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A Review of Biomass in the Bioeconomy: Availability, Competing Uses and Obstacles

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Abstract

Considering resource depletion and population pressures, the demand for bio-based materials is set to rise, intensifying competition for biomass across sectors such as food, energy, construction, and industrial production. To ensure that food security is not compromised and environmental resources are not overexploited, a deeper understanding of biomass availability, utilisation, regenerative potential, and competing uses is essential for designing policies that balance economic development with sustainability objectives. This study reviews the availability and competing uses of biomass, and the obstacles to biomass utilization in Burundi, Costa Rica, Ghana, India, Namibia, South Africa, and Uganda. The findings illustrate how these factors shape the trajectory of national and regional bioeconomy development. While biomass is essential for developing a bioeconomy, its availability has not been adequately assessed. Reported biomass sources include agricultural residues, forests, aquatic resources, and municipal wastes, yet quantitative metrics and location-specific data remain limited. Competing uses of biomass range from energy production (firewood, charcoal, biofuels, bagasse gasification) and biofertilizers to livestock feed, biopharmaceuticals, and traditional applications. Weak aggregation and supply chains, inadequate policy incentives for sorting and processing, and insufficient data to guide investment were identified as key challenges. Biomass use should be expanded beyond traditional uses to include added value in clean cooking, reduction of plastic pollution, construction, improved bioinputs in food production and biopharmaceuticals. Efforts towards growing new and more biomass to meet the demand in the different economic sectors was found necessary. The findings underscore the need for (a) improved data availability on biomass quantity, characteristics, and uses; (b) coherent bioeconomy policies and incentives that promote both efficient use and the sustainable production of new biomass; and (c) strengthened regional and international cooperation to guide biomass conservation and utilisation. Such efforts are vital for achieving a sustainable bioeconomy that supports food security, poverty alleviation, biodiversity conservation, and climate mitigation.

Keywords: Africa, bioeconomy, biodiversity, biomass, Global South

JEL codes: O13, Q20, Q42, Q55, Q57

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1 Introduction

Considering resource depletion and growing population pressures, the use of bio-based materials is set to increase. This will lead to competition for biomass between the different sectors, not only food and non-food, but also between other sectors such as energy, construction or industrial production. To develop policies and strategies that ensure food security is not compromised, and environmental resources are not overexploited, it is important to deepen our understanding of biomass availability and its competing uses. These challenges are at the heart of the bioeconomy, an approach that seeks to balance economic development with the sustainable use of biological resources.

According to the International Advisory Council on Global Bioeconomy (IACGB, n.d.), a bioeconomy is the production, use, conservation, and regeneration of biological resources to provide sustainable solutions across all economic sectors, including information, products, processes, and services. Several countries are developing dedicated bioeconomy strategies that leverage biomass potential across key sectors such as agriculture, health, industry, and the environment. These strategies incorporate indigenous knowledge to drive economic growth, job creation, and sustainable development. They are aligned with the national development plans, the African Union Agenda 2063, which promotes prosperity based on inclusive growth and sustainable development, and the UN Sustainable Development Goals, which aspire for work and decent incomes; poverty reduction, hunger elimination; social security and protection; modern and liveable habitats, and basic quality services.

Assessing biomass availability, utilisation, regenerative potential, processing technologies, and supply chains is crucial as countries and regions develop their bioeconomies. Several studies show that countries and regions develop their bioeconomies based on the comparative advantage of their biomass potential (Allaire and Daviron, 2020; Wertz et al., 2022). However, as bioeconomies evolve, competing uses of biomass, particularly in rural areas, necessitate careful evaluation to support effective policy and investment choices. Therefore, biomass valorisation within a region or country should consider market dynamics, including demand and supply forces, as well as non-market values such as biodiversity, ecosystem services, and traditional uses, which can be challenging to quantify.

Biomass can include various sources, such as agricultural biomass like stems, stalks, leaves, husks, peelings, dungs, bones, scales, and shells rich in cellulose, hemicellulose, and lignin, lipids, soluble sugars, proteins, and pectin. Other biomass sources include algae, microorganisms, insects, indigenous herbs, and wild biomass harvested from various locations. Biomass can also be found in city or urban markets, restaurants, agro-industries, and household waste.

These biomass sources are refined into higher-value products for food production, pharmaceuticals, cosmetics, bioenergy, and other uses. Advances in biomass fuel technologies offer the opportunity to convert this waste into biofuels, transforming a challenge into a valuable resource. Marine biomass, particularly seaweed, presents further economic potential. It can create employment and generate income through various algae-based products, including fertiliser for agriculture, water purification, high-quality alginates used in thickening agents, carrageenans for dairy products, biodiesel production, and cosmetics and pharmaceuticals. Wood/ forest biomass energy is dominant in Sub Saharan Africa. Crops like cassava, sugarcane, oil palm, and jatropha can serve as feedstock for bioethanol and biodiesel production, further enhancing the country's biofuel capabilities.

While biomass holds potential as feedstock for sustainable bio-refineries, supporting bioenergy and bio-based products, its use requires balancing its availability and quality with the food security and nutrition needs of a growing population. Therefore, efficient management of biomass is crucial to addressing the competing demands of bioeconomy growth, energy generation, environmental sustainability, agricultural production responding to the needs of the population. Rural and urban households' heavy reliance on forest biomass for cooking and heating has significantly contributed to deforestation. Therefore, the deployment of efficient biomass technologies and the use of alternative solid biomass from sustainable sources such as crop residues and wood waste are necessary.

Moreover, the large quantities of municipal waste generated in most African cities pose serious environmental and health challenges, such as flooding and vector-borne diseases like malaria. Further, several socio-economic challenges persist, including poverty, unemployment, energy security, and land-use conflict. Addressing these issues is critical to realising the full potential of biomass utilisation and to ensuring that bioeconomy growth contributes effectively to sustainable development goals.

Therefore, the aim of this study was to assess the availability of biomass, its competitive uses, and the challenges it faces in the bioeconomy of African and other emerging economies. The goal was to analyse its potential integration into the bioeconomy and generate evidence that supports the implementation of bioeconomic proposals at the national and regional levels. Key research questions related to biomass in the bioeconomy include:

- What skills and infrastructure should countries possess to sustainably valorise their biomass?
- What is the role of governance in biomass production and use in the global south?
- How can public-private partnerships be harnessed to support bioeconomy transitions?
- How might countries optimise their agricultural biomass use while ensuring food security?
- What policy incentives could balance traditional biomass use with new competing biomass uses?
- How will the bioeconomy impact smallholder farmers' incomes?
- How could technology transfer (for biomass conversion) be made more efficient?

2 Methodology

Seven countries were selected for a study on biomass in the bioeconomy, with a focus on biomass availability, competing uses, and opportunities and challenges for its effective utilisation. The selected countries were Burundi, Costa Rica, Ghana, India, Namibia, South Africa, and Uganda. These countries, excluding Burundi, Costa Rica, and India, were chosen because they were featured in the Malabo-Montpellier Panel Report on Nature’s Solutions: Policy Innovations and Opportunities for Africa’s Bioeconomy (2022) as case studies of countries making efforts to advance their bioeconomies in accordance with their unique needs and priorities. Burundi, Costa Rica, and India were selected due to their recent initiatives to establish or implement bioeconomy strategies.

The methodology encompassed a comprehensive desk review of data sourced from secondary sources, including peer-reviewed published articles, institutional reports, and other grey literature. Data portals and repositories such as the Alliance of Agricultural Information and Documentation Services of the Americas (SIDALC), the Economic Commission for Latin America and the Caribbean (ECLAC), the South African BioEnergy Atlas, and the Bioeconomy South Africa Portal were used as sources of data for some of the countries. Several countries referenced reports of previous biomass, e.g., the Feasibility Study on the Status of the Biomaterials Industry in South Africa (Department of Science and Technology, 2016), which provides a valuable assessment of the challenges associated with competition for biomass sources. Other grey literature includes publicly available institutional reports of government ministries, departments, and agencies responsible for environmental, agricultural, forest, and energy sectors. Namibia, in particular, drew upon data from studies and extensive stakeholder consultations that informed the Namibian National Bioeconomy Strategy launched in 2024. This strategy was complemented by relevant national policies in the fields of agriculture, health, and industry.

In general, the literature reviewed was published between 2018 and 2024, with a focus on recent innovations and applications. Most of these publications were retrieved from search databases such as Google Scholar, Web of Science, PubMed, and Scopus. The review conducted a search using a search equation that incorporated key terms from the titles, abstracts, and keywords of the publications. Subsequently, the selected terms were filtered through database search engines and data repositories.

The review presented an overview of current research on biomass valorisation techniques, products, and potential applications for residues. Notably, countries such as Uganda and Ghana concentrated on agricultural residues derived from crops, and thus used keywords such as agricultural residues, lignocellulosic biomass, bioeconomy, rice husks, coffee husks, banana peels, cassava peels, cocoa, and maize cobs.

The country reviews were presented and discussed at a workshop held during the 2024 Global Bioeconomy Summit, which took place from 23-24 October 2024 in Nairobi, Kenya. The workshop brought together key country experts from Burundi, Costa Rica, Ghana, India, Kenya, Namibia, South Africa, and Uganda. Total in person attendance at the GBS was 569 from 57 countries. The workshop itself was attended by 50 in-person participants (24% of whom were women). Several additional individuals joined the proceedings online.

3 Country Case Studies

3.1 Burundi

The Burundi case study is mostly based on first-hand accounts, experiences and personal reflections of the Burundian co-author. In Burundi, various biomass types are used and contribute to the bioeconomy in three spheres: economic, human and biospheric. Wood-energy biomass remains dominant and is a hindrance to environmental protection through its contribution to deforestation and GHG emissions. The production of ecological briquettes, biogas and peat briquettes are alternative solutions to this environmental challenge, and public policy measures and concrete actions in favour of ecological transition are proving important. Existing initiatives in support of clean energy need to be encouraged if Burundi is to make a success of the ecological transition, and this will require coordinated action at every link in the biomass value chain, from production to the use of biomass products. To make efficient use of biomass, Burundi needs a synergy of interventions by the government, stakeholders and the development partners to address the problems of technology and funding for projects to exploit and develop the potential of biomass. Burundi needs a national bioeconomy strategy, which could help to stimulate the efficient exploitation and use of biomass, and more than half of these objectives (50%) of the Burundi Vision 2040-2060 are closely linked to the bioeconomy sector.

Biomass availability

Burundi has three main biomass resources that can be exploited: urban waste, for which biomass energy is mainly used to burn a resource or residue and produce electricity; peat, for which Burundi has estimated deposits of 600 million tonnes; and sugar cane waste, bagasse, which is used in a power plant at SOSUMO. Using bagasse, SOSUMO has a 2 x 2 MW cogeneration unit fuelled by bagasse (sugar cane residue), which operates throughout the sugar season. These types of biomass available in Burundi contribute to the bioeconomy in its economic sphere through the production of wealth (briquettes, electricity, marketable products), human (job creation) and biosphere (ecological fertilisers).

Competing uses for the biomass

a. Energy production

In Burundi, biomass is an important source of energy that can be used by households and towns and cities alike. The types of biomass used range from simple agricultural waste to elaborate forms of energy-producing biomass. In terms of energy production, peat, peat briquettes, ecological briquettes from waste recycling, biogas and bagasse from the residues of sugar cane are used.

The production of ecological charcoal from maize cobs, rice husks, coffee parchment, charcoal residues, palm trees and other agricultural residues contributes to the management of organic waste, the fight against deforestation and the creation of jobs and income. Three main organisations are involved in the recovery of agricultural waste and residues: Société Kaze Green Economy (KAGE), Coopérative pour l'Innovation et Entreprendre pour le Développement (COIEDE) and GREEN POWER CORPORATION. KAGE produced 1,497 tonnes of briquettes in 2020, 1,872 tonnes in 2021, 2,496 tonnes in 2022 and 3,744 tonnes in 2023. Biogas is used to generate electricity from biodegradable waste and refuse from sanitary blocks in secondary schools, military camps and other communities. At household level, biogas also uses cow dung. Using biogas saves money, as one m3 of biogas can replace 2.7 kg of wood, and schools using biogas recover 60% of their firewood purchase budget.

The use of biogas is also beneficial to the environment (employment) and the biosphere (ecological fertilisers).

b. Industrial utilization

In terms of industrial utilization of biomass, the Office du Thé du Burundi (OTB) is one of the largest consumers of firewood. A real industrial use of biomass can be seen at SOSUMO, where a cogeneration power plant using bagasse produces electricity to run SOSUMO's machinery throughout the 6-month season.

Other industrial uses of biomass include the fertilizer manufacturer Fertilisants Organo-Minéraux Industries (FOMI) and Burundi Cement Company BUCECO, which use peat to fuel their boilers; and restaurants and bakeries that use peat briquettes. In addition, FOMI uses cow dung in the manufacture of organo-mineral fertilisers. In addition, palm kernel oil from palm nuts is widely use.

c. Agricultural inputs and livestock feed

The use of biomass as an agricultural input is based on agroforestry banana plantations. Since colonial times, banana 'fallow' has been considered a soil conservation and restoration technique that has the dual advantage of being productive and totally endogenous. In addition, trials conducted by the Burundi Institute of Agronomic Sciences (ISABU) confirm that banana plantations have a significant economic impact on the farm and contribute to the preservation and development of organo-mineral soil fertility. Similarly, palm biomass is used as a fertiliser from the processing of liquid residues from palm oil production.

With farmer animal feed, the by-products of milling are used as feedstuffs for cattle and other livestock: rice bran is used as concentrated feed, particularly for hogs, palm oil processing residues are used to produce oilcake for cattle, and sugarcane residues (molasses) are used for cattle feed.

d. Other utilizations

In tandem with energy, industry and fertilisers, there are other uses for biomass, particularly palm kernel biomass. The long, thick leaf stalks are used in construction, basketry and agriculture (as bean stakes) and as firewood. In addition, the leaflets are used to make handmade brooms that are widely used in Burundi and exported to neighbouring countries, and the palm sap is used to make palm wine. In addition, the remains of the sugar cane (molasses) are used to feed livestock.

- *Kaze Green Economy (KAGE Ltd): An interesting case study that successfully transforms biomass in Burundi*

  Founded in 2017, KAGE is a social enterprise that aims to promote the green and circular economy in Burundi. KAGE is committed to playing an important role in preserving the environment and providing environmentally friendly products. Three products are already on the market: Ecological fuel as an alternative to firewood, KABIOF Makara: Ecological fuel as an alternative to charcoal, KABIOF Mbabura is an improved fireplace made from recycled metal waste, clay and ash. In terms of prospects, KAGE is planning a 'Gasification for power generation' project to exploit gasification technology at the KAGE plant, which will involve building and operating a gasification facility with a capacity of 120 tonnes per day of biomass. The plant will produce 600 tonnes of carbonised material that can be used as biochar or transformed into clean coal. The facility will also produce syngas, which will then be used to generate 4 MWe of electricity. The electricity produced will be used to power the plant and the surplus will be sold on the national grid. The projected impact is 600 tonnes of environmentally friendly fuel per month and 4 Megawatts of electricity production, 900 tonnes of waste per month will be recycled, 40 hectares of forest cover per month will be saved, and 70 permanent jobs will be created.

Obstacles to biomass utilization

a. Technical barriers

The technical barriers to the use of biomass differ according to the type of biomass and the consequences of use and/or the cost of production. In the case of biogas, installation costs are a technical barrier, as one m3 of functional biogas is equivalent to 1.5 million FBu, and a household must own at least three cows to have waste put into fermenters/digesters.

As far as peat is concerned, the main obstacle is the weakness of the technology, because burning peat in its raw state gives off a very large quantities of fumes (COPED, 2018) and the population has shunned this fuel because it gives off noxious, dense and nauseating fumes. Weak technology is also a technical barrier to waste recovery because private operators in this sector do not have enough resources to produce energy without causing damage to the environment: pollution and GHG emissions. Lack of technology is a technical barrier that reduces use because stock-outs affect production during the rainy season due to the lack of modern dryers, and briquettes take time to be usable.

b. Economic challenges

The economic challenges of using biomass are linked to access to tools and financing for projects to transform the various types of biomass. Young people involved in briquette manufacture are faced with the challenge of mobilising funding for the operation and acquisition of equipment for large-scale manufacture. Young people's projects and initiatives by micro, small and medium-sized enterprises to manufacture briquettes have been made possible thanks to support from development partners, including the UNDP, the ADB and the Netherlands Embassy.

Regarding the use of biogas, the economic challenges for households concern access to finance for equipment and installation: the cost of functional biogas is high for rural households: 1.5 million FBu for the installation of a m. In response to this challenge, the government can subsidise (as in the past) the biogas promoter with imported equipment and get involved in the rehabilitation of biogas plants that have deteriorated and become dysfunctional. By 2003, 10,000 m3 biogas plants had been installed in public establishments and households: 21 secondary schools, 6 military camps, 7 religious congregations, 1 prison, 12 livestock farms and 90 households.

The challenge of mobilising funding also applies to the use of peat, because of the Office National de la Tourbe (ONATOUR's) limited capacity to increase production and improve the technology for manufacturing briquettes that do not generate smoke or foul odours. This is a major challenge, because ONATOUR needs to produce a large quantity of carbonised briquettes for Burundian households, whereas peat used to be used only in military camps.

c. Policy and regulatory issues

Policy and regulatory issues relating to the use of biomass can be found in planning documents because the Burundi government and its development partners recognise Burundi's strengths in making better use of biomass and residues through improved production and use techniques. For biomass energy, the revised National Development Plan (PND Burundi) 2018-2027 recognises the importance of biomass for increasing energy production in Burundi and plans to (i) identify 11 biogas sites to be rehabilitated, and (ii) rehabilitate biogas digesters in public institutions with a view to improving the production and management capacities of the energy sector.

In addition, the Environmental, Agricultural and Livestock Policy Guidance Document (2020) provides for the installation of family biogas plants, the recovery of energy from waste, the use of improved stoves and briquettes made from organic waste, and the use of peat. With this in mind, since 2022, the government, via the Agence Burundaise de l'Electrification Rurale (ABER) of the ministry responsible for energy, has been working to revive the use of biogas: more than 15 engineers have been trained in the development of biogas, and this agency will be responsible for popularising alternative energies.

In addition, ONATOUR has a project for a carbonised briquette manufacturing plant, with a production capacity of 140 tonnes of briquettes per day, which will replace charcoal. The manufacture of peat briquettes is an important environmental protection issue, as ten thousand tonnes of briquettes can preserve 80 hectares of forest.

Regulatory issues relating to the use of biomass are governed by Law No. 1/09 of 25 May 2021 amending the Environmental Code of the Republic of Burundi. This Code lays the fundamental rules for managing the environment and protecting it against all forms of degradation to safeguard and enhance the rational use of natural resources, combat various forms of pollution and nuisance and thus improve living conditions for human beings, while respecting the balance of ecosystems.

For Burundi, a bioeconomy strategy could help to stimulate the efficient exploitation and use of biomass. The importance of developing a national bioeconomy strategy was one of the priorities raised at the high-level political dialogue on bioeconomy in Burundi and East Africa in October 2023.

The development of a national bioeconomy strategy for Burundi is perfectly in line with the country's Vision Burundi Emerging Country 2040 and Developed Country 2060. The vision encompasses five essential pillars to achieve the ultimate goals of improving living conditions and well-being and reducing inequalities: state commitment, economic efficiency, social equity, sustainable ecology and heritage, and partnerships and heritage, and successful partnerships. To make this vision of emergence by 2040, Burundi has drawn up a global roadmap composed of 21 strategic objectives spread across these five pillars, and more than half of these objectives are closely linked to the bioeconomy sector. This means that the national bioeconomy strategy would play a vital role in the nation's progress through the Burundi Vision 2040-2060.

d. Social and cultural factors

There are no social and cultural factors hindering the use of briquettes except for peat. Households base their decision on the idea that peat briquettes cause rapid wear and tear on cooking pots, and that they are unpleasant because of the considerable quantity of smoke, which contains CO_2. Furthermore, peat is not very well known among the public. If there were significant demand, ONATOUR would produce large quantities of up to 20,000 to 30,000 tonnes of peat per year, compared with 10,000 to 15,000 tonnes (in 2021).

e. Environmental concerns

Environmental concerns about the use of biomass are linked to the effects of the use of wood fuel on deforestation. Biomass fuelwood, charcoal and plant waste account for 94.06% of energy balances, compared with 1.65% for petroleum products, 4.27% for electricity (Ministry of Agriculture, 2022) and, to a lesser extent, other forms of energy (solar, biogas, candles, batteries, etc.).

Wood energy therefore remains the most widely consumed fuel in Burundi, and the use of biomass resources is a factor in deforestation and encroachment on protected parks. In Burundi, the residential sub-sector (households) is the biggest GHG emitter due to the use of biomass (wood and charcoal), which increases from one year to the next because of continued population growth.

