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Bioresource use and transformation for a sustainable bioeconomy in the tropics

Case studies from Thailand, Kenya and Colombia

SEI working paper
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Mónica Trujillo
Benjaluck Denduang
Alphayo Lutta
Yudi Yepes
Francis X. Johnson

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Stockholm Environment Institute
Linnégatan 87D 115 23 Stockholm, Sweden
Tel: +46 8 30 80 44
www.sei.org

Author contact

Monica Trujillo
monica.trujillo@sei.org

Francis X. Johnson
francis.x.johnson@sei.org

Editing

Naomi Lubick

Layout and graphics

Alejandra Aristizábal

Other graphics

Noun Project, Freepik

Media contact

Natalia Ortiz Díaz
natalia.ortiz@sei.org

Cover photo

Consejo Comunitario La Plata looks for acai palms in the forest. © Juanita Gómez Gonzales / SEI

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Contents

List of tables

List of figures

1. Introduction

In this working paper, we distil useful insights regarding sustainable use of bioresources and their transformation into bio-based products. We examine the production, harvesting and transformation of bioresources in the tropics, including conventional agricultural crops and biodiversity products. The tropics are home to the greatest social and biological diversity on the planet and share many social and economic challenges (James Cook University, 2014). We focus on micro, small and medium-sized enterprises (MSMEs), smallholders and value chains that include larger producers and processors, while considering similarities and differences between Colombia, Kenya and Thailand.

The aim of a bioeconomy is to transition to a more sustainable economy by using biological resources, including related knowledge, science, technology and innovation, to provide sustainable products, processes and services within and across all economic sectors (Global Bioeconomy Summit, 2018). It is based on the idea of applying biological principles and processes in all sectors of the economy and to increasingly replace fossil-based raw materials in the economy (Dietz et al., 2018). Although this definition is comprehensive, it falls short of covering all regions and countries' particularities and priorities. This working paper guides analysts and practitioners in promoting and advancing the bioeconomy in Southeast Asia, East Africa and Latin America. We apply an analytical framework to case studies at various scales to establish lessons learned in three areas key to the success of the bioeconomy: institutions and public policies, business organization and value chains, and technology development and innovation.

First, we describe the development and application of the analytical framework for understanding the transformation of bioresources into bio-based products, processes and services and the associated sustainability challenges for the bioeconomy in each context. We then highlight the sustainability challenges and opportunities for cassava use and transformation, taking the case of this crop as a key agricultural resource for advancing the bioeconomy in tropical and subtropical regions. We complement the analysis by including a large commodity crop case as sugar cane (Thailand) and the challenges and opportunities for the sustainable use of non-timber forest products (NTFPs) in Colombia (açaí) and Kenya (croton). Sustainable use that conserves biodiversity is of crucial importance and the subject of growing interest for the bioeconomy (IACGB, 2024), especially in the tropics where most of this diversity is found. Based on these analyses, we provide some recommendations at the micro level of bioresources and enterprises to orient analysts and practitioners in advancing the bioeconomy in these tropical regions.

1.1 Bioeconomy at the micro level

The justification for the analysis of micro-level challenges and opportunities lies in the reality that location-specific bioresources play an essential role within emerging bioeconomies in many developing countries, especially in tropical zones, given the importance of the agricultural sector (Dubois & Gomez San Juan, 2016) and rich natural biodiversity endowments (Alviar et al., 2021). Activity at this micro level involves critical stakeholders such as farmers; MSMEs; large businesses; local or subnational governments; and support institutions involved in bioresource-specific value chains. Thus, our analysis of bioresource transformation considers these critical actors, given their importance in shaping the bioeconomy and possible differences in their visions of the bioeconomy (Bugge et al., 2016).

Beyond the opportunity to enhance the economic status of these key actors, the bioeconomy is also increasingly seen as a part of the solutions to global sustainability challenges (IACGB, 2024). The bioeconomy can contribute to more than eight sustainable development goals (Singh et al., 2023) if implemented correctly, ensuring sustainability in practice. As the bioeconomy is not intrinsically sustainable (FAO, 2021), ensuring sustainability implies a process of social construction and monitoring among stakeholders. Often, in real-world bioeconomy development and assessments, some aspects of sustainability are favoured over others: for example, those aspects related to economic opportunity may be favoured over environmental and social aspects.

One vision of the bioeconomy is related to economic growth and job creation, which are achieved through value chains and cascading use of biomass to maximize efficiency (Bugge et al., 2016). To achieve broader sustainable development goals, some policies are designed to promote emerging bioeconomies, focusing on promoting sustainability certification and quality standards, among others (IACGB, 2024).

While these are promising approaches, in this chapter, we aim to provide general guidance on promoting a sustainable bioeconomy, based on specific bioresources and concrete case studies in Thailand, Kenya and Colombia. In this way, we follow the socio-economic and environmental journey from resource to product or service to better understand new value chains created at the micro level and the associated enabling and constraining conditions for advancing a sustainable bioeconomy.

As part of micro-level analysis, we have drawn on established research and analytical frameworks and adapted these to consider the sustainability challenges and opportunities in the context of advancing the bioeconomy at the level of bioresource transformation into value-added products. The three country case studies allow for a comparative analysis of bioresource transformation representative of local agricultural and natural biodiversity. Our approach is described in this section, drawing also on relevant frameworks and broader perspectives from the literature. The resulting analysis spans six distinct bioresource and location-specific contexts and serves as the empirical basis for this chapter.

