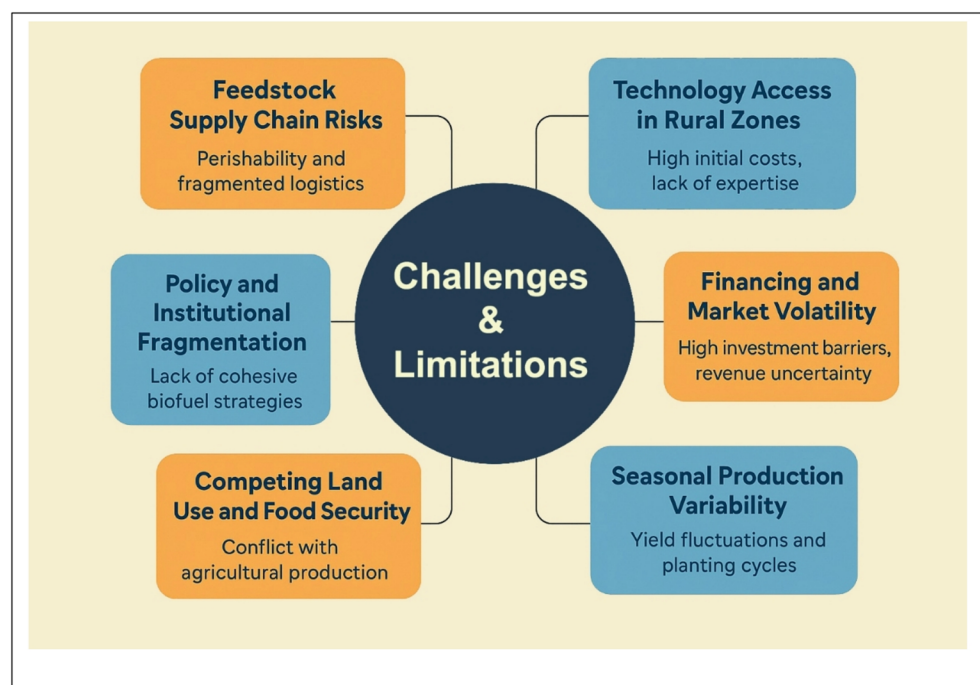
targeted subsidies, and bureaucratic delays in licensing and land access inhibit project initiation. Moreover, carbon credit frameworks often exclude small-scale bioethanol systems due to high transaction costs and complex verification protocols.

Gender and Social Equity Constraints

Although women play a major role in sweet potato cultivation, their inclusion in bioethanol value chains remains limited due to land tenure restrictions, unequal access to credit, and a lack of representation in cooperatives or PPP frameworks. Without deliberate inclusion mechanisms, bioethanol expansion may reinforce existing socio-economic disparities.

A schematic overview of the key systemic challenges affecting the scalability and sustainability of sweet potato-based bioethanol is given in Fig. 2. Six thematic areas are highlighted: supply chain risks, limited technological access in rural areas, financial volatility, seasonal production variability, competing land use pressures, and fragmented policy environments. In summary, the transition toward sweet potato-based bioethanol in tropical countries, while promising, demands systemic interventions. Addressing logistical bottlenecks, technology access gaps, policy incoherence, and social equity concerns is imperative for achieving economically viable, environmentally sustainable, and socially inclusive outcomes. These limitations should be viewed not merely as constraints but as areas for strategic innovation and targeted policy support.

Fig. 2 Challenges and limitations of bioethanol production from sweet potatoes in tropical countries



Conclusion

This review presents a comprehensive, context-sensitive evaluation of the economic, agronomic, environmental, and policy-related potential of producing bioethanol from sweet potatoes in tropical countries. Drawing from a systematic qualitative literature review and techno-economic modeling, the findings affirm that sweet potato is a highly promising, yet underutilised, feedstock for renewable liquid fuel generation in low to middle-income tropical economies. Its short growth cycle, drought tolerance, low input requirements, and high starch yield position it as a resilient and inclusive energy crop suited to smallholder farming systems.

From an agronomic standpoint, high-starch cultivars such as BRS Cuia and Xushu 18 can yield 4,500 to over 10,000 L of ethanol per hectare per year under dual-cropping systems. These yields not only rival cassava and maize but also approach those of sugarcane in favourable agroecological zones. The conversion process is technically feasible and increasingly efficient, especially with the adoption of enzymatic hydrolysis, SSF reactors, and co-product valorisation. These traits make the sweet potato particularly attractive in tropical regions with constrained water access and degraded lands.

Economically, the review reveals that feedstock and enzyme costs constitute the largest shares of production expenditure. Yet, under optimised conditions, LCOE of Ethanol estimates between \$0.50–\$0.75 per litre are competitive, particularly when co-products (e.g., animal feed, residual starch, biogas, and CO₂) are valorised. Financial viability improves markedly in systems that integrate

efficient logistics, stable market linkages, and policy support mechanisms such as feedstock subsidies and carbon credits. Break-even prices can be achieved at yields above 5,000 L/ha, with payback periods ranging from 3 to 6 years and IRRs exceeding 20% in high-yield, low-cost contexts.

However, the analysis also exposes several critical limitations. These include feedstock perishability, fragmented supply chains, limited rural access to advanced technology, seasonal yield variability, and significant capital investment barriers. Moreover, unresolved policy fragmentation, land tenure insecurity, and the persistent food-versus-fuel debate pose systemic challenges to scalability. While the use of marginal lands and dual-purpose cultivars can mitigate competition with food production, inclusive land-use planning and gender-sensitive program design remain essential for equitable outcomes.

The environmental and social dimensions offer additional promise. Lifecycle GHG emission reductions of up to 60% compared to gasoline can be achieved, particularly when cultivation relies on low-input methods and clean processing energy. Employment creation across the value chain, particularly in labour-intensive harvesting, pre-processing, and decentralised distillation, presents a pathway to rural income enhancement. Importantly, as women dominate sweet potato cultivation in many smallholder contexts, bioethanol strategies that integrate gender inclusion can magnify social co-benefits.

To operationalise the potential of sweet potato-based ethanol, tropical countries must develop coherent national biofuel strategies that integrate agrarian reform, investment facilitation, R&D support, and inclusive value chains. Incentivising smallholder participation through feed-in contracts, cooperative distilleries, and mobile processing units can help overcome logistical and financing barriers. Regional biofuel alliances and trade facilitation mechanisms (e.g., AfCFTA, ASEAN frameworks) offer additional levers for scalability. Ultimately, sweet potato ethanol can emerge as a keystone in the transition to climate-resilient, pro-poor, and diversified renewable energy portfolios across the tropics, provided it is supported by strong institutions, innovative financing, and inclusive policy design.

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