Conclusion

The biomass in the bioeconomy in Burundi focuses on green briquettes, biogas, bagasse and agroforestry banana. All types of biomass are used and contribute to the bioeconomy in its three spheres: economic, human and biosphere. However, wood-energy biomass remains dominant and is an obstacle to environmental protection in terms of the effects of deforestation and GHG emissions. Efficient use of biomass, therefore, requires a synergy of actions by the government, stakeholders and the PADs to address the problems of equipment, technology and funding for projects to exploit and develop Burundi's biomass potential.

3.2 Costa Rica

Costa Rica has established itself as a regional reference in bioeconomy by strategically integrating this approach into its political agenda through the National Bioeconomy Strategy 2020-2030 and other policies like the National Circular Economy Strategy and National Decarbonization Plan. Additionally, it has favorable resources and conditions to generate large quantities of biomass that can drive the development of this approach. Value chains with the highest production of residual biomass are found within the agricultural subsector. This waste holds great potential to produce bioenergy and biofuels, as well as their capacity to generate added value in industries such as pharmaceuticals, food, and cosmetics. However, the development of these opportunities is constrained by a lack of adequate infrastructure and limited coordination among public and private actors. While initiatives like the National Bioeconomy Strategy 2020-2030 have fostered interest in waste valorisation, greater efforts in research, infrastructure, and public policies are still needed. Various barriers such as deficiencies in governance, lack of financing, waste management systems, and the absence of integrated policies and actors in the development of the bioeconomy at the national level should be addressed. Improving infrastructure for biomass valorisation, strengthening governance, and promoting education about the benefits of bioeconomy to foster a circular economy is recommended.

Availability of harvested and residual biomass

Figure 1 shows the harvested and residual biomass production in 2023 for analysed value chains. On average, 1,369,577.5 tons of harvested biomass are produced, generating approximately 712,898.2 tons of residues per year. Coffee, with the largest cultivated area in the country (93,697 ha), generated 461,067 tons of berries in 2023, of which 50% resulted in residues such as pulp and mucilage during the processing stage (Zeledón et al., 2024; Mora-Villalobos et al., 2023).

Oil palm is another significant crop in the country, cultivated on 75,365 ha (Zeledón et al., 2024). In 2023, it produced 1,219,406 tons of fresh fruit, generating 1,630,145 tons of residues, which exceeds the harvested quantity by 131.5% (Mora-Villalobos et al., 2023). Likewise, Costa Rica is also an important producer of bananas with 46,636 ha cultivated. In 2023, 2,532,934 tons were harvested, mainly for export. The residues from this crop, such as peels and rejected fruits, reached 886,526.9 tons (Zeledón et al., 2024).

In the case of pineapples, Costa Rica stands as the world's largest exporter, with nearly 70% market share (Rabinovich et al., 2024) and 40,000 ha cultivated (Zeledón et al., 2024). In terms of production, 2,937,807 tons of pineapples were harvested in 2023. Of this amount, 1,468,903.5 tons correspond to waste generated during industrial processing, such as peels, pulp, and cores (Eixenberger et al., 2024; Janissen & Huynh, 2018).

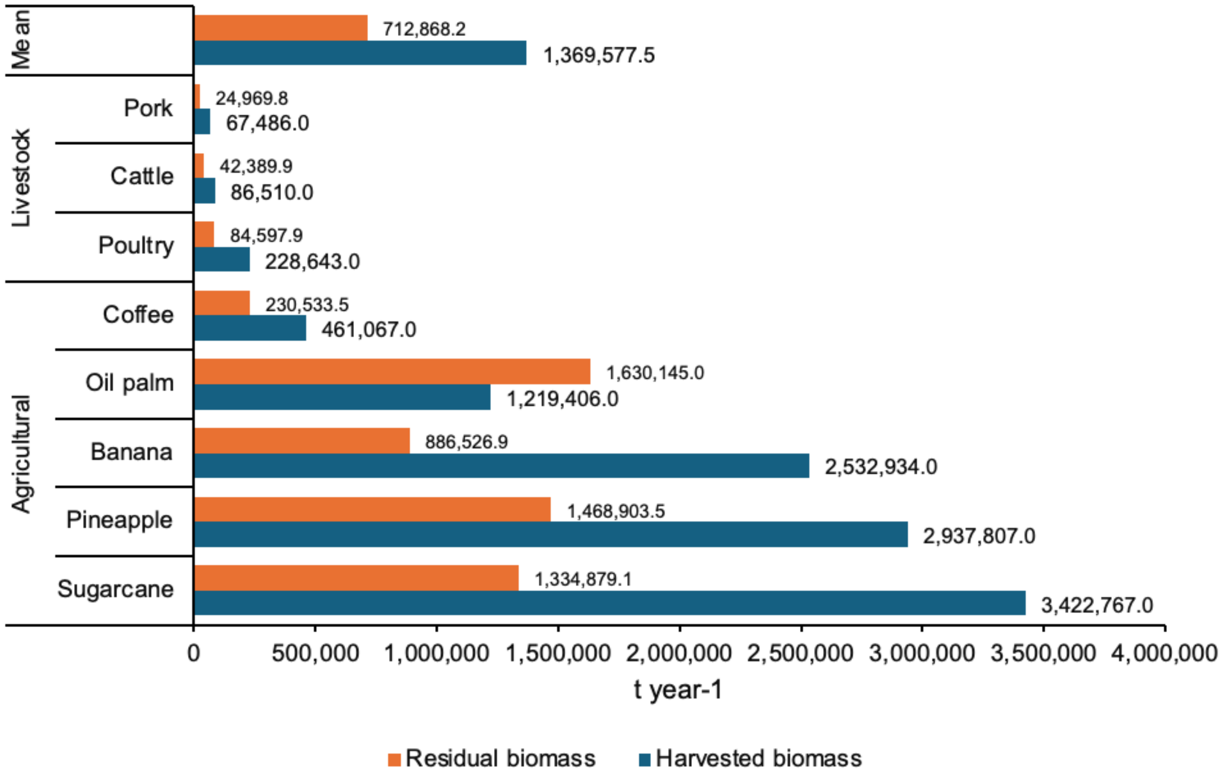


Figure 1: Production of harvested and residual biomass of selected value chains in 2023
Source: Zeledón et al., 2024; Eixenberger et al., 2024; Mora-Villalobos et al., 2023; Leiva et al., 2018

Sugarcane is the third most important crop in the country. In 2023, it produced 3,422,767 tons of biomass, generating 1,334,879.1 tons of residues in the form of bagasse and dry leaves (Zeledón et al., 2024; Chandel et al., 2012). Finally, in the livestock sector, harvested biomass is based on the number of animals slaughtered, and egg and meat production, which generates residues such as blood and bones, although in significantly smaller quantities[1] compared to crops (<84,597.9 tons per year) (Leiva et al., 2018).

Competitive uses of biomass

a. *Temporal and subsectoral distribution of the consulted studies*

Figure 2 shows that scientific output related to bioeconomy in agricultural value chains in Costa Rica is relatively low, with 2 to 7 publications per year. The increase observed in 2021 and 2022 is likely attributed to the establishment of the National Bioeconomy Strategy in 2020, which encouraged independent research initiatives in certain crops such as pineapple, coffee, and sugarcane. However, a notable reduction in the number of publications is observed in 2023, which seems to continue into the current year.

Although Costa Rica stands out as one of the countries with the highest number of scientific output on bioeconomy in Central America, it is necessary to promote more research in this field. Consequently, fostering more publications would contribute to innovation and allow for better utilization of the opportunities offered by biomass residues. This way, its potential in various applications, sectors, and industries can be explored more effectively.

[1] The results of the literature review did not allow the identification of the amount of waste in terms of animal excrement and urine.

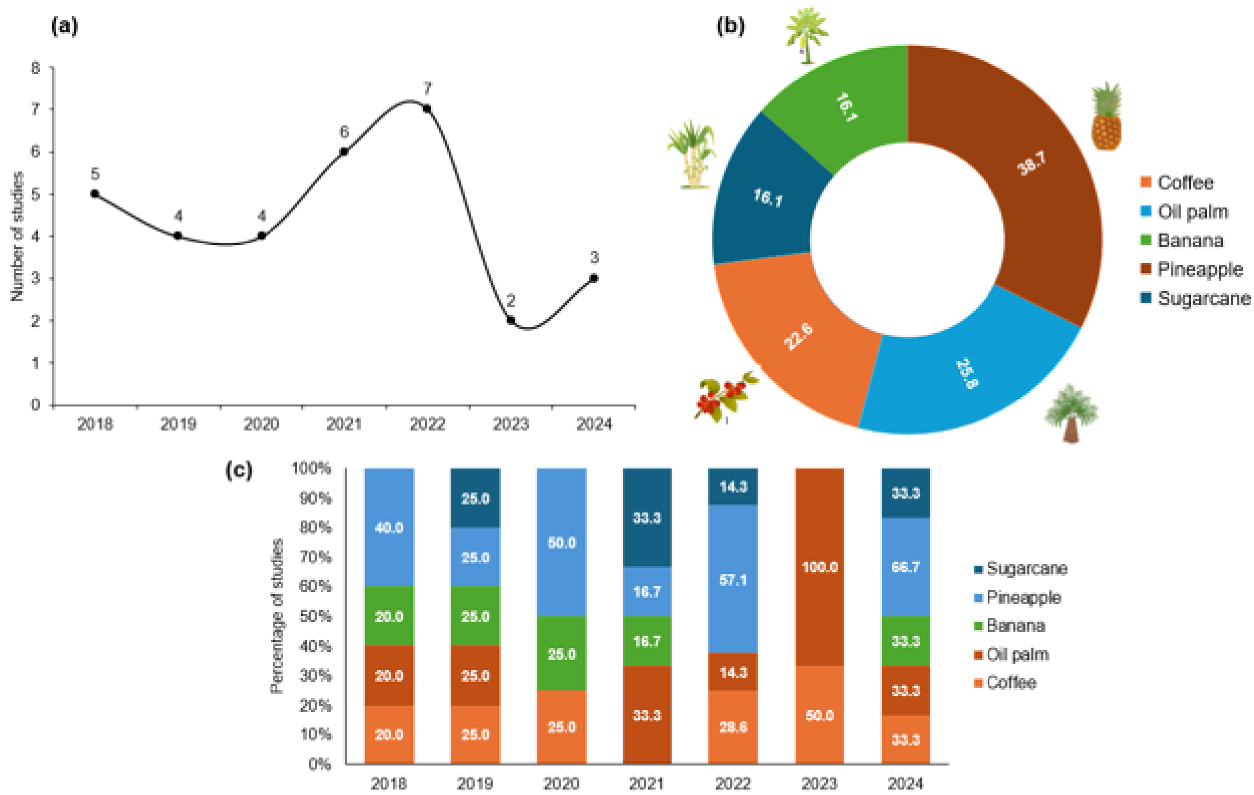


Figure 2: (a) Number of studies addressing the competitive uses of biomass from the selected sectors from a bioeconomy perspective during the period 2018-2024 in Costa Rica. (b) Percentage of studies linked to agricultural sectors. (c) Percentage of studies linked to each sector during the period 2018-2024

Source: Authors' illustration

When analyzing the percentage of total studies associated with the five agricultural sectors, it is observed that pineapple accounts for 38.7% of the publications, followed by oil palm (25.8%) and coffee (22.6%), while banana and sugarcane each represent 16.1% (Figure 2b). Although in 2024 there is a diversification in research topics, with more studies on African palm, banana, and sugarcane, the highest interest in the national research agenda is the valorization of pineapple waste, which concentrates the largest number of publications this year (Figure 1Figure 2c).

As the world's leading exporter of this fruit, it is logical that scientific output in the agricultural sector of Costa Rica is consistently focused on this crop. However, diversifying research into other crops is crucial. This could help identify new opportunities and consolidate existing applications, contributing to the development and strengthening of the national bioeconomy.

b. Number of uses identified by value chain and industry

Figure 3 reveals that the number of prospective uses of residual biomass in Costa Rica exceeds current uses. The biomass from pineapple and sugarcane has the highest number of applications, suggesting extensive utilization of this waste. Additionally, pineapple has 9 prospective uses, indicating a high potential for future innovations.

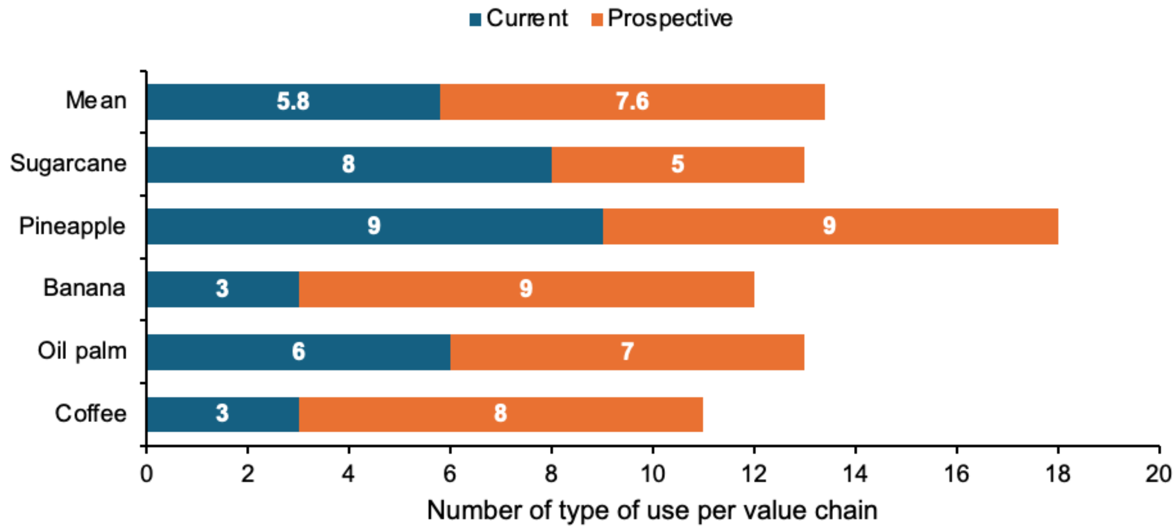


Figure 3: Number of types of use (current and prospective) identified by value chain

Source: Authors' illustration

While bananas and coffee currently have 3 main applications, their residual biomass offers significant potential with 8 and 9 prospective uses, respectively. In contrast, oil palm shows a balance between its current and future applications, reflecting steady development in its possible uses. Therefore, this analysis suggests that oil palm has made more sustained progress in leveraging its residual biomass.

When analysing biomass uses by industry, it is observed that the highest concentration of applications is found in energy and fuel production, with 15 current uses identified. Although these results suggest that the scope for developing new uses seems limited at the national level, many of the existing uses are still in the experimental phase, indicating considerable potential for commercial expansion, especially in the production of bioethanol, biodiesel, and biogas. Conversely, the food and environmental industries do not have direct uses for residual biomass; however, they present 12 and 5 prospective applications, respectively, indicating significant potential for the future, particularly in generating food ingredients and environmental remediation (Figure 4).

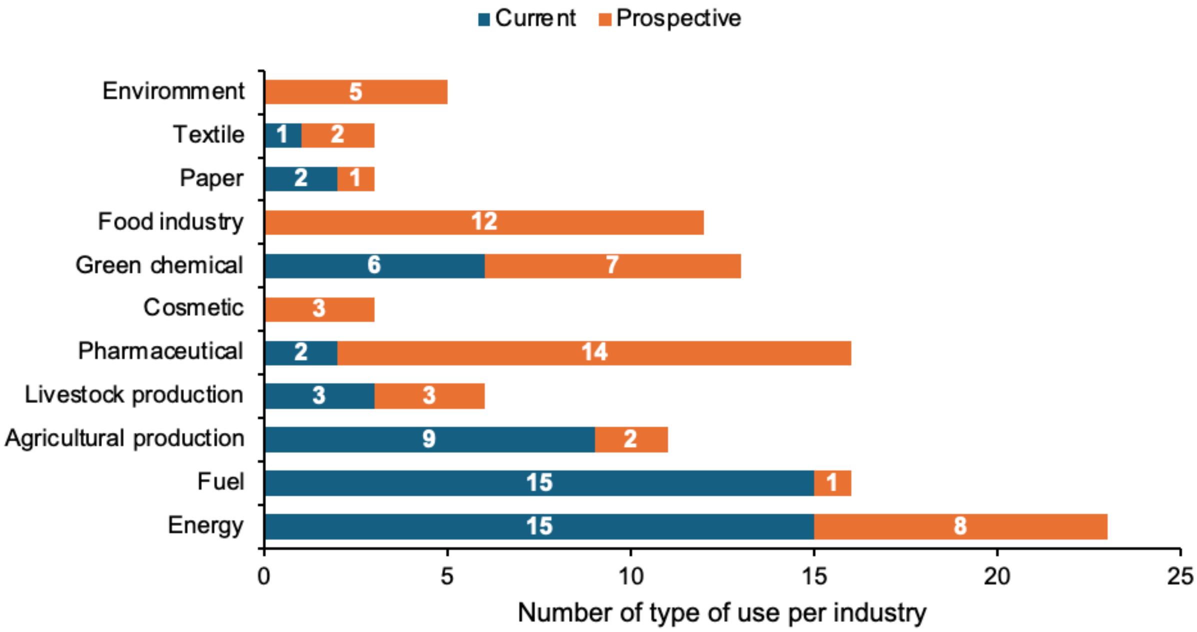


Figure 4: Number of types of use (current and prospective) identified by industry

Source: Authors' illustration

The pharmaceutical and green chemistry industries stand out for the number of identified uses. In particular, the pharmaceutical industry has only two current applications but possesses 13 potential uses focused on obtaining bioactive compounds, such as chlorogenic acid from coffee, banana, and pineapple waste (Chaves-Ulate & Esquivel-Rodríguez, 2019; Mora-Villalobos et al., 2023; Hernández-Chaverri et al., 2018). On the other hand, in green chemistry, there is a balance between current and future uses, however, many applications are still in the experimental phase or are part of bio-enterprises (Díaz, 2019), suggesting a high potential for expansion (Figure 4).

c. Current and prospective uses of residual biomass

The review of scientific literature allowed for the identification of three main applications for bananas in Costa Rica: natural composting to return nutrients to the soil, biochar production, and nanocellulose extraction (Redondo-Gómez et al., 2020; Köberl et al., 2018).

Pineapple, on the other hand, has the most uses, including the production of bioethanol, dietary fiber with antioxidant activity, nanocellulose, biogas, and the extraction of bioactive compounds such as gallic acid and chlorogenic acid, making it a crop with multiple industrial applications (Corrales-Ureña et al., 2018; Da Luz Castro et al., 2024; Hernández-Chaverri et al., 2018; Chen et al., 2020; Liao et al., 2022; Araya-Chavarría et al., 2022).

Coffee has various applications, notably the production of biochar, pellets, and organic fertilizers from treated pulp (Chatterjee et al., 2020; Infante-Amate & Picado, 2018; Mora-Villalobos et al., 2023). Meanwhile, oil palm waste is used to generate biochar, biodiesel, pellets and substrates for plants. In Costa Rica, the most common use of this waste is its combustion for electricity and steam production in oil extraction plants (Chatterjee et al., 2020; Infante-Amate & Picado, 2018; Madrigal-Valverde et al., 2018; Myzabella et al., 2019; Castellanos-Navarrete et al., 2021; Charpentier & Méndez, 2021).

Sugarcane offers a wide range of current applications, from biodiesel, bioethanol, and biochar production to the creation of fiber for paper, composite materials, and byproducts like cachaza and molasses used in the livestock industry. Currently, biochar generated from bagasse is the most efficient application for meeting energy demands in sugar processing plants (Lagos-Burbano & Castro-Rincón, 2019; Méndez et al., 2021; Aguilera et al., 2022; Eixenberger et al., 2024).

Regarding prospective uses, this analysis identified that the pineapple and banana chains have the highest number of potential applications. For pineapple biomass, waste can be used for animal feed, dietary fiber production, bromelain extraction, and biosurfactants which have applications in the food, pharmaceutical, and environmental industries (Amores-Monge et al., 2022; Da Luz Castro et al., 2024). Other uses include biobutanol production, vanillin, wood adhesives, and for the development of effluents for crop irrigation (Bolaños Picado et al., 2022; Da Luz Castro et al., 2024; Hernández-Chaverri et al., 2018; Rigg-Aguilar et al., 2020).

Banana waste has significant potential for the extraction of phenolic compounds, pectin, and antimicrobial compounds. It can also be used for obtaining enzymes, food additives and fibers, as well as for producing flour, biogas, and bioplastics. Finally, it has applications as a sorbent for pollutants (Arias-Roblero et al., 2021; Barz et al., 2019; Redondo-Gómez et al., 2020; Eixenberger et al., 2024).