The analysis in Thailand focused on cassava and sugar cane, which are considered the two key bioresources for bioeconomy development in Thailand (Aung, 2021). In both Kenya (Lutta et al., 2024) and Colombia (Canales & Trujillo, 2021), the work focused on a common example of agricultural crop, cassava; local examples of NTFPs and of local biodiversity in focus were croton in Kenya (Diaz-Chavez, 2020) and açaí in Colombia (Trujillo et al., 2025). Our selection of resources and their associated products and services is not intended to be fully representative but rather to illustrate key principles related to the advancement of the bioeconomy within a sustainable development context. By profiling both agricultural and biodiversity resources, we aim to provide concrete examples for a simple cross-section of bioeconomy development options.

1.2 Framework for analysis

Previous studies have pointed out that a bioeconomy is not inherently sustainable, as using biomass to replace fossil fuel sources does not necessarily imply ecological or social benefits (Gawel et al., 2019). Sustainability is a process of social construction and good multilevel governance. It is not spontaneously achieved simply by organizing economic activity around the use of biomass. Sustainability must be achieved at each link of the value chain related to the goods and services derived from bioresources; this includes sustainability in the extraction or production of bioresources, in its transformation and value addition, and in its consumption. This process is not standard or pre-established, and each case requires a tailored approach (Diaz-Chavez et al., 2016).

Nonetheless, frameworks have been proposed to achieve a sustainable bioeconomy. Table 1 shows one proposal for the principles that should be applied and criteria that should be met (FAO, 2021), which provides one of the frameworks used for analysing the insights gathered from the six case studies.

Some of these principles and criteria were considered to analyse sustainability at the micro level related to bioresource management and bioproduct development. We draw on elements of the new institutional economics and the tools used to analyse the competitiveness of agrifood chains and agribusinesses (Kherallah & Kirsten, 2002).

Discrete structural analysis, a framework derived from new institutional economics (Kherallah & Kirsten, 2002), offered another useful structure for understanding sustainability issues within emerging bioeconomies. Discrete structural analysis rests on qualitative analysis of the institutional, organizational and technological environments and their impact on the business landscape (Williamson, 2000). As shown in Figure 1, each level in the structure impacts and imposes constraints on the next level down (Palau & Senesi, 2013).

In 2024, the G20 agreed on 10 guiding principles for the bioeconomy, including its contribution to integrate and promote sustainable development across economic, social and environmental dimensions. The Latin American bioeconomy network, inspired by this process, also launched in 2024 the guiding principles for the bioeconomy in the region in order to guide governments, the private sector, academia and civil society organizations in the implementation of this model.

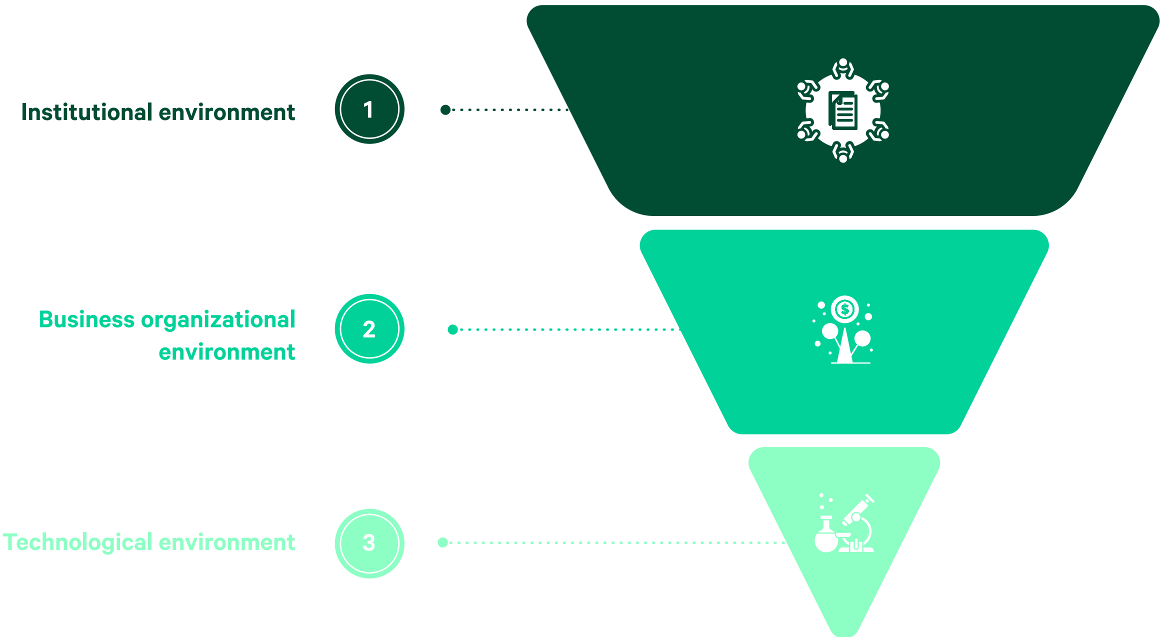
Table 1. Principles and criteria for a sustainable bioeconomy