For coffee, its waste is primarily projected for the development of pharmaceutical, cosmetic, and food products through the extraction of bioactive agents such as chlorogenic acid and vanillin. Furthermore, coffee residual biomass is a promising raw material for bioethanol production, biological fertilizers, and animal feed. Lastly, it is also employed in the development of growth media for microorganisms, with applications in the agricultural and environmental industries (Mora-Villalobos et al., 2023; Cárdenas et al., 2022; Eixenberger et al., 2024; Chaves-Ulate & Esquivel-Rodríguez, 2019).

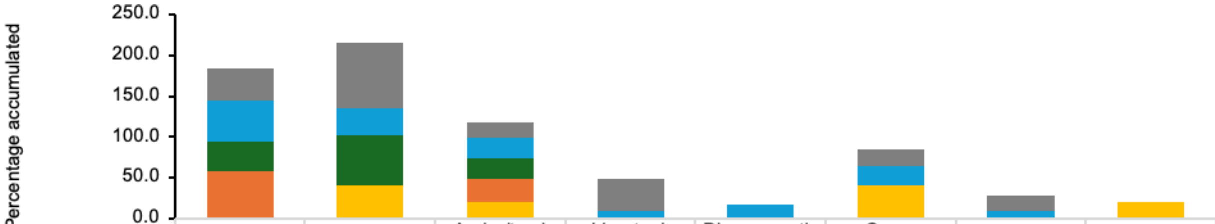
In terms of oil palm, the residues from this crop offer opportunities for renewable energy generation and biofuels, such as biodiesel and bioethanol. These residues can be used to produce methane and biobutanol, which are additional energy sources. Additionally, they are also source of by-products like glycerol, which has applications in industries such as green chemistry and pharmaceuticals, as well as in the production of nanocellulose and sorbents (Aragón et al., 2024; Charpentier Alfaro & Méndez Arias, 2021; Mora-Villalobos et al., 2023; Vargas Mesén et al., 2023).

Lastly, sugarcane waste can be utilized for lignin extraction, sorbents, glycerol, and single-cell proteins, with significant industrial and environmental applications. The potential of bagasse for ethanol production and byproducts like vinasse, which can be used as an additive in cement and asphalt manufacturing, is also noteworthy. Consequently, these residues offer various valorisation opportunities across different sectors (Rojas Álvarez et al., 2021; Eixenberger et al., 2024).

d. *Current and prospective industries associated to residual biomass from selected value chains*

Figure 5 shows that agricultural waste from the five selected chains is already being utilized in eight industries, with greater emphasis on energy and biofuels production. In particular, coffee biomass has the highest share in the energy industry, followed by pineapple, sugarcane, and oil palm. Additionally, sugarcane and oil palm are predominant in the biofuels industry.

This high utilization of waste in these industries is due to growing interest in renewable energy sources and biofuels, supported by regional policies. On the other hand, the significant number of applications in the agricultural industry is noteworthy, primarily involving the use of waste to improve crop fertilization and restore nutrients to the soil. Lastly, the figure indicates that pineapple, oil palm, and sugarcane waste also have current applications in the pharmaceutical, green chemistry, and paper industries, albeit to a lesser extent.

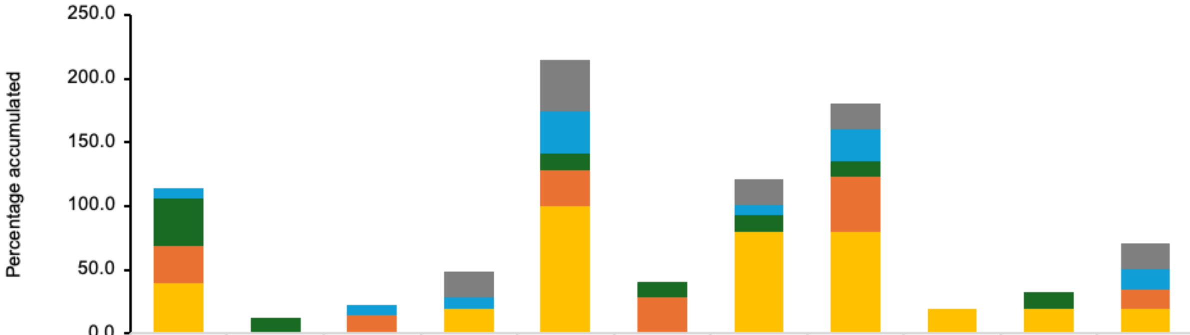


	Energy	Fuel	Agricultural production	Livestock production	Pharmaceutical	Green chemistry	Paper	Textile
Sugarcane	40.0	80.0	20.0	40.0	0.0	20.0	20.0	0.0
Pineapple	50.0	33.3	25.0	8.3	16.7	25.0	8.3	0.0
Oil palm	37.5	62.5	25.0	0.0	0.0	0.0	0.0	0.0
Coffee	57.1	0.0	28.6	0.0	0.0	0.0	0.0	0.0
Banana	0.0	40.0	20.0	0.0	0.0	40.0	0.0	20.0

Figure 5: Percentage of current industries associated with the residual biomass of the 5 agricultural value chains based on the number of identified studies

Source: Authors' illustration

Figure 6 reveals that the pharmaceutical, food, and green chemistry industries represent the main prospective opportunities for revalorizing residual biomass, especially in the value chains of banana, sugarcane, and coffee. While many crops already have applications in the energy industry, banana stands out for its potential in biogas production. Additionally, new opportunities are identified in the cosmetic and environmental industries due to the high concentration of bioactive compounds and polyphenolic in pineapple, banana, and coffee waste.



	Energy	Fuel	Agricultural production	Livestock production	Pharmaceutical	Cosmetic	Green chemistry	Food industry	Paper	Textil	Envirommment
Sugarcane	0.0	0.0	0.0	20.0	40.0	0.0	20.0	20.0	0.0	0.0	20.0
Pineappel	8.3	0.0	8.3	8.3	33.3	0.0	8.3	25.0	0.0	0.0	16.7
Oil palm	37.5	12.5	0.0	0.0	12.5	12.5	12.5	12.5	0.0	12.5	0.0
Coffee	28.6	0.0	14.3	0.0	28.6	28.6	0.0	42.9	0.0	0.0	14.3
Banana	40.0	0.0	0.0	20.0	100.0	0.0	80.0	80.0	20.0	20.0	20.0

Figure 6: Percentage of prospective or potential industries associated with the residual biomass of the 5 agricultural value chains based on the number of identified studies

Source: Authors' illustration

Banana is the crop with the highest projected uses across all analysed industries. Therefore, these results highlight its potential to diversify the current uses of its biomass, due to the large amount of waste it generates. Consequently, its biomass could be key to the development of the bioeconomy through innovative applications in various sectors and industries.

Conclusions

The value chains of pineapple, coffee, and banana have many current and prospective applications. Pineapple stands out with the highest number of both current and future applications, indicating its relevance to the national bioeconomy. However, while most of this biomass has current applications in biofuel production, such as biogas and bioethanol, these are mostly in experimental or small-scale phases. This suggests that there is still room to scale these initiatives to a commercial level.

Residual biomass offers opportunities for the development of new industries in Costa Rica, such as cosmetics, environmental and green chemistry, which could diversify the country's economy. However, persistent significant limitations exist in terms of infrastructure for large-scale biomass valorisation. As a result, this situation prevents scientific and technological innovations from being translated into industrial applications that have a substantial economic impact.

There is a need to strengthen governance, develop funding mechanisms, improve coordination among public and private actors, and establish biomass collection, mapping, and inventory systems to advance the bioeconomy. In particular, the lack of integrated policies, adequate incentives, and coordination mechanisms among different sectors has limited the development of initiatives. Therefore, it is crucial to improve collaboration and align the strategies of the involved sectors to foster sustainable growth in Costa Rica's bioeconomy.

3.3 Ghana

Besides the ocean, lagoons, and freshwater resources, Ghana is endowed with arable land and tropical rainforest that have the potential to generate significant amounts of biomass for national development. The biomass potential includes fuels from wood and wood waste, fuel from crop residues, biofuel from organic waste, bioethanol and biodiesel from crops; fuel from municipal solid waste; food and industrial raw materials from marine biomass; and non-timber forest products, including medical plants from the tropical rainforest.

Biofuel potentials of Ghana

Biomass comprises all renewable organic materials, such as agricultural products and byproducts derived from living organisms. It can be used as feedstock to generate power, heat, and steam (Duku et al., 2011), and the characteristics of any specific biomass (e.g., moisture content, calorific value, fixed carbon, volatiles, and ash content) determine its suitability as a potential feedstock for biofuel production. Ghana’s current land area is about 23.85 million hectares, of which 62% is classified as agricultural land. With an estimated population growth rate of 2% and high and rising poverty rates, especially among the rural population (39.5%) (Tsiboe et al., 2023), biomass fuel development presents an opportunity for energy sustainability.

Biofuels present viable substitutes for fossil fuels, effectively mitigating the negative externalities associated with climate change and global warming due to fossil fuel usage while also enhancing energy security (Iddrisu & Bhattacharyya, 2014). In Ghana, the energy landscape reveals a composition of 15% electricity, 37.4% biomass, and 47% petroleum products in terms of final energy demand. Like many low-income households in developing countries, many Ghanaian households experience energy poverty, relying heavily on traditional biomass sources such as wood fuel, crop residues, animal dung, and charcoal. Over 70% of the population is estimated to cook using biomass fuels, totalling approximately 20 million tonnes annually. Given the slow progress in expanding access to clean fuels and technologies, household demand for biomass is expected to rise alongside Ghana's population growth.

Over the past century, Ghana has experienced an annual deforestation rate of 2%, resulting in the loss of 85% of its forest cover, with biomass reliance accounting for 60% of this deforestation. Projections indicate that if current trends continue, Ghana’s forest cover may deplete entirely by 2050. In response to these challenges, Ghana implemented a National Energy Policy (NEP) in 2010, which aims to promote the production and utilisation of efficient biomass technologies for cooking. Key initiatives within the NEP include:

- Supporting the sustained regeneration of woody biomass resources through legislation, fiscal incentives, and attractive pricing structures.
- Promoting the establishment of dedicated woodlots for wood fuel production.
- Encouraging the production and use of improved and more efficient biomass utilisation technologies.
- Advocating for the use of alternative fuels, such as Liquefied Petroleum Gas (LPG), as substitutes for fuelwood and charcoal by addressing the institutional and market constraints that limit LPG access in Ghana.
- Ensuring that pricing reflects market forces, with taxes and levies on wood fuels regulated by relevant national agencies or local authorities as necessary.

Despite these efforts, the adoption of these technologies has been sluggish, and the biomass markets primarily function in an informal capacity. For instance, as of 2017, less than one-third of households that relied on biomass fuel as their primary cooking source used improved cook stoves, and only 22.3% utilised LPG. Between 2010 and 2019, access to clean technology and fuels increased by merely 1%.

As numerous households continue to depend on biomass as a preferred energy source for cooking and heating, many countries across the continent are seeking to valorise their diverse biomass resources. This report focuses on Ghana's biomass production potential, examining the broader scope of forest products, crop residues, energy crops, and urban and animal wastes.

a. *Wood and Wood Waste Biomass*

As previously noted, traditionally, biomass is the primary source of energy (biofuel) for households in Ghana owing to several factors, including the type and quantity of food cooked, the taste of food, and the availability of other fuel types, relative prices of fuel types among other socio-economic factors (Akpalu et al., 2011; Karimu et al., 2016). Wood biomass, primarily firewood and charcoal, accounts for around 38% of the country's energy consumption. Of the over 3 million people engaged in charcoal production, 65% are women (Mombu and Ohemeng, 2008). The reliance on wood biomass has resulted in high deforestation rates, land degradation, and related health problems from smoke inhalation (Duku et al., 2011). Households primarily use low-cost technologies that are less energy efficient. Ghana's wood fuel consumption, which was 20.7 million in 2005, increased by 45% (to 37.8 million) in 2010 (see Figure 7). As of 2022, it rose to 52.8 million, signifying an annual increase of 6% from 2010 to 2022. Charcoal consumption reflects a similar trend, increasing from approximately 1.6 million to 2.3 million metric tons (i.e., a 30% increase) between 2010 and 2022 (Figure 8). These values exceeded Ghana's energy master plan projections of 1.6 and 1.7 million metric tons for 2020 and 2025.

Moreover, after studying more than fifteen agro-processing sites, Ghana's Ministry of Energy under GEDAP found that solid biomass waste consisting of sawmills and agro-residues can generate between 600 kWp and 5 MWp in each of the more than 15 sites researched (Ghana Renewable Master Plan, 2019). To stem the high wood fuel biomass deforestation and the associated carbon emissions, energy-efficient technologies must be promoted by formulating meaningful policies. To this end, the nation's EMP recommends, among other things, using dedicated woodlots (e.g., eucalyptus) for solid biomass energy, capacity building in solid biomass technologies, using less variable biomass conversion technologies, and empowering women entrepreneurs within the biomass energy space. Beginning in 2009, a Norwegian company called African Plantations for Sustainable Development (APSD) secured 42,000 hectares of land for eucalyptus plantation to feed a biomass power plant. The plant, which was supposed to be established in 2021, had an installed capacity of 60 megawatts, requiring an annual logs supply of 600,000 m3, equivalent to 22,000 ha of eucalyptus plantation. The company's long-term plan is to generate 600 megawatts, translating 180,000 hectares of the plantation.

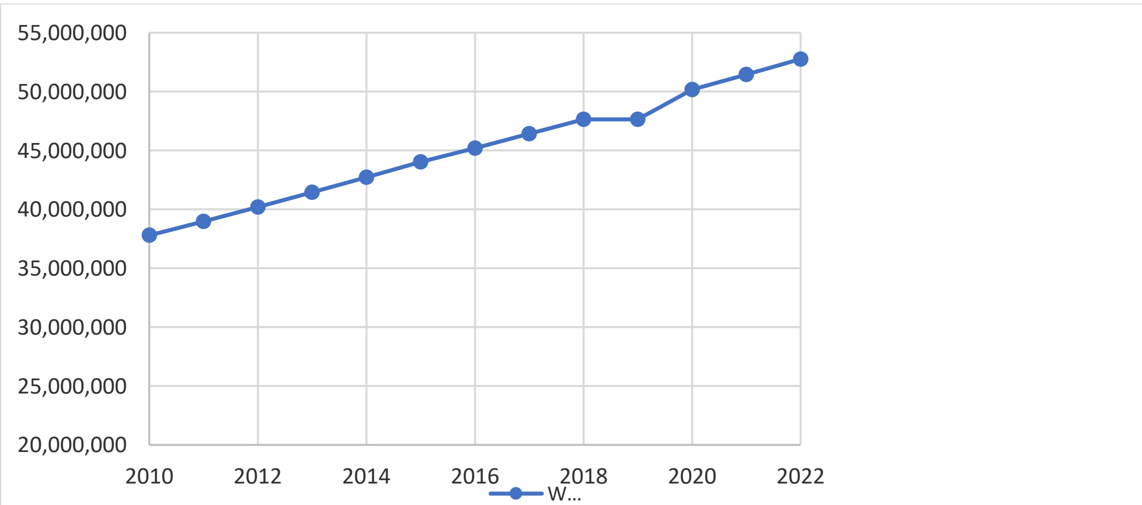


Figure 7: Consumption of Wood Fuel in Ghana (2010 – 2022)

Source: FAOSTAT (2024)

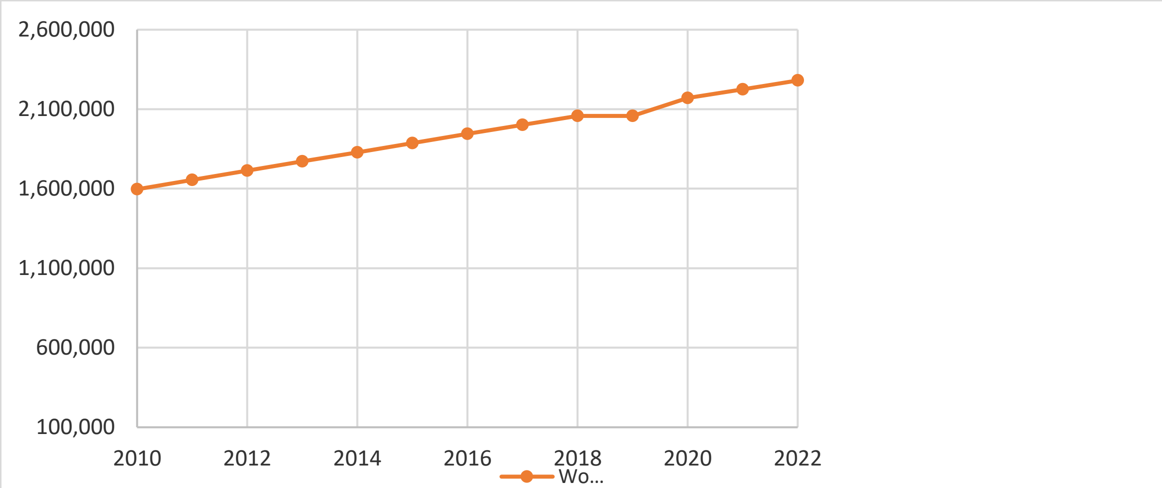


Figure 8: Consumption of Wood Charcoal in Ghana (2010 – 2022)

Source: FAOSTAT (2024)

b. Energy crops in Ghana

Ghana cultivates various energy crops, including woody and perennial crops, that can generate substantial feedstock for biofuel production (Duku et al., 2011). Notable crops include maize, millet, palm oil, rice, sorghum, coconut, coffee, cocoa, and sugarcane. According to the data in Table 1, 3.06 million hectares (i.e., 21% of Ghana's agricultural land) were devoted to cultivating these crops in 2020, with cocoa accounting for more than half (56%) of the total area. Among these crops, sorghum exhibits the highest residue-to-product ratio of 2.62.

Table 1: Energy Crop Production in Ghana 2023/2024

Crop	**Area Cultivated (2020/ha)**	**Output (10^3 Tons) 2023/2024**	**Residue Type**	**Residue to Product Ratio (RPR)**	**Moisture Content**	**Residue (10^3 tons)**
Maize	523,530	3,619	Stalk	1.5	15	5428.5
Millet	200,000	244	Stalk	3	15	732
Palm Oil	350,000	300	EFB	0.25	60	75
Rice	175,000	1,009	Straw	1.5	15	1513.5
Sorghum	24,600	439	Stalk	2.62	15	1150.2
Coconut	55,000	414	Shell	0.6	10	248.4
Coffee	17,000	461	Husk	2.1	15	968.1
Cocoa	1,700,000	656	Pods, husk	1	15	656
Sugarcane	15,000	157	Bagasse	0.3	75	47.1

Source: FAOSTAT (2024), MoFA (2021), Scarlat et al. (2010) and Lal (2005)

In terms of energy output (heating values), in 2023, maize stack contributed about 74.1 million megajoules (MJ) to biomass energy. This is followed by rice straw, which generated 2.0 million MJ. Collectively, the nine crops produced a total of 138 million MJ of energy at low heating values (see Figure 9). Between 2008 and 2023, maize production increased from 1.10 million tons to 3.6 million tons (FAOSTAT, 2008, 2023; Duku et al., 2011).

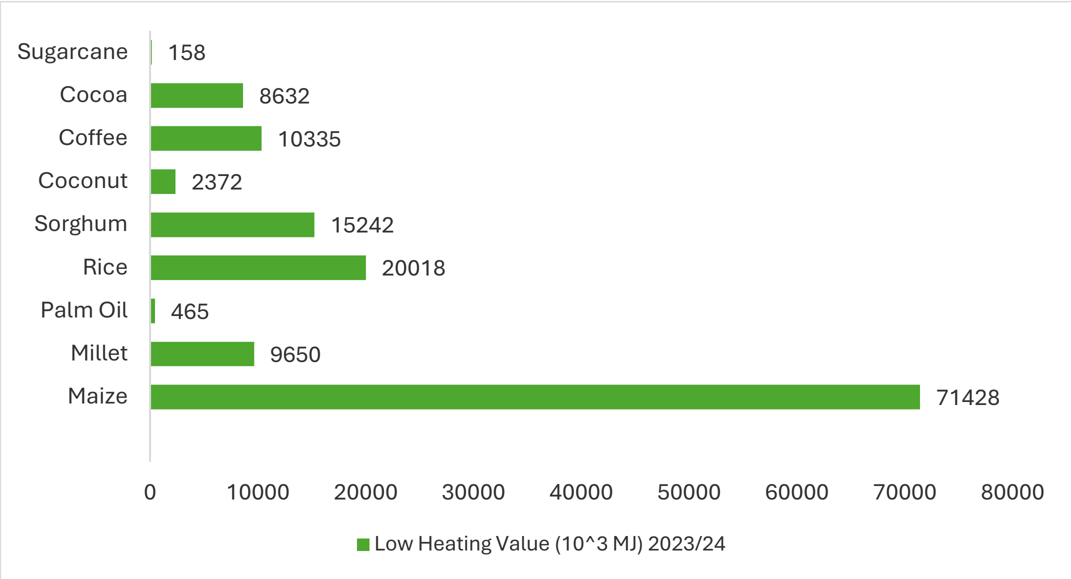


Figure 9: Heating Values of Crop Residues

Source: FAOSTAT (2024), MoFA (2021), Jenkins (1993), Demirbaş (2001), Scarlat et al. (2010)

In addition to energy derived from crop residues, some crops cultivated in Ghana serve as feedstocks for ethanol and biodiesel production (Ahiataku-Togobo and Ofosu-Ahenkorah, 2009; Duku et al., 2011). Ethanol can be produced from maize, sugarcane, sorghum, and cassava, while crops such as jatropha, oil palm, coconut, and other oilseed crops are viable sources of biodiesel. The specific characteristics of biomass, including moisture content, calorific value, fixed carbon, volatiles, and ash content, significantly influence its suitability as a potential feedstock for biofuel production.

Despite the focus on single-oil biodiesel production, there has been limited research on integrating diverse feedstocks, which could enhance energy self-reliance and reduce production costs (Nouadjep et al., 2019). Regarding national initiatives, the Ghana Oil Palm Development Company (GOPDC) manages 22,500 hectares of oil palm plantations, yielding approximately 210,000 tons of oil annually. A biomass-fired cogeneration plant at the facility generates about 2.5 megawatts of power using palm fruit fibre and kernel shells. Furthermore, the company produces biogas for processing oil palm, which conserves 615,000 litres of diesel annually for the nation (Ghana Renewable Energy Plan, 2019).

c. Municipal solid waste

Inadequate management of municipal solid waste has significant environmental and health impacts. Poor waste disposal due to insufficient infrastructure, technical inefficiencies, and lack of funding can lead to clogged drains, contribute to flooding, and create stagnant water that serves as breeding grounds for mosquitoes (Babayemi and Dauda, 2009). Ghana’s solid waste is 61% organics, 14% plastics, 5% paper, 1% leather and rubber, and 1% textiles (Miezah et al., 2015).

Recent technological advancements have increased Ghana's energy generation potential from municipal solid waste, primarily from organic materials such as food waste and agricultural residues

(Williams et al., 2023; Afrane et al., 2022). As of 2024, the country generates over 16,000 tonnes of municipal waste daily, equating to 0.47kg of waste per person. According to Ghana’s Renewable Energy Master Plan, waste-to-energy technologies are projected to generate 122 megawatts of power by 2030, representing a 123% increase over 2023 levels. Municipal solid waste is expected to account for 59% of Ghana’s renewable energy target by 2030. Additionally, technologies such as anaerobic digestion, incineration, and landfill gas recovery could provide an extra 784.04 megawatts of installed capacity by 2028 (Darmey, 2023).

Despite these potential benefits, challenges remain, including poor enforcement of waste management policies, financial constraints, and a lack of public education (Lissah et al., 2021). Currently, only 60-70% of waste generated in urban areas is collected, with lower rates in rural areas. Promoting decentralised waste management initiatives and engaging stakeholders in these processes can enhance the efficiency of waste collection and recycling (Oduro-Appiah et al., 2019).

d. Marine biomass potentials

Ghana, recognized as a fishing nation, sees its capture fisheries sector contribute approximately US$1 billion annually to the national economy (MoFAD, 2022). This sector employs 20% of the active labor force and provides 60% of the nation's animal protein requirements. Despite having numerous lakes and rivers, marine landings account for about 90% of total fish capture production. Ghana boasts a coastline of approximately 538 km and a marine area of 225,000 km², with artisanal marine fishery contributing around 70% of total catches. This sector predominantly lands small pelagic species—such as anchovy, mackerel, and sardines—considered the ‘people fish’ due to their vital role as a food source for the Ghanaian population. However, open-access management has led to overcapacity in fishing (too many canoes), resulting in biological overfishing, decreased earnings, and significant deterioration of livelihoods in fishing communities. Seaweed cultivation and algae harvesting serve as supplementary livelihood options for these coastal communities.

Ghana is home to approximately 200 algae species, making it the richest seaweed flora in Tropical West Africa. All three groups of seaweed, i.e., the green (Chlorophyta), the brown (Phaeophyta) and the red (Rhodophyta) colour-producing seaweeds, are found in Ghana. The nation’s rocky shores provide suitable, stable substratum conducive to substantial seaweed growth, hence the high species diversity (Anderson et al., 2012). About 60% of the algae are intertidal, while the remainder are subtidal (John and Lawson, 1997). The abundance and species diversity are dependent on environmental conditions such as nutrients, wave action and substratum (Thakur et al., 2008; Kang et al., 2011; Petsut et al., 2012; Akron et al., 2021). For instance, periods characterized by high nutrient levels, low temperatures, and low salinity correlate positively with seaweed abundance (Akron et al., 2021), indicating that greater seaweed harvests are likely during the major upwelling season from July to October.

In addition to serving as primary benthic producers in marine ecosystems (Petsut et al., 2012), seaweeds play a crucial role in carbon sequestration. They are rich in carbohydrates, proteins, micro- and macronutrients, vitamins, natural omega-3 fatty acids, lipids, growth hormones, and dietary fiber. Consequently, they are essential food sources for both humans and animals (Kılınç et al., 2013; Delaney et al., 2016; FAO, 2018; Akron et al., 2021). Traditionally, brown seaweed has been used primarily as fertilizer to enhance the productivity of fruit, flower crops, and vegetables. In modern applications, brown seaweed is used in the production of high-quality alginates, which generate thick aqueous solutions. Red seaweed is known for producing carrageenans used in dairy products such as ice cream, milk chocolates, and cheese, as well as in various non-food industrial applications like pharmaceuticals, cosmetics, and oil drilling. Research has demonstrated that incorporating a small quantity of Asparagopsis, a red seaweed, into ruminant livestock feed can significantly reduce enteric methane emissions (UNEP, 2023). Bioproducts from both red and brown seaweeds are also used in biofuel production.

Furthermore, green algae contribute to oxygen levels in aquatic environments through photosynthesis, with industrial applications that include biodiesel production due to their high lipid content, as well as nutritional supplements, wastewater treatment, and the production of cosmetics and pharmaceuticals. The diverse applications of seaweeds and their associated economic benefits open new market opportunities for coastal communities, thereby supporting local industries and enhancing exports (UNEP, 2023).

e. Medical plant biomass

An estimated 35-40% of primary medicines used for disease treatment are derived from plants (WHO, 2013). The rising global demand for herbal medicine prompted the World Health Organisation (WHO) to develop its Traditional Medicine Strategy 2014–2023, which promotes integrating traditional and complementary medicine into universal healthcare. By 2029, the global market for herbal medicinal products is expected to reach USD 177.65 billion, with an anticipated value of US$5 trillion by 2050 (Singh et al., 2014).

Ghana is home to approximately 3,600 plant species, with 60-70% of the population relying on plant-based medicine for healthcare (Minta et al., 2022).[2] The integration of traditional medicine into the healthcare system began in 2012 to improve the quality, safety, and efficiency of herbal medicine delivery. In 2010, 951 tonnes of crude herbal medicines worth US$7.8 million were traded in Ghana's herbal markets (van Andel et al., 2012).

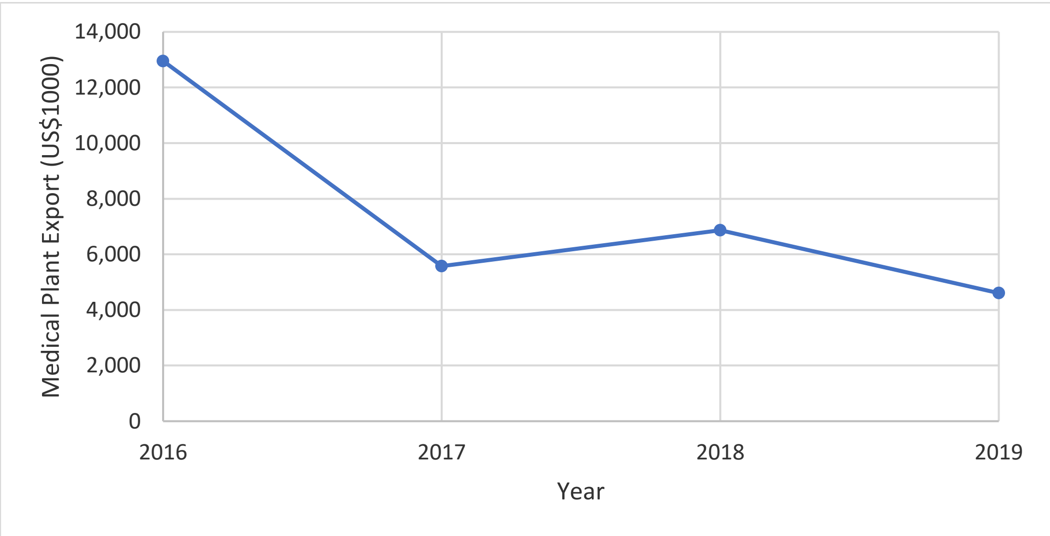


Figure 10: Medical Plant Export from Ghana (2016 – 2019)

Source: Ghana Export Promotion Authority (GEPA), 2020

As the global herbal industry continues to grow, Ghana stands to benefit significantly from exporting medicinal plants, medical, and pharmaceutical products, as well as from domestic revenue generation and employment creation. According to the United Nations Conference on Trade and Development (UNCTAD, n.d.), Ghana exported US$1.3 million worth of medical and pharmaceutical products in 2022, a 36% increase from the previous year. However, revenues from the export of medicinal plants have declined, falling from US$13 million in 2016 to US$4.6 million in 2019. The main export markets are China (42%), Switzerland (32%), and Spain (15%).

[2] https://www.cbd.int/countries/profile?country=gh

Conclusion

Like many countries, Ghana faces the dual challenges of rising energy demand and ensuring environmental sustainability. Biomass, as a renewable energy source, has the potential to contribute significantly to the country's energy needs while reducing its reliance on fossil fuels. In addition to fuel biomass, the nation is endowed with marine and non-timber forest resources that could generate significant social and economic benefits. This section explored Ghana's biomass potential by examining various biomass resources, including wood, agricultural residues, energy crops, municipal solid waste, marine biomass, and medicinal plants. It also assessed the current state of biomass use in Ghana and the prospects for expanding biofuel production as a pathway to energy security, reduced carbon emissions, and socio-economic development. The analysis demonstrates that with suitable investments and policy incentives, Ghana can sustainably harness its abundant biomass resources to meet future energy needs, raise revenue and provide employment opportunities.

3.4 India

India's bioeconomy is a significant driver of economic growth, contributing to the country's ambition of achieving a trillion-dollar economy. In *2023*, India's bioeconomy was at *USD 151 billion (4% of GDP)* and estimated to be *USD 300 billion* by *2030***.** Key sectors of India's Bioeconomy are *BioIndustrial***,** *BioPharma***,** *BioAgri*, and *BioIT and Research Services* (Figure 11). The government is actively promoting a circular economy through initiatives such as the *BioE3 Policy (Biotechnology for Economy, Environment, and Employment)*[3], *Ethanol Blended Petrol (EBP) Programme*, and the "Lifestyle for the Environment (LiFE)" campaign (Global Bio-India, 2024). India's bioeconomy is projected to nearly double, a cumulative growth of 98.7%, between 2023 and 2030, equivalent to a compound annual growth rate (CAGR) of roughly 10.2%.

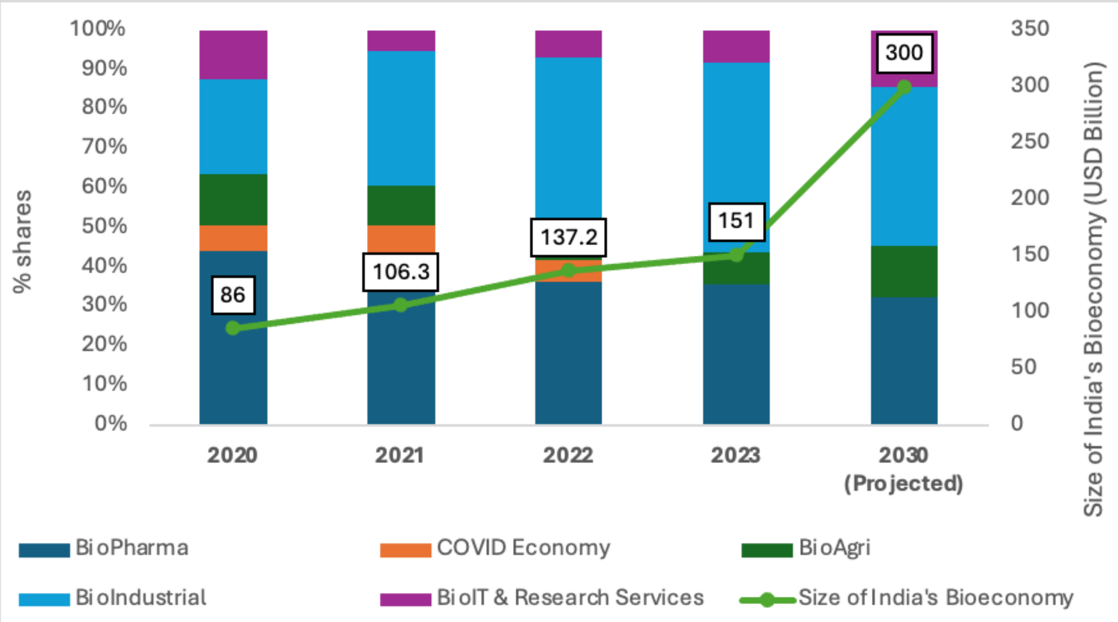


Figure 11: Size of Bioeconomy in India: Sub-sectoral Analysis

Source: Birac, 2024

Agricultural biomass availability for bioeconomy applications

The demand for agricultural biomass in the bioeconomy sector is expected to grow in coming years. This includes applications in bioenergy, biofertilizers, biochemicals, and biodegradable packaging, among others. Agricultural biomass, derived from crop residues, animal and poultry litter, and other agricultural by-products, presents a vast potential to support this shift. To meet the growing demand, it is critical to understand the types of agricultural biomass available, their current competing uses (such as animal feed, composting, etc.), and how they can be strategically leveraged to maximize their contribution to bioeconomy applications without compromising food security or other essential uses.

Key biomass crops- supply, demand, and competing uses

a. Crop biomass

The data on key crop residues in India (Table 2) reveals a significant amount of biomass that can be harnessed for bioeconomy applications. In 2023, sugarcane, maize, cotton, and rice generate a combined total of around 500 metric tons (MT) of biomass in the form of bagasse, molasses, straw, husk, stover, and other by-products. These residues present untapped potential for the bioeconomy.

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[3] The six pillars of BioE3 policy are 1. Bio-based chemicals and enzymes; 2. Functional foods and Smart proteins; 3. Precision biotherapeutics; 4. Climate resilient agriculture; 5. Carbon capture and its utilisation; 6. Futuristic marine and space research.

For instance, sugarcane, a leading biomass generator, produces by-products like bagasse (135.9 million metric tonnes (MMT), molasses (22.7 MMT), and press mud (22.7 MMT). Currently, 38% of this biomass is considered surplus and can be used for bioenergy, paper production, and bioethanol industries (Venkatraman et al., 2021). With projected production set to rise to 600 MMT by 2047, the surplus available from sugarcane is expected to increase, further enhancing its contribution to the bioeconomy. Similarly, maize and rice, which generate stover, cobs, straw, and husk, also hold significant bioeconomy potential. Maize generated around 67.8 MMT of biomass in 2023, with 30% of this available as surplus for bioeconomy applications, such as bioethanol and biogas. The projected biomass increases to 144 MMT (doubling) by 2050 is interesting to note. Rice, whose residues (straw, husk and bran) generate the highest total biomass among these crops at 245.3 MMT in 2023, offers a surplus of 73.6 MMT that can be directed towards bioenergy and biodegradable packaging with straw alone contributing 206.7 MMT of this total.

As seen in Table 2, the growth projections indicate a steady rise in crop production and biomass availability by 2047. For instance, the surplus biomass from sugarcane alone is expected to reach 91.2 MMT, while rice could offer 82.2 MMT of surplus biomass. These growing figures highlight the increasing potential for using agricultural residues in bioeconomy sectors. However, competing uses must also be considered. Many crop residues are currently used for animal feed, soil amendment, and fuel, which can limit their availability for bioeconomy applications. Efficient management and technological innovation will be key to optimizing the utilization of surplus biomass without disrupting existing uses, thus ensuring a sustainable supply for the emerging bioeconomy.

Table 2: India's Biomass production and projected supply

Crop	**Production in MMT (2023)**	**Total Biomass Generated (MMT)**	**Surplus Bioeconom y Potential MMT**	**Projected Production in MMT (2047)**	**Projected biomass MMT (2047)**	**Projected surplus biomass MMT (2047)**
Sugarcane	453.16	181.3	68.9	600	240	91.2
Maize	37.67	67.8	20.3	80	144	43.4
Cotton	5.5	5.5	2.5	6.8	6.8	3.06
Rice	137.83	245.3	73.6	154	274.12	82.2

Source: Agricultural Statistics at a glance, 2022 and Venkatraman et al., 2021

Note: Projections for Rice, Maize, and Sugarcane for 2047 are based on the NITI Aayog (2024) Working Group Report on Crop Husbandry, Agriculture Inputs, Demand and Supply, applying the annual production growth rates reported therein 1.58%, 3.71%, and 1% respectively observed over 2011-12 to 2019-20 (a pre-pandemic reference period) and assumed constant through 2047. For cotton, an annual growth rate of 0.89% is assumed through 2047, consistent with the observed trend in the said period. The growth rate is assumed to be constant for upto 2047. Biomass generated per kg for Sugarcane- Bagasse: 0.3 kg, Molasses: 0.05 kg, Press Mud: 0.05 kg; Maize-Stover: 1.5 kg, Cobs: 0.3 kg; Cotton- Hulls: 0.15 kg, Seeds: 0.35 kg, Stalks: 0.5 kg and Rice-Straw: 1.5 kg, Husk: 0.2 kg, Bran: 0.08 kg. Surplus biomass availability in per cent: Sugarcane 38%, Maize and Rice is 30%, Cotton is 45%.

India generates approximately 696.38 MMT of crop biomass residues annually, with cereals like rice, wheat, and maize contributing 364.27 MMT (Table 3). Sugarcane and horticultural crops like coconut and banana also produce significant residues. Of this, 209.69 MMT are surplus and available for bioenergy production, with cereals and sugarcane accounting for about 75% of the surplus, offering significant potential for bioenergy applications (Venkatraman et al., 2021).

Table 3: Potential scope of biomass in bioeconomy

Crop	Gross Biomass Potential (MT)	Surplus Biomass Potential (MT)	Competing Uses	Surplus Availability	Bioeconomy Applications
Rice	156.9	46.9	Animal feed, cooking fuel, bedding material	30%	Bioethanol, bioenergy, bioplastics, compost production
Wheat	149.1	48.7	Animal feed, soil mulching	33%	Bioenergy, biochar, biocomposite materials
Maize	43.2	12.8	Livestock feed	30%	Biogas production, bioethanol, bio-based chemicals
Sugarcane	119.3	44.9	Sugar industry, Molasses for alcohol, bagasse for power generation	38%	Bioethanol, bioplastics, biodegradable packaging
Cotton	28.6	12.7	Paper, textile industry	45%	Bioenergy, biocomposite materials, biofertilizers
Jute and Mesta	3.2	0.9	Textile, packaging materials	28%	Biodegradable packaging, composting
Coconut	52.7	21.4	Fuel, coir products, animal feed	41%	Biocomposite materials, bioenergy, natural fibers for textiles
Banana	68.9	27.6	Animal feed, pulp for paper	40%	Bioenergy, biodegradable packaging, bioplastics

Source: Adapted from Venkatraman et al., 2021

India generates around 611 MMT of agricultural field residues annually, with 158 MMT (25%) classified as surplus and currently underutilized, making them available for bio-based industrial applications (Cardoen et al., 2015). Yield improvements, especially in crops like maize, could significantly increase residue production, potentially by up to five times. Major surplus sources include sugarcane bagasse (41 MT/year), paddy straw (28 MT/year), wheat straw (21 MT/year), and cotton stalks (19 MT/year). Thus, studies by Venkatraman et al., (2021) and Cardoen et al., (2015) highlight the vast untapped potential of India's agricultural biomass for bioenergy and other bioeconomy sectors. Given these surpluses, it's crucial to assess the forecasted demand for India's bioeconomy through 2030 and beyond.

b. *Livestock and poultry biomass*

Livestock biomass, mainly in the form of manure, is a valuable source of organic matter for bioenergy, especially biogas production. In India, there are around 192.5 million cattle and 109.85 million buffaloes, with a total livestock population of 535.8 million and poultry at 851.8 million (NDDB, 2023). These animals produce significant amounts of dung, with each adult cattle generating 10-15 kg of manure daily (Gupta et al., 2016). Assuming an average of 12 kg/day, cattle and buffaloes together contribute around 1,100 million tonnes (MMT) of manure annually. Additionally, India produces about 4.9 MMT of poultry litter each year, primarily from broiler production (Sharma et al., 2022).