Principles	Criteria
1. Sustainable bioeconomy development should support food security and nutrition at all levels.	**1.1.** Food security and nutrition are supported
	1.2. Sustainable intensification of biomass production is promoted
	1.3. Adequate land rights and rights to other natural resources are guaranteed
	1.4. Food safety, disease prevention and human health are ensured
2. Sustainable bioeconomy should ensure that natural resources are conserved, protected and enhanced	**2.1.** Biodiversity conservation is ensured
	2.2. Climate change mitigation and adaptation is pursued
	2.3. Water quality and quantity are maintained, and, as much as possible, enhanced
	2.4. The degradation of land, soil, forests and marine environments is prevented, stopped or reversed
3. Sustainable bioeconomy should support competitive and inclusive economic growth	**3.1.** Economic development is fostered
	3.2. Inclusive economic growth is strengthened
	3.3. Resilience of the rural and urban economy is enhanced
4. Sustainable bioeconomy should make communities healthier, more sustainable, and harness social and ecosystem resilience	**4.1.** The sustainability of urban centres is enhanced
	4.2. Resilience of biomass producers, rural communities and ecosystems is developed and/or strengthened
5. Sustainable bioeconomy should rely on improved efficiency in the use of resources and biomass	**5.1.** Resource use efficiency, waste prevention and waste re-use along the whole bioeconomy value chain are improved.
	5.2. Food loss and waste is minimized and, when unavoidable, its biomass is reused or recycled
6. Responsible and effective governance mechanisms should underpin sustainable bioeconomy	**6.1.** Policies, regulations and institutional structures relevant to bioeconomy sectors are adequately harmonized.
	6.2. Inclusive consultation processes and engagement of all relevant sectors of society are adequate and based on transparent sharing of information
	6.3. Appropriate risk assessment and management, monitoring and accountability systems are put in place and implemented
7. Sustainable bioeconomy should make good use of existing relevant knowledge and proven sound technologies and good practices and, where appropriate, promote research and innovations	**7.1.** Existing knowledge is adequately valued, and proven sound technologies are fostered
	7.2. Knowledge generation and innovation are promoted
8. Sustainable bioeconomy should use and promote sustainable trade and market practices	**8.1.** Local economies are not constrained but rather expanded through the trade of raw and processed biomass, and related technologies
9. Sustainable bioeconomy should address societal needs and encourage sustainable consumption	**9.1.** Consumption patterns of bioeconomy goods match sustainable supply levels of biomass
	9.2. Demand-side and supply-side market mechanisms and policy coherence between supply and demand of food and non-food goods are enhanced
10. Sustainable bioeconomy should promote cooperation, collaboration and sharing between interested and concerned stakeholders in all relevant domains and at all relevant levels	**10.1.** Cooperation, collaboration and sharing of resources, skills and technologies are enhanced when and where appropriate

Source: FAO,2021

The transition to a bioeconomy implies institutional arrangements and governance that go beyond traditional ways of approaching and coordinating an economy. Proper governance mechanisms for a bioeconomy are essential to ensure sustainability in the bioeconomy (Dietz et al., 2018). The institutional environment impacts the business organizational environment, and in turn, these two influence the technological environment. Change processes at the institutional level are generally slower, as the rules of the game are more difficult to transform. In contrast, technological and innovation processes are constantly changing. In the middle lie business organizations that try to adapt. In some respects, this framework suggests that those promoting emerging bioeconomies need to pay attention to slowly calibrating the institutional environment to the ever-changing technical landscape, so as to create clear and achievable opportunities for businesses.

Figure 1. Discrete structural analysis of institutional economics



Source: Adapted by authors based on Williamson (2000) and Palau & Senesi (2013). Graphics: ©Freepik

In all six case studies, SEI researchers applied standard qualitative research methods. The first methodology included a review of existing published literature, grey literature and official policy documents. In addition, semi-structured interviews were conducted with relevant actors associated with each location-specific bioresource studied (see Annex 1), the results of which we analysed using standard coding techniques (Braun & Clarke, 2006).

To apply this framework, for the institutional environment, we analysed the rules and regulations, in the form of public policies related to use and exploitation of bioresources in six location-specific case studies. For business associated with these bioresources, we analysed their behaviour and relationships, their prevailing governance structures, and their transactions within the value chains in which they participate, especially the relationships between producers and processors. Finally, at the technological level, we analysed the bioproducts generated and the capacity for innovation related to the value chains associated with specific bioresources.

The micro-level analysis in this chapter was conducted with the goal to identify opportunities for emerging bioeconomies to increase adherence to sustainability standards: namely, we used a novel approach that combined the discrete structural analysis model in Figure 1 with some of the FAO bioeconomy sustainability principles and criteria in Table 1. The approach allowed us to target the most appropriate sustainability criteria for key actors promoting emerging bioeconomies within the institutional, business organizational and technological environments suggested by discrete structural analysis (Tables 2-4).