Competing uses of livestock and poultry biomass

In India, livestock manure and poultry litter serve multiple purposes, primarily as organic fertilizers due to their rich nutrient content (N, P, K). Cattle dung cakes are also used as fuel in rural households, particularly in states like Uttar Pradesh and Bihar. Additionally, manure is often composted to improve soil fertility. However, a significant portion, around 30-40% of cattle and buffalo manure, remains underutilized, representing an opportunity for biogas production—around 330-440 MMT annually. With advancements in anaerobic digestion technology, even partially composted or stored manure can be used in biogas plants. Poultry litter, with its high nitrogen content, offers around 1-2 MMT for energy production, but its lower bulk poses challenges for large-scale application (Sharma et al., 2022).

a. Forecast for 2030 and beyond

Optimistic estimates (Table 4) predict that the bioeconomy will reach USD 330.7 billion (India Bioeconomy Report (BIRAC, 2023)). This rapid growth reflects a 12% CAGR, denoting India's bioeconomy scope. This expansion will be fuelled by key segments, including biofuels, bio services, therapeutics, with bioethanol alone projected to contribute USD 20 billion by 2030.

Table 4: Bioeconomy projections for 2022-23 in USD billion (optimistic estimate)

Sector	**2022**	**2023**	**2024**	**2025**	**2026**	**2027**	**2028**	**2029**	**2030**
Bioservices	9.3	11.2	13.6	16.4	19.9	24	29	35.1	42.4
Bioagri	11.5	13.4	15.6	18.2	21.2	24.8	28.9	33.7	39.3
Bioindustrial	59	64.6	70.6	77.3	84.5	92.5	101.1	110.6	121
Biomedical	57.3	63.4	70.1	77.5	85.6	94.7	104.7	115.8	128
Total	**137.1**	**152.6**	**169.9**	**189.4**	**211.2**	**236**	**263.7**	**295.2**	**330.7**

Source: Birac, 2023

b. BioIndustry- bioethanol and potable and industrial alcohol

India is the world's third-largest producer and consumer of ethanol (BIRAC, 2024). The bioethanol sector has expanded rapidly, driven by the Government of India's Ethanol Blended Petrol (EBP) Programme. Notably, India achieved the milestone of 20% ethanol blending in petrol in 2025, five years ahead of the original 2030 target under the National Policy on Biofuels, reflecting the rapid scale-up of domestic ethanol production. Building on this success, the government is now exploring higher blending levels to further strengthen energy security and reduce fossil fuel imports. In India, ethanol production is mainly done using sugarcane as feedstock. To meet the rising demand, the Government has progressively widened the basket of approved feedstocks to include sugarcane juice, B-heavy molasses, sugar syrup, maize, damaged food grains and surplus rice from the Food Corporation of India (FCI). These are also called First-Generation (1G) Feedstocks.

While this diversification has strengthened feedstock availability, it also raises important questions regarding the optimal allocation of agricultural resources between food, feed and fuel, particularly in a country where food security, fiscal sustainability and natural resource conservation remain major policy priorities. On one hand, sugarcane is a highly water-intensive crop and largely irrigated crop in India. On the other hand, diverting rice into fuel addresses the symptom of excess public stocks rather than the structural policy distortions that created those surpluses in the first place. India's large rice stocks are primarily the outcome of open-ended MSP procurement, generous procurement bonuses in some states, and highly subsidised electricity and fertilisers that continue to incentivise water-intensive paddy cultivation in regions such as Punjab and Haryana. Instead of correcting these incentive distortions and promoting crop diversification towards pulses, oilseeds and maize, the current policy effectively creates an additional outlet for surplus rice through ethanol production.

Further, the economic cost of procuring, handling and storing rice by the FCI is estimated at around INR 42-44 per kg, yet rice is supplied to distilleries at approximately INR 22-23 per kg, implying a substantial implicit subsidy financed through the food security budget. Rice cultivation is among the most water-intensive and greenhouse gas-intensive agricultural activities, contributing significantly to groundwater depletion as well as methane and nitrous oxide emissions. In contrast, maize offers a more sustainable long-term pathway for grain-based ethanol production because of its substantially lower water requirement and comparatively smaller environmental footprint. Maize needs only three to four irrigations, whereas in Punjab rice needs about 22 irrigations, and in Maharashtra sugarcane requires 25-30 irrigations. However, the competitiveness of maize-based ethanol in India is constrained by low productivity. While average maize yields in the United States exceed 11 tonnes per hectare, India's yields remain around 3–3.5 tonnes per hectare. Improving maize productivity through technological innovation—including improved hybrids and appropriate biotechnology—will be essential for expanding ethanol production without intensifying competition between food, feed and fuel uses.

Second-generation (2G) lignocellulosic feedstocks—including agricultural residues and other non-food biomass—offer potential for expanding bioethanol production. However, agricultural biomass has several competing uses that must be carefully balanced. For instance, nearly 60% of maize stover is currently utilized as animal feed, while sugarcane molasses also serves as an important feed ingredient. Of the approximately 136 MMT of bagasse generated in 2023, an estimated 51.7 MMT could be diverted for bioethanol production (Venkatraman et al., 2021). Likewise, around 30% of the 56.5 MMT of maize stover is considered surplus and can be utilized for bioethanol and biogas production. Sugarcane bagasse, in particular, represents one of the most promising lignocellulosic feedstocks for second-generation biorefineries, with considerable scope for value addition beyond its traditional use in cogeneration.

Biomedical sector

The biopharma sector is projected to grow from USD 53.8 billion in 2023 to USD 97.3 billion by 2030 (Birac, 2024), with key segments including vaccines, therapeutics, and diagnostics & medical devices. The therapeutics sector, valued at USD 19.4 billion in 2023, highlights the growing use of medicinal plants, particularly in Ayurvedic medicine, underscoring agriculture's role. India, leveraging its rich biodiversity, supplies raw materials like Ashwagandha and Turmeric to global markets, boosting farmer incomes. For instance, the GI-tagged Lakadong turmeric from Meghalaya, known for its high curcumin content, has gained global attention and is expected to increase farmers' earnings (India Today, 2023; MOFPI, 2022).

India produces 80% of the world's turmeric and exports 62% globally (MOFPI, 2022; GoI, 2023b). Turmeric exports were valued at USD 207.4 million in 2022-23 and are expected to reach USD 1 billion by 2030. Post-pandemic, global demand for turmeric has surged due to its immunity-boosting properties, with rising demand across pharma, food, and cosmetics (MOFPI, 2022). As the bioeconomy grows, leveraging GI-tagged varieties like Lakadong turmeric can significantly boost farmer incomes.

Biofertilizer industry

Biofertilizers are an essential part of India's push toward sustainable agriculture. While conventional chemical fertilizers dominate, biofertilizers are gaining traction. The biofertilizer market in India is currently valued at USD 1.4 billion (2023) and is projected to grow at 12% (CAGR) by 2030 (Birac, 2024). It currently captures a relatively small share of the overall fertilizer industry but its growth is encouraged by the increasing awareness of sustainable farming practices and government incentives promoting organic (natural microbes based) agriculture.

a. Biomass sources for biofertilizer industry

Key biomasses used in biofertilizer production in India include agricultural residues such as rice straw, sugarcane bagasse, and coconut coir pith, as well as composted manure and vermicompost. These organic materials serve as substrates for microbial inoculants like Rhizobium, Azotobacter, Azospirillum, etc, which fix nitrogen and solubilise the phosphates while enhancing soil health, phosphate solubilization, and overall soil health improvement (Table 5).

Table 5: Agriculture Biomass for biofertilizer industry

Biomass Source	Biomass Type	Uses in Biofertilizer Industry
Animal Manure	Cow dung	Rich in NPK nutrients for soil fertility
	Poultry litter	Enhances microbial activity and soil structure
Plant Residues	Rice straw	Improves soil organic matter, supports microbial growth
	Maize stover	Used in composting to produce nutrient rich organic fertilizers
	Sugarcane bagasse	Source of carbon for compost; supports microbial communities
	Cotton stalks	Improves soil structure and enhances nutrient availability
Green Manure	Leguminous plants	Fix atmospheric nitrogen, enrich soil with organic matter
	Cover crops	Improve soil structure, suppress weeds, enhance soil fertility

Source: Chojnacka et al., 2020

Punjab, Maharashtra, and Tamil Nadu are leading producers of biomass, primarily from rice, sugarcane, and other crops, driven by government initiatives like the Paramparagat Krishi Vikas Yojana (PKVY) promoting organic farming. However, this must be accompanied by **quality assurance and standardisation to** ensure consistent quality and build farmer confidence in microbial products.

Demand for biodegradable packaging (non-food demands)

The demand for agri products in the production of biodegradable materials is another key driver of growth. Natural fibres such as cotton, silk and hemp are increasingly being used as alternatives to synthetic fibre in the textile industry. With the modernization of recycling processes, these biodegradable materials are being used more efficiently to produce sustainable packaging products. For example, rice straw and sugarcane bagasse are significant sources of cellulose, and their utilization reduces the environmental impact of traditional packaging materials like plastic. Intercropping of pulses, wheat and other crops with Poplar trees is a positive step in linking agriculture with bioindustry thereby augmenting farmers' income.

India’s future in bioeconomy

India aims for a USD 300 billion bioeconomy by 2030, supported by policies, investments, and market expansion in bio-based sectors. Agriculture will play a key role in this growth, but the rising demand for agri-crops raises concerns about balancing food security with sustainability. Precision agriculture technologies can help address this by improving resource efficiency, boosting yields, and optimizing inputs, aligning with India’s focus on sustainable farming.

To achieve both food security and bio-based production, policy alignment is crucial. Promoting sustainable cropping systems and incentivizing non-food crops for bio-industries—such as bio-packaging, bioplastics, and biofuels—can meet demand in sectors like consumer goods, automotive, and construction. The Bio E3 policy supports this shift, aiming for high-performance bio-manufacturing in line with India’s Net Zero target by 2070 and the LiFE approach.

Bioethanol production will remain central to this trajectory, but its feedstock composition matters as much as its scale. Maize offers the more sustainable long-term pathway, requiring only three to four irrigations against rice, but realising this potential depends on closing India's productivity gap and average yields of 3-3.5 tonnes per hectare remain well below the 11 tonnes achieved in the U.S., the benchmark maize-ethanol producer. Sustained investment in yield-enhancing technology, including improved hybrid and genetically modified varieties, will determine whether maize can be scaled as a competitive feedstock without repeating the cost and resource distortions currently associated with rice-based ethanol. The bioindustrial sector is projected to reach USD 121 billion by 2030, driven by bio-based chemicals and products (Birac, 2024).

Conclusion

Bioeconomy expansion should follow a targeted approach that integrates food security goals by focusing on the cultivation of dual-purpose crops such as maize and sugarcane. Regions with high agricultural productivity should be reserved for food crops to safeguard food security, while less fertile areas should be dedicated to bioeconomy. It is recommended to target regions with food surpluses for bio-based crop production and leverage off-seasons/fallows for bio-based materials. Further, the cultivation of high-value bioeconomy crops like GI turmeric should be encouraged to augment farmers’ incomes.

To encourage bio-based production transformation, farmers should be incentivised to shift from traditional crops like wheat and rice. For biofuels, crops like sugarcane and maize (especially during the kharif season) should be prioritised over rice as feedstocks, given maize's substantially lower irrigation requirement and the fiscal and environmental costs associated with diverting FCI rice stock to ethanol production. In regions with abundant water, such as north Bihar, eastern Uttar Pradesh, and Assam, sugarcane can be a key source of ethanol, transforming natural water flows from the Himalayas into a path for prosperity and sustainability.

- Guaranteed Market Access: Establishing secure market channels is crucial for farmers to transition to bio-based crops. This can be achieved by creating contracts between farmers and industries, ensuring a reliable outlet for their products. Additionally, implementing stable pricing mechanisms can shield farmers from market volatility, providing them with a predictable income while reducing financial risk.
- Investment in Research and Development: Investing in the development of high-yield, drought-resistant, and pest-resistant crop varieties is vital particularly for maize, where closing the productivity gap with global benchmarks (India's 3-3.5 tonnes/hectare against the United States' 11 tonnes/hectare) is a precondition for maize to become a genuinely competitive ethanol feedstock. Such advancements can make bio-based crop cultivation more productive and sustainable, leading to higher profitability for farmers.

- Crop Diversification Programs: Integrating bio-based crop cultivation into existing crop diversification programs can highlight the economic and environmental benefits of growing these crops alongside traditional varieties.
- Public-private partnerships can foster innovation and collaboration in addressing challenges related to bio-based crop production. This can be achieved by establishing innovation hubs that connect researchers, farmers, and entrepreneurs for resource and knowledge sharing.
- Circular economy practices should also be emphasised, particularly for crops that contribute to food security and the bioeconomy. For instance, by-products from food crops like rice (such as rice husk instead of grain) or corn can be used in biofuel and bio-plastic production.
- Furthermore, training and capacity building should be provided to smallholders with agri and bio-based production systems. This will enable them to grow food while producing bioeconomy crops to augment their income.

3.5 Namibia

In 2019, the National Commission on Research, Science and Technology (NCRST) and FAO commissioned a study to develop a baseline of existing programmes and policies within the scope of the bioeconomy and assess potential gaps and challenges towards the development of a national bioeconomy strategy. This section uses first-hand accounts from minutes taken during the stakeholder consultation in the process of formulating the Namibia Sustainable Bioeconomy Strategy 2024 to 2029 and a review of literature and policy framework around sustainable biomass production. The economic, social, cultural and regulatory challenges are explored and the findings from this stocktaking exercise as well as the systematic review is discussed. The bush biomass value chain was used as an example of an established sustainable bioeconomy value chain in Namibia. This section shares findings of the strides made over past 10 years of bush biomass production including the establishment of energy production, livestock feed and charcoal value chains and future prospects.

Overview of Namibia's Bioeconomy policy framework

Namibia's agricultural sector, comprising livestock and crop farming, contributes 5% to GDP and employs nearly 170,000 people. Women dominate communal farming, particularly in northern regions, but face challenges like limited land access and financing. Communal farmers, practising mixed farming, are vulnerable to pests like fall armyworms and locusts, impacting crop yields and straining state resources.

Namibia's agricultural policies, including the National Agricultural Policy of 2015, aim to increase production, promote sector growth, and develop the value chain. The policy aligns with bioeconomy activities through objectives related to agroindustry development and research and development. Additionally, the Forest Act of 2001 governs community forests, ensuring sustainable resource management and community benefits.

Namibia's bioeconomy legal framework is governed by the Ministry of Environment, Forestry, and Tourism (MEFT) and administered by the Interim Bio-Prospecting Committee (IBPC). The framework emphasises sustainable natural resource management, including conservation, utilisation, and value addition of biological resources. Key players include local higher education institutions, the NCRST, and the Namibia Association of CBNRM Support Organisation (NACSO).

The Namibia Sustainable Bioeconomy strategy focuses on health, agriculture, natural resources management, and cross-cutting issues. The strategy emphasises environmental sustainability, value addition, RDI, and awareness.

Availability of biomass

a. Bush Biomass

Namibia's bush biomass production value chain was birthed from the challenge of bush encroachment which is defined as "the invasion and or thickening of aggressive undesired woody species, resulting in an imbalance of the grass-bush ratio, a decrease in biodiversity, a decrease in carrying capacity and concomitant economic losses" (De Klerk 2004 as cited in Namibia's Bush Biomass Sector report [NBBS], 2024). Approximately 45 million hectares of land in Namibia are bush encroached, resulting in an economic challenge for Namibian rangeland and consequently livestock farming. This vegetation is mainly made up of woody shrubs and is a result of diverse man made and climatic changes (NBBS, 2024). These include changes in rainfall, soil type, migration patterns and decrease in large herbivore population in specific areas amongst others.

According to the National Strategy for the Sustainable Management of Bush Resources 2022–2027 (NSSBR, 2022-27), bush encroachment is a threat to food security, ecosystem services and biodiversity. Initial interventions to prevent bush encroachment included controlled fire programmes, however government policies promoting controlled fires were overridden in favour of protecting human settlements in rangeland areas, giving way to encroaching woody plants in areas where grassland savannah was dominant (Glatzel et al, 2024). The multiple factors that lead to bush encroachment have led to government interventions towards sustainable practices to mitigate land degradation (NSSBR, 2022-27). The production potential of current biomass stands at approximately 10 to 30 tonnes per hectare that can be harvested in a sustainable manner for use, however bush encroachment is estimated at an increase of 3% annually if the problem is not addressed (Glatzel et al, 2024; NBSS, 2024).

b. Biowaste

Municipal biowaste

Municipal biowaste includes organic waste generated from households, commercial activities, and public institutions. In Namibia, the total amount of municipal solid waste (MSW), which includes biowaste, is on the rise due to population growth, urbanization, and increased consumption (MEFT 2017; EEA, 2020). The waste generation rate in Namibia's urban areas, including major cities like Windhoek, Swakopmund, and Walvis Bay, is estimated at 0.4 to 0.6 kg per person per day, with biowaste accounting for around 63 % of total municipal waste in Windhoek in 2014 (Ntesa and Hauptfleisch, 2014). In smaller towns and rural areas, although the volume of biowaste is lower, the proportion of organic waste is often higher due to agricultural activities.

Municipal biowaste in Namibia has several potential uses that align with sustainable waste management practices, though the country faces challenges in fully leveraging these options:

- Composting: Biowaste, especially from markets and households, can be composted to produce organic fertilizer, which is in demand for agricultural activities. However, composting initiatives are still limited in Namibia, particularly at the municipal level. Private initiatives and NGOs have implemented small-scale composting projects, but large-scale municipal composting is not widely practiced.
- Biogas Production: Biowaste, particularly food scraps and green waste, can be used to produce biogas through anaerobic digestion. Although Namibia has experimented with small biogas projects in rural areas, urban centres have yet to adopt large-scale biogas facilities to process biowaste. This represents a missed opportunity, as biogas can help address energy security while also reducing greenhouse gas emissions.
- Animal Feed: Some biowaste, particularly from food markets, is suitable for livestock feed. However, this practice is not widely adopted, with the main challenges being transportation costs and inconsistent quality of biowaste suitable for animal consumption.
- Mulching and Soil Improvement: In agricultural regions, organic waste can be used directly as mulch to improve soil structure, water retention, and organic content. This practice, however, is more prevalent in rural areas and less so in urban centres where most waste is currently disposed of in landfills.

Namibia’s waste management practices vary significantly between urban and rural areas. While cities like Windhoek have more formal systems, rural areas face greater challenges in terms of infrastructure and resources. Landfills remain the primary method for waste disposal in Namibia. Municipalities collect and transport waste to landfills, where it is deposited without much segregation, a phenomenon common in most middle- and low-income countries (Baquero et al., 2022). When biowaste is not treated separately from general waste, it decomposes anaerobically and contributes to methane emissions (IPCC, 2022; Nordahl et al., 2023). The Kupferberg landfill in Windhoek is the largest in the country, but it lacks advanced waste treatment facilities like biogas plants or composting units.

Urban areas, especially Windhoek, have structured waste collection systems, but biowaste separation at the source is minimal. Recycling efforts are primarily focused on non-organic materials such as plastics, glass, and metals. Organic waste recycling, such as composting, is still in its infancy. There are some private sector-led initiatives focused on organic waste recycling, but these are small-scale and not integrated into the municipal waste management framework.

The informal waste collection and recycling sector is active in Namibia, particularly in larger cities. However, their focus is on recyclable materials like metals, plastics, and paper, rather than biowaste. The informal sector plays an important role in reducing waste sent to landfills, but its impact on biowaste management is minimal due to the challenges of processing organic material.

Namibia has established the Environmental Management Act of 2007, which emphasizes the importance of sustainable waste management, but enforcement remains inconsistent. Municipalities are required to develop waste management plans, though many struggle with limited resources. Furthermore, Namibia's National Solid Waste Management Strategy seeks to promote waste minimization and the development of waste-to-energy projects, though progress has been slow (MEFT 2017).