Table 2. Sustainability criteria for institutional actors

Institutional Environment		
Key question: What are the central public policies that promote the management of bioresource/bioproducts for bioeconomy? How do they address the three dimensions of sustainability?		
Environmental criteria	**Social criteria**	**Economic criteria**
Sustainable use of natural resources and biodiversity (species, ecosystems) is promoted.	The promotion of green and decent jobs is included in the policy.	Economic objectives to increase income, growth, or productivity are included
Circularity is promoted in the processes of management: waste recovery, recycling, correct disposal, and reduction of raw materials, among others.	Inclusion of vulnerable groups (women, Afro, indigenous, youth) are promoted in these jobs	Promotion of local/regional development. Short marketing / trade circuits are included
	Issues related to gender equality (such as marginality, parity, roles, etc.) are included	Equitable distribution of income in the value chain is promoted

Source: Authors' own

Table 3. Sustainability criteria for business organization actors

Business Organizational Environment		
Key question: What are the main business models / value chain performance for this bioresource? How do the business models address the three dimensions of sustainability?		
Environmental criteria	**Social criteria**	**Economic criteria**
Actors within the value chain have standards or norms for the sustainable use of resources, biodiversity and monitoring systems	Green and decent jobs are promoted	Producers, SMEs and other businesses of the value chain are profitable, they generate profits
Actors within the value chain have circularity policies or practices: waste reuse, recycling, among others.	Representation of discriminated groups in representative positions in trade bodies, associations, companies, is promoted or included in agreements	Business models promote local/regional development short marketing / trade circuits
The actors have or are in process to achieve environmental certifications	Formal contracts are used to provide certainty to chain actors, especially with rural producers or SMEs in the first link	Business models promote equitable distribution of income in the value chain
	Issues related to gender equality (such as marginality, parity, roles, etc.) are included in agreements / contracts	

Source: Authors' own

Table 4. Sustainability criteria for technology and innovation development actors

Technological Environment		
Key question: What are the technologies that are implemented? How do these techs manage the 3 dimensions of sustainability?		
Environmental criteria	**Social criteria**	**Economic criteria**
The main technologies implemented for bioresource management and bioproduct development reduce pollution and promote the sustainable use of biodiversity	The technologies are easily accessible to different chain actors: small producers, SMEs, others*	Technologies and innovation process reduces operating costs
The technologies implemented in the production system and transformation for added value promote circularity and reuse of waste	The technology is responsive to the needs of people of different groups	Technologies and innovation process increase productivity or the quality of the final product
Technologies in the processing and value-added processes include Wastewater Treatment	Technologies, innovation process and decision making are easily accessible and include vulnerable and marginalized populations.	Technologies and innovation process generate added value

Source: Authors' own

This tailored framework was applied to the six distinct cases analysed here with two primary aims or emphases. The first emphasis was on the sustainability challenges around the use and processing of cassava as a bioresource of great importance and special significance to tropical countries.

The second aim was to apply this framework to sugar cane in Thailand and to two NTFPs, croton in Kenya and açaí in Colombia. This latter effort aimed to compare the sustainability challenges between global agro-industrial commodities such as sugar cane and more specialized non-agricultural bioresources such as croton and açaí.

2. Cassava within the bioeconomy

Cassava, a root originally from the Amazon, has enormous potential for the bioeconomy due to its adaptability to diverse agroecological zones, relatively low resource requirements and multiple uses (Kleih et al., 2019). For this reason, it has been identified as an important agricultural bioresource within bioeconomies.

The bioeconomy is emerging as an alternative to the fossil fuel economy, and the current environmental crisis urgently highlights the need for this transformation (Yang et al., 2021). Nonetheless, it would be naïve to assume that a transition from the fossil fuel economy model to a bioeconomy model will be free of conflicts or trade-offs, particularly when it comes to an agricultural bioresource with a long legacy of production and commercialization within existing fossil fuel economies. It has been argued that these trade-offs arise in part because societies continue to use the instruments and norms of the past as they attempt to innovate and move forward (Trigo, 2023). Using the framework presented in Tables 2–4, this chapter describes adaptations within institutional, business organizational and technological environments required to support the transition to sustainability as it pertains to promoting agricultural bioresources within emerging bioeconomies, using cassava as a case in point.

2.1 Public policies related to cassava

Many of the rules that shape today's bioeconomies, in the three countries analysed, were developed decades ago when the bioeconomy model was not part of national policy. Thus, the policies that promoted the use of certain bioresources, such as agricultural commodities, did not consider all aspects of sustainability. The transition to a bioeconomy, therefore, implies an essential role for the state. It requires that the state goes beyond regulating and also creating markets, making them more inclusive and fostering innovation systems with enterprises (Mazzucato, 2011).

Case studies focused on cassava in Thailand, Kenya and Colombia reveal institutional environment challenges associated with sustainable promotion of agricultural bioresources within emerging bioeconomies. Table 5 (p. 17) shows the similarities and differences in the policies that promote cassava in the countries of the three regions and the reflections on sustainability, in summary of the discussion below.

Thailand

Cassava is a commodity of great importance for Thailand's economy due to its diverse uses in different sectors. All cassava production in Thailand is processed into chips, pellets, cassava starch, animal feed and ethanol, among other products. In 2022, Thailand had 1.5 million hectares (ha) of harvested area and produced 34 million tons (FAOSTAT, 2023). Each year, domestic demand for cassava is approximately 25–30% of total production, and export demand is around 70–75% (AFSIS, 2019). Thailand is the world's leading exporter of cassava starch (WITS, 2021) and its processed products. Cassava starch is utilized in various industries such as food processing, pharmaceuticals, textiles, adhesives and bioplastic.

The market, rather than public policy, has been the major driver of cassava production in Thailand. Thai cassava production has not been supported by a comprehensive policy or specific legal framework to govern the sector and promote innovation; however, there are two key institutions that promoted the success of this industry. To increase export value, maintain price stability and improve access to high-yield and disease-resistant cultivars, the Thai Tapioca Development Institute, established in 1992, promotes cassava research and development; and the Cassava Management and Policy Committee, formed in 2014, coordinates policy related to the sector. The committee consists of the Ministry of Commerce; the chair of the Thai Tapioca Development Institute, with a focus on marketing and trade; the Ministry of Agriculture and Cooperatives, with a focus on production; the Ministry of Higher Education, Science, Technology and Innovation, with a focus on research and innovation; and the Ministry of Energy, with a focus on increasing ethanol use through alternative energy policies.

While this coordinated approach has yielded positive impacts on the cassava industry (Arthey et al., 2018) interviews with industry stakeholders reveal shortcomings in terms of government support to boost cassava yields. Between 2017 and 2023, cassava yield per hectare has been reduced by at least 3 tons per hectare (tons/ha), from 21.7 tons/ha in 2017 to 17.7 tons/ha in 2023 (TTDI, 2023). As a result, concerns have been raised about the gap between the current average yield and the aspired target, as well as the gap in cassava industry development strategy – that is, inadequate cassava supply, essentially out of synch with advancements in cassava processing and marketing performance.

There are no public policies specific to cassava for environmental and social sustainability. On the environmental front, the impetus for transitioning toward more sustainable practices primarily comes from consumers and market demands. Several interviewees emphasized that embracing sustainability can provide the industry with a competitive edge. Conversely, the absence of sustainability considerations could potentially jeopardize Thailand's standing as a leading global exporter of cassava, for example, in the form of trade barriers due to failure to adhere to certain sustainability standards. This underlines the pivotal role that sustainability plays in shaping the future of the cassava industry in Thailand.

For the social aspect of sustainability, the Bio-Circular-Green Economy model adopted by the Thai government (NSTDA, 2021) seeks to elevate Thailand out of the "middle-income trap" (a situation in which a middle-income country is unable to take on the new economic structures needed to sustain high-income levels; World Bank, 2024). Several interviewees reported that persisting challenges in the cassava sector such as poverty, household debt, labour shortages and a low mechanization rate among farmers have not been addressed since the adoption of the model. Although the government introduced several policies, such as a cassava pledging program (The Nation, 2011) and income insurance aiming to incentivize farmers to stay in business, doubts remain regarding their long-term effectiveness. There also has been a failure to establish a relationship in which stakeholders in the value chain wield equal negotiation power (e.g. small producers with starch processors), as exemplified by the abandonment of a Cassava Act draft, proposed by the Thai Cassava Farmers Association, intended to address these issues (Phaisa-ard, Rangsee, personal communication, 2023). Apart from the policies mentioned above, no other policies link cassava development to other broader social outcomes, such as gender equality or participation of specific vulnerable groups in decision-making.

Despite these deficiencies, the industry has provided rural employment and livelihoods, generating jobs along upstream to downstream operations, from daily contractors and truck drivers to factory and biorefinery workers. Around half a million households grow cassava, and the processing and downstream parts of the industry value chain, employ over one million people (Lilavanichakul & Yoksan, 2023).

The measures to develop Thailand's bio-industry focused, in the first phase, on building competitiveness for entrepreneurs to achieve economies of scale in production by establishing bio hubs in potential areas. This involved linking the agricultural sector to the industrial sector, creating a complex in the same location.

Office of Industrial Economics, 2024

The attempt to adopt bioeconomy as an overarching industrial development model started in 2018, following the vision of Thailand 4.0, an innovation-driven economic model. Some of the objectives for successful bioeconomy policy implementation, stated in policy documents (NSTDA, 2021), explicitly point to improved quality of life, inclusive economic growth and biodiversity conservation, as well as efficient resource utilization. Therefore, on the policy level, it appears that Thailand attempted to incorporate into the development of its bioeconomy all three dimensions of sustainability: social, economic and environmental.

However, actionable measures that promote social sustainability are not as clearly stipulated and enforced, unlike their economic and environmental counterparts, which entail, for instance, the creation of high-skilled jobs and environmental compliance for efficient resource use. Nonetheless, the government has identified cassava as a priority crop for bioeconomy development (Aung, 2021), due to the fact that it is produced in large quantities in Thailand and because of its versatility when it comes to being developed into a wide range of value-added products, including bioplastic and biofuel, among others (Thai Ministry of Industry, 2018).

Kenya

Africa is the world's leading cassava-producing continent. Production is focused primarily in West Africa: cassava is Sub-Saharan Africa's second most crucial staple food crop, with per capita consumption of around 800 g per person a day, serving as the primary energy source for almost 40% of the population (Adebayo, 2023). Kenya, located in East Africa, produced 775 000 tons in 2022, harvested from nearly

66 000 hectares (FAOSTAT, 2023), ranking 35th in the world in cassava production and 10th in Africa.