Namibia faces several challenges in effectively managing its municipal biowaste:

- Lack of infrastructure: There are limited facilities for composting, anaerobic digestion, or other forms of biowaste recycling in Namibia's urban centres. Most municipalities rely on landfilling as the default waste management option, and investment in alternative technologies has been slow.
- Public awareness and participation: Public participation in source-separation of waste is low. While some efforts have been made to promote recycling and composting, widespread adoption of these practices is hindered by a lack of awareness, education, and incentives.
- Financial constraints: Municipalities in Namibia often face financial constraints that prevent the development of comprehensive waste management systems. This limits their ability to invest in infrastructure for biowaste processing and recycling.
- Environmental impact: As a significant portion of biowaste ends up in landfills, Namibia faces challenges related to methane emissions, which contribute to climate change. Additionally, untreated organic waste can contaminate groundwater and surface water sources.

Namibia has several opportunities to improve its biowaste management practices such as waste-to-energy projects which will aim to expand biogas projects to process municipal biowaste which could provide a renewable energy source while reducing waste sent to landfills. These projects could be especially beneficial for larger urban areas where significant volumes of organic waste are generated. Establishing centralized composting facilities could help divert a significant portion of biowaste from landfills and provide valuable organic fertilizer for agriculture, thereby closing the loop in waste management. Furthermore, encouraging collaboration between municipalities and the private sector can help drive innovation in waste management. Private companies could invest in biowaste processing technologies, while municipalities provide regulatory support and waste collection services. Moreover, increasing public awareness of the benefits of biowaste recycling through composting and biogas production could help improve source separation and reduce the burden on landfills. Namibia has a significant opportunity to improve its municipal biowaste management practices. While current practices largely involve landfilling, there is potential for several complementing uses for biowaste, such as composting and biogas production, that remain under utilized. Addressing the challenges of limited infrastructure, financial constraints, and public awareness could help Namibia move towards more sustainable waste management practices and make better use of its organic waste resources.

Sewerage wastes

Across the country, significant volumes of waste are generated, particularly from high-density urban areas and informal settlements, which contribute to both formal and informal waste management challenges. Sewerage and toilet waste, if treated properly, can have several beneficial uses which include biogas and fertilizer production from sewage sludge (often a byproduct of wastewater treatment plants) (Kirchmann et al., 2017). However, in Namibia most sludge from sewage waste is either buried or dumped at solid waste disposal sites. The nutrient content in treated waste, such as nitrogen and phosphorus, makes it valuable for improving soil fertility. Although this practice is more common in developed countries, Namibia has yet to fully explore this option due to challenges in public perception, safety concerns, and limited infrastructure.

Namibia's waste management practices for sewage and toilet waste are characterized by a mix of formal and informal systems, with varying levels of treatment and reuse across different regions. In urban areas, most of the sewage waste is collected and treated in centralized wastewater treatment plants (WWTPs). Windhoek operates one of the most advanced wastewater treatment and water reclamation systems in the world. The plant treats both sewage and greywater, converting it into potable water for reuse. Other urban centres like Walvis Bay and Swakopmund also have formal treatment facilities but lack the advanced recycling technology seen in Windhoek. In rural and peri-urban areas, formal sewer systems are rare. Instead, households rely on pit latrines or septic tanks for sewage disposal. These systems often face issues with maintenance, overflow, and groundwater contamination, particularly in informal settlements. In informal settlements, where access to sanitation infrastructure is limited, open defecation, illegal dumping, and makeshift pit latrines are common practices. This poses significant public health risks, including the spread of diseases and contamination of water sources. The National Solid Waste Management Strategy of Namibia emphasizes improving sanitation infrastructure in informal settlements.

Public-private partnerships have been encouraged to address the infrastructure gap in waste management. Several initiatives are in place to promote the development of waste treatment facilities and improve sanitation access, particularly in underserved areas. However, more investment is needed to expand sewage infrastructure and adopt innovative waste treatment technologies, such as biogas plants and composting toilets.

Livestock biowaste

In Namibia, commercial livestock farming, particularly cattle, produces significant amounts of organic waste, primarily manure, which is a byproduct of raising over 2 million cattle annually. On average, cattle generate large volumes of manure—approximately 10 to 20 kg per day per animal, depending on factors like diet and farming methods (Waqas et al., 2023). This equates to thousands of tons of manure per year from commercial farming alone.

Livestock waste, primarily manure, can be repurposed for several uses such as composting, biogas production, animal bedding and rangeland rehabilitation. Livestock waste, especially manure, can be composted and applied to improve soil fertility, particularly in arid regions like Namibia where soil degradation is a concern. The National Solid Waste Management Strategy highlights composting as a key method for turning organic waste into a resource (MEFT, 2017). Another use of livestock waste, particularly manure, is biogas production. Manure can be processed in anaerobic digesters to generate biogas, which can be used as a renewable energy source for heating, electricity, or cooking (Sohil and Kichloo, 2023). Although Namibia has seen limited adoption of biogas technology in livestock farming, it remains a viable future option for waste management and energy generation. Furthermore, waste materials like manure mixed with straw or sawdust are sometimes reused for animal bedding, especially in poultry farming. Producers such as Greenfield Organic Fertilisers and some farmers have explored integrating livestock manure with bush biomass to create compost for improving soil fertility (N-BiG, 2024).

Waste management in commercial livestock farms in Namibia faces several challenges, which include lack of Infrastructure, environmental concerns and Government initiatives. There are few large-scale facilities for processing livestock waste in Namibia and most waste, particularly manure, is either left untreated or poorly managed. Moreover, poor management practices, such as indiscriminate disposal of manure, can lead to groundwater contamination and methane emissions, which contribute to environmental degradation. Efforts such as the Livestock Productivity and Resilience Support Project (supervised by MAWLR) also aim to improve livestock waste management by strengthening value chains and implementing better waste management strategies, though progress is slow. Furthermore, Namibia's National Solid Waste Management Strategy seeks to improve waste management practices, including the handling of agricultural waste. The strategy promotes recycling, composting, and other sustainable practices (MEFT, 2017). However, enforcement remains a challenge, especially in rural areas where livestock farming is predominant.

Complementing uses for bush biomass

Bush biomass uses in Namibia include energy, charcoal, livestock feed production, and building materials. Furthermore, novel uses for bush biomass in Namibia are continually being explored. Examples of these are the use of encroacher bush species to cultivate edible mushrooms and turn the waste into building materials such as bricks (Mbathera, 2024). However, it is important to note that the expansion of such new ideas is often hindered by finances and the slow uptake of new technologies. Despite the wide array of uses for encroacher bush biomass, there is a need to upscale solutions in bush harvesting and processing due to the extensive problem of encroacher bush on Nambian rangelands (NBBS, 2024). This section will focus on the three main uses of bush biomass in Namibia which are energy production, charcoal production and livestock feed production.

a. Energy production

Bush biomass has been used as a source of energy in Namibia since the early 2000, with the Cheetah Conservation Fund as the pioneer for the first industrial scale production plant for wood briquettes (Laufs et al., 2024). The industry saw continued growth and expansion and the first large scale mechanised operation was piloted by Ohorongo Cement in 2011—sourcing over 50 000 tonnes of woodchips annually for heat production. Large industries such as the Namibian Breweries also use woodchips for heat generation in their operations (DAS, 2017). In 2015 NamPower, Namibia's national power utility company, with support from the German Development Bank (KfW) investigated the development of decentralised power plants with 5-20 MW capacity to address the issue of encroacher bush biomass (Ruppel and Althusmann, 2016). In 2018 NamPower ratified the implementation of the Otjikoto Biomass Power Station, which is to be located near Tsumeb, a town in north central Namibia (NamPower, 2024). The project aims to source woodchips through a combination of long-term fuel and ad hoc fuel supply contracts; a strategy aimed to involve various stakeholders in the production process (NamPower, 2018). The 40MW Otjikoto Biomass Powerplant is projected to consume over 200 000 million tonnes of encroacher bush biomass per year (Ruppel and Althusmann, 2016).

Given the large amount of encroacher bush biomass available for uptake (at least 13 million tons of bush biomass annually), investing in large scale energy projects will prove valuable in not only combating encroachment, but expanding the biomass industry, while diversifying the energy sector and contributing to renewable energy efforts within the country.

b. Charcoal production

Charcoal is the oldest and most developed bush biomass value chain projected to grow at a CAGR of 4.2% globally in the forecast period of 2024-2031, especially due to the demand in high-paying international markets for certified charcoal (MITSMED, 2013; Carbon Capital 2020; SkyQuest, 2024). The charcoal value chain has a combined biomass consumption of approx. 1.2 million tonnes per year and produces close to 270 000 tons of charcoal per annum (Rupple and Althusmann, 2016). Charcoal production is largely focused on farms in the country's northern and central regions, with an estimated 240 active charcoal producers and over 6000 people directly and indirectly employed in the industry in 2015 (MITSMED, 2013; DAS, 2015a). Most of the charcoal in Namibia is produced in portable round drum kilns on site (farms) (DAS, 2017; Tintner et.al, 2020) and then sold and transported to charcoal and exporting companies. Investment in traditional technology of charcoal production is relatively low as harvesting and production are done onsite with simple traditional steel pots, and no additional inputs such as water and electricity are required (DAS, 2017). The largest buyers of Nambian charcoal are South Africa and Europe and there is much scope to increase supply to these markets due to an undersupply of charcoal and an increasing global demand (DAS, 2017).

c. Biochar

Biochar is a form of black carbon produced by pyrolyzing biomass in the absence of oxygen (Woolf et al., 2010; Alkharabsheh et al., 2021). When applied to soils, biochar is highly stable and can sequester carbon for hundreds or even thousands of years, making it a crucial tool for carbon capture. The biochar's high surface area and porous structure make it ideal for trapping CO_2 (1 kg of biochar can sequester up to 3 kg of CO_2) and other gases, which are then immobilized in the soil (GIZ-NUST, 2020; Alkharabsheh et al., 2021) — underlining its potential contribution to climate change mitigation.

Namibia's encroacher bush is an excellent source of biomass for biochar production. The Kon-Tiki kilns and other local technologies used for biochar production can easily convert smaller bush fractions into biochar, creating opportunities for farmers and commercial enterprises (GIZ-NUST, 2020). The production process, including the quenching and crushing steps, ensures that biochar can be optimized for use in soils or as animal feed.

Biochar can also play a vital role in rangeland rehabilitation. When used as a soil amendment, biochar improves soil fertility, water retention, and nutrient availability (Stavi, 2012; Alkharabsheh et al., 2021). This not only enhances agricultural productivity but also helps in restoring degraded lands affected by bush encroachment.

The storage of carbon through biochar production provides potential access to international carbon markets. Biochar sequesters carbon over long periods, making it eligible for carbon credits under voluntary carbon offset schemes. Carbon credits can serve as an additional revenue stream for biochar producers in Namibia, providing incentives to invest in bush harvesting and biochar production technologies.

The market for biochar is rapidly expanding, driven by the increasing global focus on sustainable agriculture and climate change mitigation. In Namibia, institutions such as the Namibia Biomass Industry Group (N-BiG) and the Namibia University of Science and Technology (NUST) are working on certification and testing biochar to meet international standards, including the European Biochar Certificate (EBC), which is crucial for access to international carbon markets (GIZ-NUST, 2020).

The global biochar market hit a value milestone of $600 million (USD) in 2023— representing a 91% CAGR production growth rate since 2021 (IBI, 2024). Namibia's bush biomass offers a sustainable feedstock for biochar production, enabling the country to tap into this growing market. The country could become a key exporter of certified biochar, particularly to regions like North America and Europe, where demand for biochar for agricultural and carbon sequestration purposes is high.

Additionally, biochar production from bush biomass can complement Namibia's existing industries, such as charcoal and animal feed production. For example, biochar can be produced from the bush fractions that are not suitable for charcoal or animal fodder, ensuring full utilization of harvested biomass.

d. Livestock feed production

Bush biomass has become an important staple in livestock agriculture, especially during draught periods where livestock access to grass is limited (DAS, 2017; NOA, 2022). In 2019, approximately 102,914 tonnes of bush feed were produced, but only about 6,500 tonnes were sold, generating NAD 14 million (N-BiG, 2024). Bush feed has been shown to obtain significant growth rates in livestock (7kg a week in cattle and 1.5kg a week in sheep) (NOA, 2022), which makes it a good alternative and/or supplement in livestock farming. However, much of the production of livestock feed from encroacher species are done informally, with no formal chains that add value found in Namibia (DAS, 2015a).

There are many options to produce livestock feed, as a result this makes it difficult to estimate the required investment for a large-scale production plant (DAS, 2015a). Two pilot projects under the “Support to de-bushing" project were carried out in Namibia to scientifically test the use of bush biomass in agricultural feed on both commercial and communal farms (DAS, undated; Honsbein, 2018). These projects are a result of a bilateral agreement between Germany (GIZ) and Namibia’s Ministry of Agriculture, Water and Land Reform (MAWLR). Despite the large potential for using bush biomass for livestock feed, the lack of reliable knowledge and relevant guidelines, leads to unnecessarily high costs of feed production (Honsbein, 2018).

e. *Case study: The Greenfields Model: Turning Bush Biomass into Fertilizer*

Greenfields Organic Fertilizers (GOF) is a Namibian enterprise leveraging the country’s abundant bush biomass to produce organic fertilizers. Greenfields Organic Fertilizers focuses on converting the woody biomass cleared during bush control efforts into high-quality organic fertilizers (N-BiG, 2024). They work in partnership with bush control operations, sourcing biomass from encroacher species. The company collects bush clippings, chicken manure, horse and cattle dung, and turn these into rich compost through a careful fermentation process. This compost not only helps restore soil fertility but also creates a circular economy where waste is turned into value-added products. The composting process enhances the nutrient profile of the biomass, making it suitable for use as a soil amendment. The resulting organic fertilizer is rich in essential nutrients like nitrogen, phosphorus, and potassium, which are crucial for crop growth. Greenfields has diversified its product offerings to include not only raw compost, but also specialized blends of organic fertilizers tailored to different agricultural needs. These blends improve soil structure, water retention, and nutrient availability, enhancing the productivity of both commercial and small-scale farmers.

Obstacles to biomass utilization

a. Technical barriers

Expansion of value addition chains of bush biomass is often constrained due to a lack of access to appropriate technologies and finance (DAS, 2015b). Harvesting technologies can pose significant challenges to utilising biomass, as harvesters and producers often rely on semi-mechanic and manual extraction methods— both of which are time consuming and labour intensive, despite being more cost effective. The use of fully mechanised harvesters is limited in the Namibian landscape due to the large variation in density and hardness of encroacher bush, which also contributes to high cost of wear and tear (Laufs, 2023a). Moreover, the risk of re-encroachment after bush thinning is high and requires consistent and well-informed aftercare practices (de Klerk, 2004; Laufs, 2023a). This need for consistent aftercare adds to the complexity and cost of biomass utilization.

In terms of energy production, energy conversion and processing technology are a major constraint to converting and upscaling bush biomass into useful energy forms like electricity. This is due to the lack of advanced conversion technologies in the region in combination with inconsistent biomass supply (MEFT, 2022).

While the biochar industry in Namibia has immense potential, several challenges must be addressed. These include:

- Access to international markets: Certification is crucial for entering international biochar markets. Namibia’s biochar producers need to meet strict quality standards, such as those set by the European Biochar Certificate, which requires testing for carbon content and the presence of harmful substances like Polycyclic Aromatic Hydrocarbons (PAHs).
- Infrastructure and investment: Large-scale biochar production requires significant investment in kilns and testing facilities. While technologies like the Kon-Tiki kiln offer scalable solutions, the development of more efficient industrial-scale retort kilns could further enhance production capacity.

- Awareness and adoption: The benefits of biochar, both for soil enhancement and carbon sequestration, need to be more widely communicated to farmers and stakeholders in Namibia. Increased awareness and technical assistance could drive adoption, particularly in regions severely affected by bush

b. *Economic and regulatory challenges*

Despite the huge potential to utilize biomass, market access limitations (critical mass off takers) remain a major constraint in the industry. This is due to various factors such as the fragmentation of the industry and technical barriers as mentioned above (DAS, 2015b). Many small-scale farmers and local communities lack the financial resources to invest in the required machinery, training, and post-harvest management, furthermore, high upfront costs required in bush biomass value addition chains discourage broader participation in the biomass sector (MEFT, 2022).

According to the Malabo Montpellier Panel (MMP) 2022 report, approximately 650 farmers and SME owners were trained in the processing of bush biomass and consequently 11,000 jobs were created. Although efforts to create meaningful employment have been made through introduction of minimum wage, better housing conditions and protective work gear, most of these jobs remain informal and semi-skilled as informed through stakeholder engagements (MMP, 2022; National stakeholder engagement minutes).

Another economic barrier is the two-property system in which the Namibian land ownership is divided. Approximately 35% of the land is communal or free-hold and 48% is commercial, the remaining 17% is protected areas including national parks, the complication involves different law governing the harvesting in these areas (Laufs, 2023b). Commercial landowners can harvest bush biomass for sale whilst communities living on communal land can only harvest for household use. This hinders participation for the previously disadvantaged majority black population. The findings from stakeholder consultation revealed that the Forestry Act 12 of 2001 is seen as a stumbling block by communal farmers as this legislation limits communal farmers from participating fully in biomass programmes that result in economic activities such as bush feed production, charcoal production, and conversion of encroacher bush wood chips to bioenergy.

c. *Social, cultural and environmental factors*

This section mainly highlights the results of minutes from the stocktaking exercise through the BMWG. The stakeholders were asked to identify social economic constraints, and the following challenges were highlighted:

- Lack of capacity for rural communities to create value chains of potential products and by-products emanating from biological resources. Rural communities lack the skills to allow them to process raw materials into semi-finished or finished goods.
- Lack of funding schemes from banks and other funding institutions
- Lack of training incentives for private manufacturers who would like to offer in-service training to unemployed youth.
- Limited or no known rebates for manufacturing novel products
- Fragmented legal framework, for example, permits for research are issued by different organisations, there is no one-stop
- Stakeholders were concerned that research is undertaken in their communities and published without any feedback.

Conclusion

The fundamental message of this systematic review and the stocktaking exercise was the need to invest in research and development in producing novel bioproducts as well as building capacity in an industry beyond semi-skilled and unskilled labour. There is a need to come up with a more inclusive model that can assimilate most of the population in communal areas and give them equal participation in biomass production.

3.6 South Africa

The South Africa case study is mostly based on first-hand accounts, experiences and personal reflections of the South African co-authors. Biomass holds promise for advancing South Africa's bioeconomy, but sustainable production and use are key. This review assesses biomass's availability, competing uses, and obstacles in South Africa's economy, with resources drawn from agricultural residues, forestry by-products, and organic waste. Despite its potential, regulatory, economic, environmental, social, and technological challenges limit sustainable utilisation. Key obstacles include policy and market limitations, environmental and social concerns, and technological gaps.

Biomass Availability in South Africa

Considerations for biomass production

South Africa's diverse climate and geography provide for several biomass resources. Despite some soils being sandy and acidic, careful management and proper fertilization may lead to high productivity (von Maltitz & van der Merwe, 2017). Key biomass sources include primary crops, agricultural and forestry residues, animal waste, and organic municipal waste. However, South Africa faces challenges due to its limited rainfall and competing demands for biomass across sectors such as food, fibre, animal feed, chemicals, materials, and energy.

Biomass supply in South Africa is influenced by inter alia climate, soil quality, access (through a permitting system) to water, complexity of land use practices, arable land access and practices, and food security (Hugo, 2015; Stafford, 2023). Primary production, climatic conditions, and land use patterns are crucial determinants of biomass availability (South African BioEnergy Atlas, 2015). Furthermore, technological advancements in biomass conversion impact decisions regarding biomass utilisation.

Looking ahead, climate variability is expected to have a significant effect on biomass production, with rainfall playing a critical role in determining an area's potential for high biomass yields. The interplay between rainfall, temperature, duration of rainy season, soil conditions, and sunshine hours influences biomass potential (von Maltitz & van der Merwe, 2017). The availability of biomass is subject to seasonal variations, with certain types following specific cycles and others, such as agricultural and forestry residues, depending on the management goals of their production activities.

Mapping of biomass resources

Mapping biomass resources in South Africa has been conducted to varying degrees, but high-resolution, comprehensive mapping remains limited. Projects like the CSIR Biomass Atlas and BioEnergy Atlas have advanced resource quantification but face challenges due to inconsistent data and environmental variability. Detailed mapping has been done for sectors like sugar (bagasse) and forestry (wood residues), and invasive alien plants, notably through the Working for Water program.

Institutions like SANEDI and SAEON contribute to mapping efforts through platforms like the Renewable Energy Data and Information Service (REDIS), covering resources such as agricultural and forestry residues, invasive alien plants, and sugarcane production. These efforts provide valuable insights, though more detailed mapping is needed to fully assess biomass potential.