Cassava is a resilient and versatile crop in Kenya, adaptable to diverse agroecological zones and requiring relatively low inputs (e.g. fertilizer, water and so forth). It plays a key role in sustainable bioeconomy development, contributing to food security, agriculture, industry, renewable energy among others. Cassava is processed into various food products, including flour, starch and snacks (Okuku, 2018), providing income opportunities for farmers and small-scale entrepreneurs. The industrial utilization of cassava is currently limited, with a small proportion of cassava being used as raw materials in industrial processes, in contrast to the predominant use of cassava for food consumption (Osewe et al., 2021).

In 2019, the government formulated its National Root and Tuber Crops Development Strategy (Government of Kenya, 2019b). The primary objective of this strategy was to facilitate the conversion of root and tuber crops into a financially sustainable enterprise, consistent with the Agricultural Sector Development Strategy. It also aims to transition Kenya's agricultural sector from subsistence to commercial agriculture, addressing both local and export demands (Government of Kenya, 2019b), with a focus on value addition within agricultural value chains through processing and retail activities, while reducing biowaste.

From our review, policies do not expressly recognize the private sector as an essential partner in the development of the bioeconomy, nor do they accelerate the development of critical small business enterprises. Furthermore, support for the informal sectors that predominantly engage in the bioprocessing of products within the Kenyan context is severely lacking. The growth of bioprocessing efforts and value addition to the food produced in East Africa is also hindered by the prevalence of an informal sector with limited access to investment.

From a social perspective, our review shows the current policies fail to promote inclusivity within Kenya's bioeconomy. This is evident in the lack of emphasis placed on involving local communities at the forefront of bioeconomy development, as well as the failure to incorporate traditional local knowledge into the development of bio-based products. The significance of traditional knowledge lies in its crucial contribution to the preservation of biodiversity and the protection of ecosystem integrity.

In 2022, a regional bioeconomy strategy was developed for the East African Community, covering seven countries, to prioritize food systems, health, sustainable energy and bio-based industrialization (EASTECO, 2021). This strategy aims to integrate Agenda 2063 and the UN 2030 Agenda for Sustainable Development, leveraging existing science, technology and innovation policies for sustainable development and socio-economic transformation.

Colombia

Cassava is Colombia's fifth most produced agricultural commodity in volume, making Colombia the third largest cassava producer in Latin America (Canales & Trujillo, 2021).

In 2022, Colombia planted 201 114 ha of cassava, of which 94% was sweet cassava and 6% was industrial cassava (Agronet, 2022a), producing more than 2.3 million tons.

Given its multiple uses, cassava has enormous potential for the bioeconomy in Colombia, in particular, the bioplastic and biomaterials industry, animal feed, and the production of gluten-free products from its flour are the value chains with the greatest potential. Minimizing imports of maize and other feed grains by increasing utilization of domestically grown cassava and its derivatives would also be of great importance to encourage territorial development in Colombia. However, there are environmental, productive and social challenges that need to be overcome (Canales & Trujillo, 2021).

Despite the importance of cassava in Colombia, specific public policies have been lacking for its promotion and use, unlike other agricultural products such as palm (CONPES, 2007) or sugar cane (CONPES, 2008). However, in 2022, the Ministry of Agriculture and Rural Development launched the Cassava Country Plan to enhance the industrial cassava value chain (Agrosavia, 2022). Its primary purpose was technology transfer in the first link in the chain, through the delivery of high-quality certified seeds, the provision of technological innovations. Also relevant is the Strategic Plan for Science, Technology and Innovation (Plan Estratégico de Ciencia, Tecnología e Innovación en Agricultura, PECTIA) of the Colombian agricultural sector that defines objectives and actions over a 10-year horizon (Ministerio de Agricultura y Desarrollo Rural, 2015). For cassava, technological actions were prioritized primarily to increase productivity. Only one of the prioritized actions focused on sustainability, specifically the management and efficient use of natural resources. In terms of social benefits, no specific actions were identified.

There is a lack of technological packages associated with more sustainable production as an alternative to monoculture. Those policies do not focus explicitly on the social dimension; however, they recognize the small producer as the primary user and beneficiary of the innovations. There are no explicit elements that promote decent and green jobs from industrial cassava, nor elements to favour the inclusion of vulnerable groups such as young people or women.

In 2020, the government of Colombia launched the Bioeconomy Mission, a national public policy, to promote the bioeconomy as an engine of sustainable development in the country. In the social sphere, the valuation of ancestral knowledge, rural development, nutrition, equity and well-being of all Colombians is mentioned. Regarding the environment, emphasis is placed on adaptation and mitigation of climate change, on reducing the impacts on biodiversity and incorporating circular economy criteria. However, the goals focus specifically on economic aspects, such as the generation of employment, income and bioproducts with high added value (Government of Colombia, 2020).

In 2024, the roadmap for the bioeconomy and territory mission, the current government's strategy, was launched. It details eight subsectors in which work will be carried out and proposes short-term goals. The subsectors on which it focuses are functional foods and beverages, agricultural bio inputs (e.g. fertilizers, insecticides or other added substances made from biological sources, not manufactured chemical products), biopolymers, biorefineries, phytomedicines, biocosmetics, nature tourism and bioremediation (Ministerio de Ciencia, Tecnología e Innovación, 2023). See Table 5 for summary and comparative analysis of the three countries' policies.

Table 5. Bioeconomy and cassava policies in Thailand, Kenya and Colombia

Public policies / sustainability issues	Thailand	Kenya	Colombia
National Bioeconomy policy or strategy	Bio Circular Green Economy (2021)	Not yet. There is a Regional Bioeconomy Strategy for East Africa (2022-2032), which includes 8 countries of the region, including Kenya.	Bioeconomy Mission (2020) and Bioeconomy Roadmap (2023).
Cassava public policies and institutions	Strategy for cassava production (2017-2026). It has institutions as: Cassava Management and Policy Committee (2014). Thai Tapioca Development Institute (1992) Independent non-profit organization.	National Root and Tuber Crops Development Strategy (2019-2022) National policy on the cassava industry (2006)	Cassava Country Plan (2022). Strategic Plan for Science, Technology and Innovation of the Colombian Agricultural Sector "PECTIA" for cassava (2014).
Cassava country uses	Agro-industrial uses, primarily focussed on export markets. Domestic demand is approximately 25-30% and export is 70-75%.	Food security and recently industrial uses such as starch and flour.	90% food security, 10% industrialization starch. Mainly for domestic market.
Environmental Sustainability considerations	Absence of guidelines or standards to strengthen sustainable use of natural resources and biodiversity. Lack of comprehensive policy framework for circular practices.	Policies mention the proper use of resources but do not elaborate on strategies to achieve this. There are no guidelines for using residual biomass in a circular way.	Lack of technological packages to more sustainable production as an alternative to monoculture. No circularity is promoted.
Social Sustainability considerations	There is no clear link between cassava development and social outcomes, other than broadly suggesting that the Bioeconomy will create more income for farmers. There is no explicit consideration for vulnerable population groups	Dearth of support for the informal sectors that dominate the bioprocessing initiatives. Insufficiency in promoting inclusivity.	Recognition of small producers and their needs in terms of productivity. Lack of emphasis on decent and inclusive jobs
Economic Sustainability considerations	The economic and productive dimension is predominant. The advancement of technology and digitalization could potentially exclude the artisanal industry. Facilitating technology adoption is needed to increase yield and thus farmers' income. Lack of clear and sustainable institutional arrangements to guarantee equitable income for all stakeholders in the value chain, especially for farmers.	Lack of support to the productive sectors especially small business enterprises. Do not expressly recognize the private sector as an essential partner in the entire bioeconomy development. Minimal bioprocessing and value addition.	The economic dimension is predominant. The objective is to increase productivity, competitiveness, employment and income generation.

Source: Authors' own

2.2 Cassava business and value chains

While government support for cassava production exists to varying degrees in Thailand, Kenya and Colombia, the production, processing and commercialization of this agricultural bioresource remains dominated by private sector actors. These include producers, from small holders to industrial farming operations; input providers; transporters; processors; wholesalers and retailers. These actors play a crucial role in the development of sustainable bioeconomies based on cassava by supporting research and development, technology adoption and investment in facilities. This section explores current value chain organization and commercial arrangements for cassava in each of the three countries. See Table 6 (p. 24) for a comparative analysis of cassava in the three countries analysed and the challenges for business organization in environmental, social and economic terms, in summary of the discussion below.

Thailand

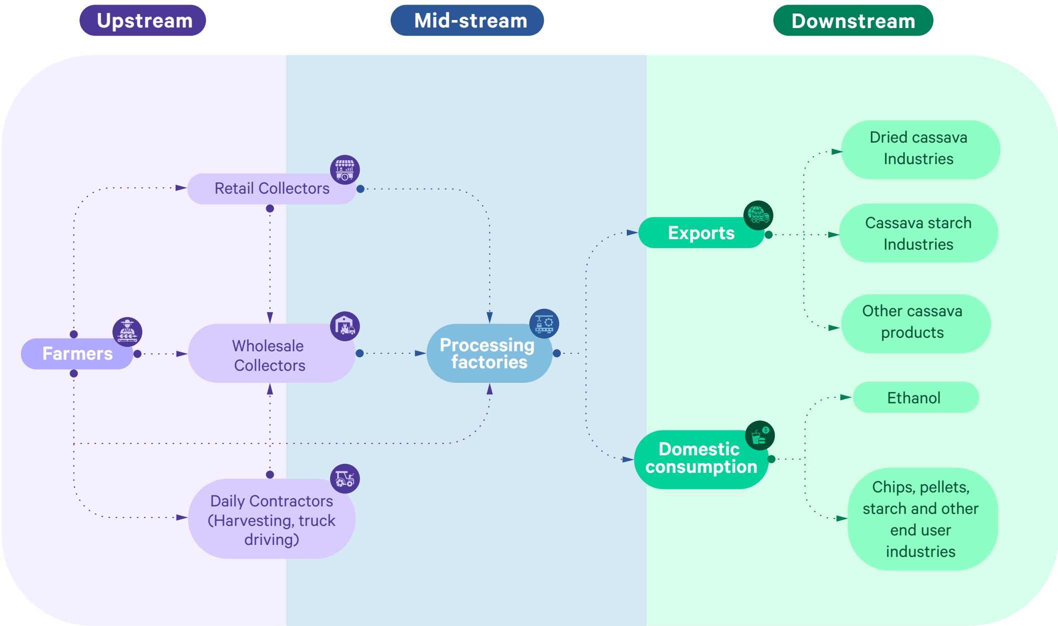
Linking companies with universities is essential for driving technological development and sustainability in the cassava value chain. By leveraging initiatives such as communities of practice and the Asean Cassava Centre for Sustainability, stakeholders can collaborate to address environmental challenges, improve productivity, and ensure the long-term viability of the cassava industry. Thailand's success in technology transfer serves as a model for neighboring countries, highlighting the importance of knowledge sharing and collaboration in achieving sustainable growth.