In South Africa, the biomass value chains are linked to the country's diverse agricultural, forestry, and waste management sectors. These include:

- Primary production
- Agricultural residues
- Plantation forestry residues
- Invasive alien plants

- Dedicated energy crops
- Algal biomass
- Animal waste
- Organic municipal waste

a. *Primary Production:*

Primary agriculture contributes 2.5% to South Africa's GDP and about 8% to formal employment, with the agro-industrial sector representing 12% of GDP. In 2022, agriculture’s value stood at R419.7 million, with a GDP contribution of R145 million. The sector has grown by 7.5% per year since 2008, compared to the economy's overall 6.6% growth (Department of Agriculture, Land Reform and Rural Development, 2021, 2022).

Biomass cultivation is influenced by climatic conditions, particularly rainfall, with higher productivity in the eastern regions and coastal areas (South African BioEnergy Atlas, 2015). Sugarcane is a key crop for biofuel, while crops like sweet sorghum, cassava, and tropical sugar beet show potential but require further research (Stafford et al., 2019). Sugarcane offers high ethanol yields but faces constraints such as water demand and irrigation reliance (von Maltitz & van der Merwe, 2017). Maize is excluded from biofuel strategies due to food-fuel conflicts.

The forestry industry, representing 9.8% of agricultural GDP and 4.9% of manufacturing GDP, is crucial to the economy. Exporting over R38.4 billion in value, it supports over half a million people. Managing 1.37 million hectares, the sector generates biomass from residues like sawdust and bark, with availability dependent on land management (Forestry South Africa, 2024; ICFR, 2020).

b. Agricultural Residues:

South Africa’s agricultural sector produces significant biomass from crops like maize, sugarcane, and wheat, though data is fragmented and outdated, with no integrated assessments. Agricultural residues such as maize stalks, sugarcane bagasse, and wheat straw offer seasonal biomass potential. Maize residues are estimated between 10-15 million tons annually, though not formally measured. Sugarcane data is typically collected at the mill level, but SAEON provides detailed field-level data, estimating in-field sugarcane residue at 20-30% of total biomass (Hugo et al., 2016). The sugarcane industry has a well-established value chain, utilizing bagasse for cogeneration and ethanol production. Wheat residues are estimated at 2.6 million tons, based on a residue-to-product ratio of 1.3:1. Sunflower and sorghum also contribute significant residues, with estimates of 200 000 – 300 000 tons and around 1 million tons, respectively. The main challenge is developing efficient systems to collect, process, and convert these residues into valuable products.

c. Plantation Forestry Residues:

The plantation forestry sector produces significant biomass, including woodchips, sawdust, and bark. Plantations of pine, eucalypts, and wattle offer a steady supply of these residues. Traditionally used for internal energy generation, these residues have potential for broader bioeconomy applications. High productivity areas of South Africa have a sizeable allocation to commercial forestry, and the waste products are of some use as bioenergy sources. The sawmilling industry in South Africa processes millions of cubic meters of timber annually, generating significant amounts of sawdust and wood shavings. Estimates suggest that sawdust alone can amount to over 1 million tons annually. Bark typically constitutes 10-15% of the total volume of a log, and with an annual industrial roundwood production of around 20 million cubic meters, bark residues could amount to approximately 2-3 million tons annually. The quantities of plantation forestry biomass residues are documented in industry reports, forestry resource assessments, and academic studies (Forestry South Africa regularly publishes data on wood production, including residues). However, as with agricultural residues, detailed and up-to-date quantification is region-specific and influenced by factors such as forest management practices, market demand, and technological advancements in residue utilisation.

d. Alien Invasive Plants (AIPs):

Invasive alien plant species, such as certain exotic Acacia species, are spread across South Africa's landscape, particularly in water-scarce areas. These plants, while threatening biodiversity and water resources, provide a biomass source for bioenergy and other products, and are removed as part of environmental management efforts. The Working for Water (WfW) program, a government initiative aimed at controlling invasive species, has conducted several studies on the distribution, density, and biomass potential of AIPs in South Africa, and they are estimated to cover between 10-20 million hectares of land in South Africa. The density and type of species vary widely across regions. Estimates from the South African National Biodiversity Institute (SANBI) suggest that the total above-ground biomass of AIPs could range between 15-25 million tons per year. This biomass can be harvested and used across various sectors of the bioeconomy. The scattered and often dense nature of AIP infestations makes harvesting and transport challenging. Efficient logistical systems are needed to make biomass utilisation economically viable, and the use of AIPs in the bioeconomy must be carefully managed to ensure it contributes to their control and eradication, rather than encouraging further spread.

e. Dedicated Energy Crops:

While still emerging, some areas in South Africa are exploring the cultivation of dedicated energy crops such as switchgrass, sorghum, and certain types of fast-growing trees. Switchgrass (Panicum virgatum) is well-suited to South Africa's diverse climatic conditions, particularly in regions with moderate to high rainfall. It is a low-input crop that can grow on marginal lands, reducing competition with food crops. There is limited large-scale commercial cultivation of switchgrass in South Africa currently, so precise quantities are not well-documented, though research suggests that yields can range from 10 to 20 tons of dry biomass per hectare per year, depending on soil and climate conditions. Sorghum (Sorghum bicolor) is drought-tolerant and can thrive in South Africa's arid and semi-arid regions, making it a workable option for biomass production in areas where water is limited. Sorghum yields can vary widely, with estimates ranging from 5 to 15 tons of dry biomass per hectare per year. Fast-Growing Trees (e.g., eucalypts, poplar, willow) are well-suited to South Africa's plantation forestry regions, particularly in the higher rainfall areas. They can be grown in short rotations, typically 3-7 years, depending on the species and intended use. While the potential for these energy crops exists, large-scale commercial cultivation specifically for biomass production is still limited in South Africa, and thus, precise documentation of quantities is sparse.

f. Algal Biomass:

Algal bioprocessing has been put forward as a flagship technology for driving the South African bioeconomy. Microalgae have exciting potential as a bioresource in South Africa, and globally, due to its ability to take up carbon dioxide, cultivate more rapidly than plants and grow on non-arable land. Algal biomass has a high organic content and metabolic properties that make it a promising resource for profitable biobased products. Species such as Chlorella and Spirulina are commonly studied for biofuel production due to their high lipid content. The Energy and Water Sector Education and Training Authority (EWSETA) has supported research on algal biofuels, with findings suggesting that microalgae could yield up to 100 tons of dry biomass per hectare per year under optimal conditions.

g. Animal Waste:

Livestock farming, notably cattle and poultry, produces organic waste suitable for biogas production. Provinces such as KwaZulu-Natal, Free State, and Mpumalanga, with substantial livestock populations, offer significant potential for utilizing animal waste in energy and fertilizer production. South Africa's livestock population includes approximately 13 million head of cattle, 24 million sheep, 6 million goats, 1.6 million pigs, and 180 million poultry birds. Cattle are the largest source of manure, producing an estimated 10-12 tons of manure per head per year. This results in over 130 million tons of cattle manure annually. Poultry farms generate significant amounts of litter, with estimates suggesting that broiler production alone could produce millions of tons of waste annually. Pigs produce approximately two tons of manure per head per year, contributing to millions of tons of waste annually.

h. *Organic Municipal Waste:*

Urban areas generate substantial amounts of organic municipal waste, including food and garden waste, and sewage sludge. The growing urban population increases this biomass source, though challenges in waste segregation and collection efficiency affect its effective utilisation. Municipal solid waste (MSW), agricultural waste, and industrial waste, including food processing residues, contribute to the biomass supply. The quantities of municipal waste biomass in South Africa have been documented through national and municipal reports, though the data is often segmented by region or waste type. South Africa generates approximately 54 to 60 million tons of MSW annually. Of this, a sizeable portion is organic waste, which is the primary source of biomass, and makes up about 40-50% of the total MSW by weight. Organic waste is estimated to account for approximately 18 to 30 million tons annually. This includes food waste from households, restaurants, and markets, as well as garden waste from municipal green spaces. Food waste alone is estimated to be around 10 million tons per year, making it a major contributor to the organic waste stream. Currently, a significant portion of municipal organic waste is landfilled, with only a small fraction being composted or processed for energy recovery.

Competing uses for the biomass

The availability of biomass in South Africa is influenced by multiple competing uses across various sectors, each with its own implications for sustainability, resource allocation, and socio-economic priorities. Understanding these competing uses is crucial for balancing needs and achieving optimal *biomass utilisation.*

a. *Current Agricultural Land and Food Production*

Agricultural biomass is vital for food production, with residues such as maize stalks and wheat straw playing a key role in maintaining soil health and fertility. These residues often remain on fields to prevent erosion, enhance soil structure, and retain nutrients. Removing them for energy or materials can degrade soil quality and reduce agricultural productivity. Additionally, using food crops like maize and sugarcane for biofuel production raises concerns about food security, particularly in a country with significant food insecurity issues.

b. *Bioenergy production*

Bioenergy production is a major industrial use of biomass in South Africa, encompassing electricity, heat, and biofuels. Biomass conversion methods include combustion, gasification, and anaerobic digestion. For instance, sugarcane bagasse is utilized in cogeneration plants for electricity and heat, while forestry residues are used in biomass power plants. The growing interest in biofuels, such as bioethanol and biodiesel, increases demand for biomass, creating competition with food production and other uses. The Integrated Resource Plan (IRP) of South Africa includes biomass in the energy mix, highlighting its role in renewable energy. However, the competition between bioenergy and other uses, such as soil conservation and animal feed, is a recognized challenge.

c. *Bio-based Materials*

The production of bio-based materials, including bioplastics, bio-composites, and biochemicals, represents a significant use of biomass. These materials offer sustainable alternatives to fossil-based products and support the circular economy. The forestry sector contributes wood fibres for bio-composites used in construction and automotive industries, while agricultural residues are being explored for bioplastics. Nonetheless, this use competes with biomass's role in energy and food production.

d. Environmental Management

Biomass is essential for environmental management, particularly in controlling invasive alien plants and rehabilitating degraded landscapes. Invasive species, such as certain Acacia spp. and Eucalyptus spp., consume substantial amounts of water and displace native vegetation. While harvesting these plants for biomass can aid ecosystem restoration and improve water availability, careful management is needed to avoid ecological imbalances. Organic waste used for composting and soil amendment supports sustainable agriculture but also competes with its use in biogas production.

e. Carbon Sequestration

Biomass plays a crucial role in carbon sequestration, which is vital for climate change mitigation. Forests, grasslands, and agricultural lands act as carbon sinks, storing carbon in plant biomass and soils. Balancing biomass use for energy or materials with the need to preserve and enhance carbon sinks is essential. For instance, wood harvesting for bioenergy should not lead to deforestation or forest degradation, and removing agricultural residues must be managed to prevent reductions in soil organic carbon levels.

f. Agricultural inputs, including as livestock feed, etc.

Biomass can also be used as agricultural inputs, such as livestock feed, which contributes to the agricultural economy. The use of biomass for feed competes with other uses, including energy and materials.

g. *Other uses (traditional, cultural, eco-tourism, or related uses)*

Biomass has traditional, cultural, and eco-tourism uses, which may include craft materials, cultural practices, and enhancing biodiversity. These uses, though less quantifiable, contribute to the socio-cultural fabric of South Africa and may influence how biomass resources are distributed and managed. Although likely to be a very low levels overall in terms of biomass, under the Bioeconomy Strategy of South Africa there are also programmes to assist in valorising and marketing of traditional knowledge products. These efforts are expanding wild harvesting and are likely impacting the biodiversity in some rural areas and more particularly around urban areas.

Obstacles to Biomass Production and Utilisation – Trade-offs and Challenges

The expansion of South Africa's bioeconomy, while promising, faces several obstacles and trade-offs. Addressing these challenges is crucial for developing a sustainable and equitable bioeconomy. Key issues include technical barriers, economic considerations, policy and regulatory frameworks, social and cultural factors, environmental concerns, and gaps in biomass mapping.

a. Land Availability and Competing Land Uses

Land has significant economic, social and environmental value in South Africa, but much of the land surface is susceptible to degradation and desertification, and the amount of land available for biomass production is an uncertain factor. Agricultural land in South Africa is limited, with only about 10% of the total land area being arable, and needed for food production, urban expansion, and conservation efforts, which limits the space available for dedicated biomass production. In addition, land degradation (soil erosion, nutrient depletion), and desertification are ongoing concerns in South Africa, reducing the productivity of existing agricultural and forestry lands. Competing land uses for food production, urbanization, and conservation efforts can significantly constrain the land available for biomass production for the bioeconomy. Changes in agricultural practices, reforestation, or afforestation policies also influence estimates.

b. Water Scarcity

Biomass production, particularly for crops like sugarcane and certain energy crops, requires significant water resources. South Africa is a water-scarce country, with uneven distribution of water resources, which could constrain biomass production, especially in drought-prone areas. Reliance on irrigation for biomass crops in dry regions puts added pressure on already scarce water supplies, potentially leading to conflicts with other water users, such as agriculture and urban areas.

c. Climate Change

Climate change is expected to alter rainfall patterns, increase the frequency of droughts, and lead to more extreme weather events. These changes could reduce crop yields and the availability of water, thereby limiting biomass production. While some areas may benefit from longer growing seasons, others may face reduced productivity due to heat stress, changes in pest and disease patterns, and other climate-related factors.

d. Technical Barriers

Technical challenges in biomass use include limitations in technology and infrastructure. These barriers affect the efficiency and effectiveness of biomass conversion processes, such as gasification, combustion, and anaerobic digestion. Additionally, the variability in biomass quality and composition can affect the performance of conversion technologies and the consistency of end-products.

e. Economic Barriers

The economic costs of producing, harvesting, and processing biomass can be high, especially in areas far from processing facilities or markets. Without subsidies or incentives, these costs might make biomass production economically unviable. The demand for bio-based products and bioenergy is still emerging in South Africa, and without sufficient market demand, there may be little incentive for farmers and landowners to invest in biomass production.

In addition, the use of food crops for biofuel production presents a trade-off between energy needs and food security. In South Africa, where food insecurity is a concern, diverting food crops like maize to biofuel production can potentially worsen the situation, particularly with a growing population. Policymakers need to carefully balance the benefits of biofuels with their impact on food availability and affordability. 21% of South Africans are food insecure (Statistics South Africa, n.d.). In addition, food security is not a national, but a regional challenge, and trade agreements with neighbouring countries must be considered.

f. Policy and regulatory issues

Developing a sustainable bioeconomy requires supportive policies and regulatory frameworks. These frameworks must address land use, resource allocation, and environmental protection. Policies should promote sustainable biomass use while ensuring that benefits are equitably distributed and that marginalized communities are not disproportionately affected. Certain regulation needs to be updated to allow more effective bioeconomy applications (e.g. The Sugar Act (9 of 1978), GMO Act (15 of 1997). There is no fuel ethanol blending regulation yet instituted to drive biofuel applications, and there are efficiency challenges for a variety of regulatory processes. Effective regulation is necessary to align bioeconomy activities with broader sustainability goals.

g. Social and cultural factors:

Traditional practices, cultural values, and community needs can influence how biomass resources are used and managed. Engaging with local communities and understanding their perspectives are essential for developing inclusive and effective biomass strategies.

h. Environmental concerns:

While biomass use for example for energy production can enhance energy security by reducing reliance on fossil fuels, it can also lead to environmental issues if not managed sustainably. Overharvesting of wood for bioenergy, for example, can result in deforestation, loss of biodiversity, and soil erosion. Similarly, removing agricultural residues for energy can affect soil fertility and contribute to desertification. The balance between biomass use supporting a bioeconomy and environmental conservation is a key challenge. There is a need for metrics and standards that could guide primary production for biomass to ensure social and environmental sustainability.

Challenges and Gaps in Mapping

- Data fragmentation: Biomass availability data is fragmented across different sectors, making it difficult to develop a comprehensive national overview. Integrating datasets from various sources is essential for a complete understanding of biomass resources.
- Dynamic trends: Biomass availability is affected by dynamic trends such as changes in agricultural practices, climate variability, and policy shifts. Maintaining up-to-date biomass maps in light of these changes is a significant challenge.
- Holistic evaluation: There is a need for more holistic evaluations that account for all competing uses and their market impacts. Current studies focus on specific sectors or regions, so a broader, systems-based approach could better capture the trade-offs and synergies between different biomass uses.
- Economic modelling: Economic modelling of biomass markets is still developing. While some studies assess the viability of bioenergy projects, few have explored how competing demands across sectors might affect market dynamics and prices. Advanced economic models are needed to understand these interactions and inform policy decisions.

Opportunities for the Future

South Africa's biomass resources, including agricultural residues, forestry residues, invasive alien plants, and organic waste, offer potential for advancing the bioeconomy. The "Biomass Atlas" and "BioEnergy Atlas" have highlighted the spatial distribution and potential of these resources. The sugarcane industry, plantation forestry, and agriculture could contribute to the bioeconomy, but the competition among various sectors (animal feed, energy production, soil improvement, pulp and paper production, bioenergy, bio-based material production) for biomass underscores the need for integrated and sustainable management approaches. Competing demands can create conflicts, particularly between energy generation and traditional uses. The literature indicates a need for integrated approaches to manage these competing demands sustainably.

The potential for greater use for example for bioenergy production is significant, particularly from agricultural and forestry residues and organic MSW. Studies highlight the use of biomass in cogeneration plants within the sugar and forestry industries. However, limitations include the logistical challenges of collecting and transporting biomass (especially if widely dispersed), the seasonal availability of certain residues, and the need for infrastructure investment. Additionally, the energy sector faces competition from other uses that may be more economically viable in the short term. Environmental considerations associated e.g. with alien invasive plants depend on careful management to prevent negative environmental impacts. Social impacts, such as the role of biomass in rural development and job creation, are frequently mentioned. Studies argue that expanding biomass use could enhance livelihoods but must be balanced with food security and ecological conservation.

While several studies provide estimates of biomass availability, there is a lack of comprehensive, up-to-date, and regionally specific data. Many studies rely on broad estimates, which may not capture the local variability in biomass availability. Similarly, there has to date been insufficient focus on competing uses, and there is limited research on how to prioritise or integrate competing uses. There is a need for studies that explore the economic and environmental trade-offs between different biomass applications. Accurately mapping biomass sources in South Africa requires a comprehensive, integrated approach that uses technology, data collection, stakeholder engagement, and policy support.

Possible options include:

- Advanced remote sensing and GIS Technologies (satellite imagery and GIS systems)
- Field data collection and ground-truthing
- Integration of existing data sources (data harmonisation and use of national and regional databases)
- Dynamic and temporal mapping (seasonal variability and long-term monitoring)
- Stakeholder engagement and collaboration (multi-stakeholder involvement, capacity building)
- Development of high-resolution biomass atlases
- Use of ddvanced modelling techniques (biomass estimation models, climate and land-use models)
- Policy and institutional support (national biomass mapping initiatives, data sharing)
- Incorporating sustainability criteria (Environmental Impact Assessments, Sustainability Indicators)
- Continuous data updating

There are also underexplored value chains, such as dedicated energy crops or the use of biomass for advanced biochemicals. The literature primarily focuses on established sectors like sugarcane and forestry, with less attention on emerging opportunities. Similarly, there appears to be a gap in research on the policy and regulatory frameworks necessary to support sustainable biomass use. Studies often mention the need for supportive policies but provide limited analysis of existing frameworks or how to improve them. In this context, more research is needed on the socioeconomic impacts of expanding biomass use, particularly in rural areas. The literature recognizes the potential for job creation and poverty alleviation but lacks detailed studies on how these benefits can be realized in practice.

Despite the challenges, the bioeconomy presents opportunities for South Africa. By leveraging its abundant biomass resources, the country can develop a bioeconomy that contributes to sustainable development, job creation, and environmental protection, and reduction in carbon intensity of the economy. Some of the key opportunities include:

a. Value-Added Products

Developing value-added products from biomass can create new markets and generate economic value. Examples include bio-based chemicals which can replace petrochemical derivatives, bioplastics that are biodegradable or derived from renewable sources and bio-composites that combine biomass with other substances for use in construction, automotive, and other industries. These products can help reduce dependence on fossil-based materials, provide economic benefits, and support sustainable development goals.

b. Rural Development

The bioeconomy can stimulate rural development by creating jobs and income opportunities. Potential areas include bioenergy production, creating employment opportunities in the production of bioenergy and bio-based products, and improved energy access in rural areas through local biomass energy projects. This can contribute to poverty alleviation, enhance livelihoods, and reduce energy poverty, fostering economic growth in rural areas.

c. Climate Change Mitigation

Biomass plays a role in mitigating climate change by providing renewable energy, and enhancing carbon sequestration through development of a wide range of biomaterials. The restoration of degraded lands through biomass production can increase carbon sequestration and improve ecosystem resilience. This can contribute to national and global climate goals.

d. Waste Management and Circular Economy

The bioeconomy offers opportunities to improve waste management and promote a circular economy. By converting organic waste into valuable products such as biogas, compost, and bio-based materials, South Africa can reduce its reliance on landfills, decrease environmental pollution, and create a more sustainable and circular economy. These practices can reduce landfill use, decrease environmental pollution, and promote a circular economy by recycling and reusing materials.

e. Research and Innovation

There is potential for research and innovation in the bioeconomy. South Africa can invest in the development of innovative technologies and processes for biomass conversion, as well as in the exploration of new biomass resources. This can drive the growth of the bioeconomy and position South Africa as a leader in bio-based innovation. Investment in research and innovation can drive the growth of the bioeconomy, enhance competitiveness, and position South Africa as a leader in bio-based technologies.

Conclusion

South Africa's bioeconomy has potential for growth, but faces challenges including data gaps, insufficient exploration of new value chains, and the need for integrated management of competing uses. Addressing these challenges through comprehensive studies and policy development is crucial for sustainable growth. The future size of biomass resources is uncertain due to various factors, making it essential to continually update models and assumptions.

3.7 Uganda

Uganda's bioeconomy is underpinned by modernization of traditional economic sectors through the application of biotechnology and nanotechnology in biosciences and engineering. Significant effort has been made in developing local technologies and understanding around the valorisation of biomass especially banana peels, rice husks, coffee husks, cassava peels and maize cobs and stover. A robust scientific foundation has been built for Uganda's bioeconomy to kick-off. However, the lack of optimization of processes, insufficient economic modelling and life cycle assessments taking into consideration the entire value chain for these residues in their local contexts needs to be addressed.

Availability of Agricultural Residues

a. Agricultural residues availability

Agricultural residues are a potential renewable and sustainable bioresource for the bioeconomy in Uganda. Over 19 million tons of agricultural residues are generated in Uganda annually with crop residues having an energy potential of 150 PJ per year (Okello 2013). However, the degree of additional value chain development for these agricultural residues into "biorefineries" is still limited (Virgin et al., 2022). Figure 12 shows the total production for some of the major crops grown in Uganda (UBOS, 2020). The most grown crops in Uganda are banana for food and cassava, followed by maize and sweet potatoes. The total production for all these major crops is over 18 million metric tons on a planted land area of over 8.2 million hectares (UBOS, 2020). Therefore, it is imperative that the entire value chain for each of these crops be incorporated into the bioeconomy strategy of Uganda.

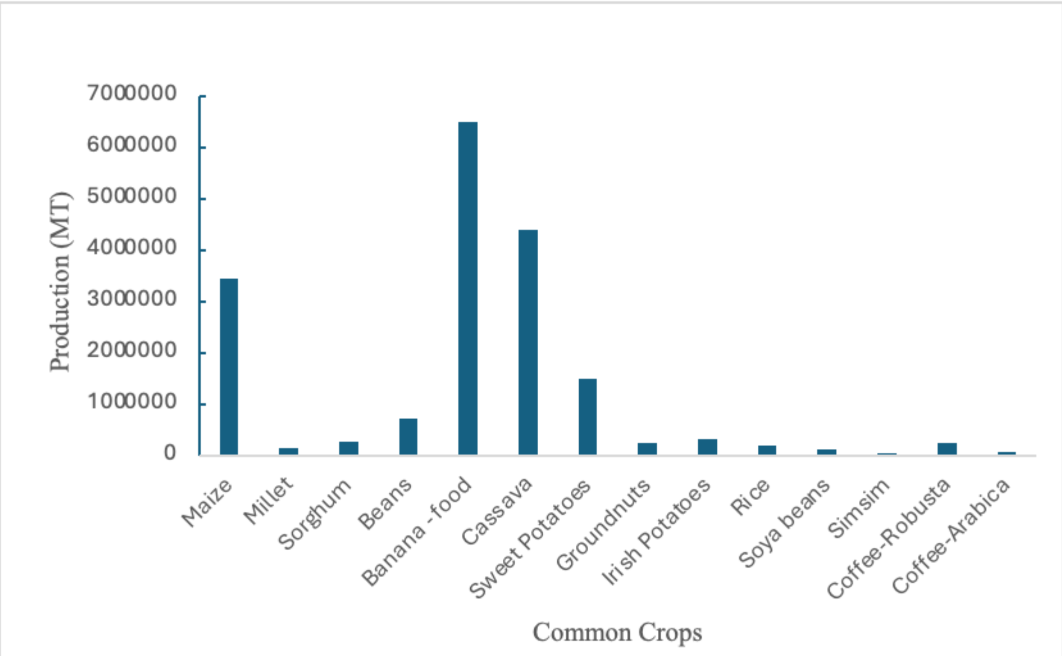

Figure 12: Total production of the major crops grown by households in Uganda

Source: UBOS, 2020

b. Banana wastes

Studies have shown that for every ton of harvested banana, about 4.18 MT for lignocellulosic biomass wastes are generated in the form of pseudo stems, pseudo stem fibres, leaves, rhizomes, fruit bunch stem, banana peels, rejected fruits, rejected chips and flour dust (Kabenge et al., 2018; Olupot et al., 2024). About 30 – 40% banana is peelings (Bhavani et al., 2023). Banana peels are a rich source of carotenoids, biogenic amines, polyphenols, phytosterols and antioxidants. It contains iron, calcium, sodium, phosphorus, and magnesium. Banana peels are used in cosmetics, medical, food processing, beverages, textiles, energy resources, paper manufacture, bio-adsorbents, biofuel production and agricultural sector industries (Khawas et al., 2017; Bhavani et al., 2023). Energy content of banana waste is a potential source of renewable energy through anaerobic digestion as the most viable waste-to-energy technique to propel Uganda's biomass industrialization (Gumisiriza et al., 2017). Optimization studies for the slow pyrolysis of banana wastes to enhance value added production of vinegar, tar and biochar (Omondi, 2016). Composite carbonized briquettes developed from banana and pineapple peels have a calorific value of 22.77 MJ/kg (Mibulo et al., 2023). Composite briquettes produced from carbonized banana peels and waste glass have an increased thermal efficiency of 40% (Nyakoojo et al., 2024). Banana peels have also been shown to be a very good source of bioethanol within acceptable standard for ethanol for use in spark-ignition (SI) engines (Yusuf and Inambao 2019, 2020). The energy potential and methane production potential for anaerobically digested banana waste amounts to 60 GWH of electrical energy per year from biogas plants (Khan et al., 2016). The efficacy of cactus-banana peel composites as natural coagulants for water treatment indicates good performance compared to 82 – 99% for alum which is the commonly used commercial coagulant (Kalibbala et al., 2023). Banana peels are also shown to have relatively good removal efficacy (70%) for purification of zinc contaminated water (Asio and Nassozi, 2020). Xerogel-immobilized quartz-banana peels activated carbon are used to remove both pharmaceuticals and toxic heavy metals from water resulting in removal efficiency of over 95% (Karume et al., 2023). Bio-composites made from bio-resin from banana peel and sisal fibres show good tensile strengths comparable to commercial composite and solid wood boards (Mwesigwa and Mwasiagi, 2018). Paper manufactured and optimized from banana stem pulp results in paper of comparable density to commercially available paper (Yiga et al., 2023). Different inoculums can be used to treat banana peels during aerobic and anaerobic composting resulting in high potential source of K and N fertilizer (Kalemelawa et al., 2012). Inclusion of banana peelings to cattle feed moderately affects feed degradability and rumen environment of cattle (Nambi Kasozi et al., 2016).

c. Rice husks

For each ton of harvested paddy rice, 1.35 tons of rice straw are generated. Each tone of processed paddy rice generates 200 kg of rice husk, 100 kg of rice bran and 140 kg of broken rice (Moraes et al., 2014). Briquettes developed from carbonized rice husks with cassava starch as binder have average heating values ranging from 15.9 – 16.6 MJ/kg (Lubwama and Yiga, 2018). Rice husks biochar briquettes can be developed with municipal solid waste cassava, sweet potato and matooke peelings as binder. The highest calorific value of 21.75 MJ/kg is obtained for rice husk briquettes with 15% matooke peelings organic binder (Lubwama et al., 2024). Biochar biocomposites briquettes of rice and coffee husks are observed to require the shortest time to boil water using the water boiling test with calorific values ranging between 16.6 and 22 MJ/kg (Lubwama et al., 2020). Different rice husks varieties in Uganda have different characteristics that affects their techno-economic feasibility in gasification. The presence of considerable ash content in rice husks necessitates downdraft gasification as the most viable option with the electricity production cost for a 250-kW rice husk gasifier system at US$ 0.22 /kWh (Olupot et al., 2016). A techno-economic assessment of rice husk powered gasification systems for rural electrification in Uganda shows that 12,591 tons of rice husks, equivalent to 4.6 MWe can be generated from rice processing villages and could sustain 135 rice husk powered gasification systems (Turinayo and Okure, 2018). Rice husks have also been extensively used as precursors in the production of activated carbon. NaOH pre-treatment reduces ash content by 74 – 93% and enhanced surface area, volatile matter and carbon content of the rice husks (Menya et al. 2018, 2020). Significant research effort has also been made on utilization of rice husks as reinforcements in fibre-reinforced plastics due to rice husks higher resistance to thermal degradation (Yiga et al. 2019, 2021). Combustion and thermodynamic characteristics of rice husks and rice husk biocomposites show that increasing the heating rates results in an increase in temperature required for thermal degradation of these composites (Yiga et al., 2023). Alkaline pre-treatment of rice husks with NaOH and $Mg(OH)_2$ has been shown to result in increased thermal stability of the Polylactic acid rice husk fibre reinforced composites characterized with increasing peak temperatures (Yiga et al., 2022). In a study to evaluate how different contents of rice husk added to concrete influence its workability, water absorption and compressive strength, it was shown that unburnt ground rice husks could replace 15% of cement without compromising concrete compressive strength characteristics (Lawal et al., 2019). Rice husk particleboards made with sawdust and different adhesives have density ranging from 510-610 kg/m^3, thickness swelling between 9 and 31% and linear expansion between 3 and 7% making them adequate for furniture boards and sound proofing applications (Opolot et al., 2022).

d. Cassava peels and rhizomes

Cassava borne environmental waste can be used to develop biodegradable materials for food packaging applications (Tumwesigye et al. 2016). Cassava peelings starch can be used as novel binders in the development of rice husk biochar briquettes as a potential alternative to the cassava starch processed from the tuber which is commonly used in briquette production (Lubwama et al., 2024). Cassava rhizomes can be combined with groundnut stalks and jackfruit waste and used as a binder to develop composite briquettes with enhanced mechanical and thermal properties. Calorific values for these composite briquettes ranges between 18.1 to 24 MJ/kg (Owino et al., 2024). Non-food parts of cassava (Manihot esculanta Crantz) can be used to produce bioethanol resulting in 60% ethanol from 8.5 g sugar derived from 28% peels and stems (Nuwamanya et al., 2011).

e. Coffee husks

Coffee husk briquettes can be developed with cassava starch and clay as binder material. Calorific values for coffee husk briquettes developed with cassava starch binder ranges from 21.9 to 23.0 MJ/kg and from 13 to 19.5 MJ/kg when clay binder was used (Lubwama and Yiga, 2018). These calorific values are similar for coffee and rice husk composite briquettes developed with gum Arabic, clay, hybrid binders and starch binders (Lubwama et al., 2020; Celestino et al., 2023). Coffee husks have been recommended as a preferred source of fuel compared to coffee pulp due to higher calorific values for coffee husks compared to coffee pulp (Twinomuhwezi et al., 2021). In a study that reported on the gasification of coffee husks, it was shown that 36,355 tons of coffee, equivalent to 21.1 MWe of husk powered system performance, could sustain 615 such systems (Turinayo and Okure, 2017). Gasifier-derived coffee husk biochar was also shown to be an effective soil amendment due to its ability to mitigate soil acidity (Deal et al., 2012). Unmodified coffee husks can be used as fillers in fibre reinforced polypropylene resulting in tensile strengths and percentage elongation varying between 27.4 and 37.4 MPa and 2.4 to 70.3%, respectively (Yiga et al. 2019). Coffee parchment husk ash can be used to develop porcelain tiles.

f. Maize cobs and Maize husks

A study on the biomass potential of agricultural and forest residues in Uganda shows that maize residues are the main crop residue with an energy potential (Okello et al., 2013). An assessment of the biochemical methane potential of various biomass types in Uganda after aqueous ammonia pretreatment shows that maize bran had the highest conversion efficiency at 83.1% with a methane yield of 291.5 mL CH_4/g chemical oxygen demand (Oliwit et al., 2020). Maize cobs can be used to develop particle boards using resins of different amounts. The densities of the particle boards range from 386 to 723 kg/m^3, which are comparable to those of the wood industry that range from 590 to 800 kg/m^3. However, the maize particleboards show poor moisture resistance properties (Sekaluvu et al., 2023). Maize stover is also a promising gasification feedstock. However low bulk densities of maize stover necessitates an increase in production costs to compact it to achieve higher conversion efficiencies (Olupot, 2023). Increasing the pressure of compaction from 150 to 250 MPa and processing temperature from 20 to 80 ℃ can increase briquette quality (Okot et al., 2018). Maize cob-based biochar filters can be used for water purification. Acceptable standards for potable water can be achieved when 2.5 kg of maize cob biochar is used (Oluk et al., 2020). The potential of maize cobs as electrodes for supercapacitors has been recently investigated after chemical activation at different temperatures. Capacitance of 456 F g^{-1} was obtained at activated temperature of 700℃ at specific current of 0.25 A g^{-1} in 6 M KOH electrolyte (Kigozi et al., 2020).

Conclusion

Biomass residues have been acknowledged as a sustainable renewable energy resource for Uganda, that can contribute to reduction in environmental degradation (Okello et al., 2013). Life cycle assessment of biorefinery systems for biomass resources in Africa has shown that they are a sustainable suggesting that biorefineries are an option for bioeconomy strategies as they enable optimal utilization of agricultural and food residues, while maintaining the net environment gains and a circular economy (Patrizi et al., 2020; Padi et al., 2022). Policy implications for enhancing the biorefineries in rural communities have shown that there is still significant need for financial subsidies and rural-based support measures for adoption of specific biorefinery technologies (Kayiwa et al., 2021b). However, promoting technologies in the bioeconomy will require meeting food security demands by increasing production through planting high yield varieties. Therefore, a delicate balance and compromise is required (Opolot et al., 2022).

4 Conclusions and recommendations

While biomass is essential for developing a bioeconomy its availability in Africa, Latin America and India has not been adequately assessed. In serval countries, biomass production ranges from agricultural residues, forest, aquatic biomass, and municipal wastes. However, reported biomass availability metrices are few and mostly based on scattered case studies. In most cases they do not represent the whole sector, regional or national scales. Similarly, competing uses of biomass have been reported to include energy, e.g., firewood and charcoal, biofuels like bioethanol and biodiesel, and gasification of bagasse (from sugarcane) to produce electricity. Other reported uses include composting to make biofertilizers, herbal medicines, livestock forage, fermentation to produce beneficial proteins, and traditional and cultural uses.

Several obstacles to effective biomass utilisation have been identified. These include weak aggregation and supply chains, inadequate policy incentives to encourage sorting at source and disposal, and lack of comprehensive data to support investment in biomass dependent enterprises. Other challenges include limited access to investment capital, and technologies for valorisation of the biomass. Addressing these challenges requires strengthening data systems, improving policy incentives, and enhancing technological innovation. In this regard, science and innovation play a crucial role in exploring new biomass sources and ensuring their sustainable supply and use. Expanding knowledge and innovation capacities will be essential to overcome current barriers and to enable a more efficient and sustainable bioeconomy transition.

Documenting availability of biomass is a necessary first step, but not sufficient. Characterising the biomass value, use and regeneration potential are most important – the concept of “bioclass”. Understanding use characteristics (or bioclass potential) can expend biomass use beyond traditional ones to include added value in clean cooking, reduction of plastic pollution, construction, improved bioinputs in food production and biopharmaceuticals. Such added value does not only augment use of existing biomass but also stimulates effort towards growing new and more biomass to meet the demand in the different economic sectors. In this regard, the role of science and innovation to explore new biomasses and their sustainable supply and use is essential.

Some more specific discussion pertaining to the countries were as follows:

- **Burundi**: Environmental impact of biomass usage, particularly its contribution to deforestation due to reliance on wood for cooking, which affects 95% of the population is of great concern. Only about 10% of the population has access to electricity, emphasizing the importance of biomass as a primary energy source. There is need to develop a national strategy for bioeconomy to align with the National Vision for Emergency established in 2014, which links 50% of its objectives to bioeconomy and biomass.
- **Costa Rica**: The need for more research into biomass opportunities beyond the pineapple sector was emphasized, indicating a concern for diversifying biomass applications. Costa Rica was noted as the first country in Latin America to have a national bioeconomic strategy, which is a significant milestone in the region's approach to biomass. Future recommendations included enhancing infrastructure through financial incentives and improving governance and coordination for expanded research and innovation in the biomass sector.
- **Ghana**: The degradation of forests in Ghana is alarming, with predictions indicating that if current trends continue, the forests could be completely gone by the year 2050. In 2022, wood fuel consumption in Ghana reached about 52.8 million tons, indicating a significant reliance on biomass for energy. The fisheries currently generate about a billion dollars a year, but this has been decreasing over time. The fisheries sector has seen a significant revenue decline of 40% over the last decade due to declining fish stocks and increased small-scale fishing

activities. Encouragement of alternative uses of the ocean, specifically the cultivation and harvesting of seaweeds, is being promoted as a potential revenue source.

- **India:** India's bioeconomy has grown from 10 billion dollars in 2014 to 151 billion dollars in 2023, with projections to reach 300 billion dollars by 2030. The need to balance food availability, affordability, and accessibility for India's large population while committing to biomass production. Balancing food security with bioeconomic goals, particularly regarding the use of food grains for bioethanol production is a key concern. Three key elements-institutional support, incentives, and innovations-are essential for India's progress.
- **Namibia**: Namibia is one of two African countries with a dedicated national bioeconomy strategy, which is significant for a population of 3 million people. The most advanced sub-sector for bush biomass production is charcoal production, which is certified by the Forest Stewardship Council for sustainable harvesting. The high cost of biomass production and the lack of production guidelines are significant challenges that hinder the effective utilization of bush biomass in Namibia. There are technical barriers to biomass utilization, including the need for imported mechanical instruments and the labor-intensive nature of the production process. Awareness and adoption of biomass utilization practices are low, particularly among communal farmers, which limits participation in the sector. Regulatory challenges exist, particularly for communal farmers who are restricted to subsistence harvesting, limiting their economic participation.
- **South Africa**: There is lack of data on biomass and challenges in collecting agricultural residues, particularly those of low value. This indicates a gap in understanding the available resources for bioeconomy initiatives. Agricultural residues and animal waste contribute significantly to biomass availability, with 130 million tonnes of cotton manure and 18 to 30 million tonnes of organic municipal waste produced annually in South Africa. There is a competition between biomass use for energy and food security. There is a need to explore the use of remote sensing and satellite imagery alongside field data to better estimate biomass availability and quality.
- **Uganda**: Uganda generates 19 million tons of household waste, which presents an opportunity for biomass valorisation and research. There is a low degree of value addition for underutilised agricultural residues, which hinders the potential of the bioeconomy in Uganda. Very few studies have focused on life cycle assessments in the context of the bioeconomy in the country, which is crucial for achieving sustainability goals. The need for financial subsidies has been highlighted as essential for the bioeconomy to develop effectively in Uganda, balancing bioeconomic growth with food security.

Several countries are pursuing bioeconomy growth opportunities through strategic investments based on their available biomass. A proper assessment to establish biomass availability, including characterisation (the bioclass concept) and competing uses spurs efforts towards not only biodiversity conservation, but also production of new and more biomass to meet the demand necessary for a just, inclusive and sustainable bioeconomy development.

Based the review, it is recommended that:

a. more information and metrics on the available biomass, quantity, characteristics, use, and locations on accessible databases is needed to ensure effective planning for and development of a sustainable bioeconomy.

b. collaborative efforts should be made to establish bioeconomy policies or strategies that provide incentives not only for biomass use, like financing, and processing technologies, but also on ways to produce new and more biomass to meet specific demands in several sectors. Policies should also seek to ensure that biomass use does not undermine broader objectives related to food security, poverty alleviation and environment sustainability.

c. As certain biomass of critical importance, like forest, insect and aquatic biomass can be transboundary, regional and international cooperation are necessary to establish frameworks for use and conservation. But most importantly, such cooperation is necessary to achieve the overarching goal of bioeconomy transition, which is reduced emissions, biodiversity and ecosystem health, better nutrition and human development and a healthy planet.

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