Warinthorn Songkasiri, Senior Researcher, BIOTEC

In the 1970s, cassava in Thailand was grown for export to Europe, mainly as dried chips and pellets for animal feed, while domestic consumption was related to starch as an ingredient in traditional desserts (Ratanawaraha et al., 2000). Thailand's cassava industry is predominantly characterized by small-scale farmers, with most operating on less than 25 Rai (less than 4 ha) (Arthey et al., 2018). To access government benefits such as disaster compensation or loans, these farmers are required to register with the Ministry of Agriculture and Cooperatives. Additionally, to become part of the Thai Cassava Farmers Association, which represents farmers' concerns in the Cassava Management and Policy Committee, farmers must be members of a cooperative, a community enterprise or a group. However, membership in these groups does not necessarily correlate with improved farm management practices. The president of the Thai Cassava Farmers Association highlighted that these groups primarily serve the purpose of facilitating group loans, with limited engagement in knowledge sharing, resource pooling or collective actions (Phaisa-ard, Rangsee, personal communication, 2023).

The cassava value chain in Thailand (Figure 2) can be divided into three main segments, including upstream comprising farmers, midstream consisting of processors (chip and starch factories), a connector layer between upstream and midstream involving daily contractors for harvesting or truck driving, retail/wholesale fresh cassava collectors, and downstream involving traders, exporters, and end-user industries both domestically and internationally, primarily in China.

Figure 2. Representation of the cassava value chain in Thailand



Source: Author's research and adapted from Sowcharoensuk (2024). Graphics: NounProject

Workers in the upstream and midstream segments typically lack formal workers' rights and social security protections. The cassava value chain typically operates without formal contracts, and even when contracts exist, they often need to be enforced. According to the president of the Thai Cassava Farmers Association, cassava farmers typically function as renters of production means from the factories, with limited opportunities for knowledge transfer and profit-sharing (Phaisa-ard, Rangsee, personal communication, 2023), with some exceptions, such as the Nakornratchasima or Korat Cassava Cluster.

One of the most significant challenges related to cassava in Thailand is that while substantial advancement in logistical management, facilities and technological capabilities within the mid- and downstream segments of the value chain have been achieved, there is not sufficient cassava production (Sowcharoensuk, 2024). The growing demand for cassava forces processors to operate their facilities at suboptimal production capacity and causes domestic supply instability. Furthermore, insufficient domestic supply necessitates reliance on cassava imports from neighbouring Southeast Asian Nations, where the cassava industry is competitively expanding thanks to Chinese investments.

Increasing yield has always posed a challenge to the Thai cassava industry. Usually the missed potential is explained by slow technology adoption by few small producers, limited knowledge exchange and support for good practices, labour shortages and climate-environmental factors, among others. In terms of climate-related factors, research indicates that both the harvested area and cassava yield were expected to decrease because of dry conditions as climate change continues to intensify (Pipitpukdee et al., 2020). Besides making the soil less productive, dry conditions and drought can also amplify the risk of disease outbreaks; the cassava mosaic disease currently posing a substantial threat in approximately 30 out of 40 provinces where cassava is cultivated (Phaisa-ard, Rangsee, personal communication, 2023). Climate change will adversely affect cassava yield and the bioeconomy, putting the livelihoods of half a million cassava farmers at even greater risk.

Producers are also hampered by covering costs: a substantial portion of cassava farmers' revenue generated goes to contractors engaged in tasks such as cultivation and harvesting, either manually or with machine assistance, as well as cassava transportation. While there is a sense that mechanization is essential to reduce expenses incurred by cassava producers, the prohibitive cost of imported technology, exacerbated by tax barriers and inadequate knowledge transfer to farmers, compels farmers to rely on manual labour, which is becoming increasingly scarce, and therefore more expensive, as younger individuals who in past generations would have been in the pool of farm labourers now gravitate towards the industrial sector.

The development of the cassava industry has also been shaped by the expansion of road networks, which have mitigated transportation costs for farmers (Arthey et al., 2018). However, interest remains in the potential benefits of an improved railway system (Phaisa-ard, Rangsee, personal communication, 2023).

International consumer markets – not domestic governmental enforcement – are pushing cassava value chain actors to better manage environmental impacts of cassava production, including waste creation, water pollution and land use change (B. Wattanaruangrong, personal communication, 2023). Practices and standards associated with sustainability, such as life cycle assessments, carbon footprint calculations, and water footprint tracking, are increasingly adopted within the cassava value chain (Napasintuwong et al., 2024). Agricultural product-specific guidelines are increasingly incorporated into internal auditing processes of cassava processors; for example, they can use the Sustainable Agricultural Initiative (SAI) Platform, a non-profit network with working groups in different agricultural sectors, without the necessity of formal membership (B. Wattanaruangrong, personal communication, 2023).

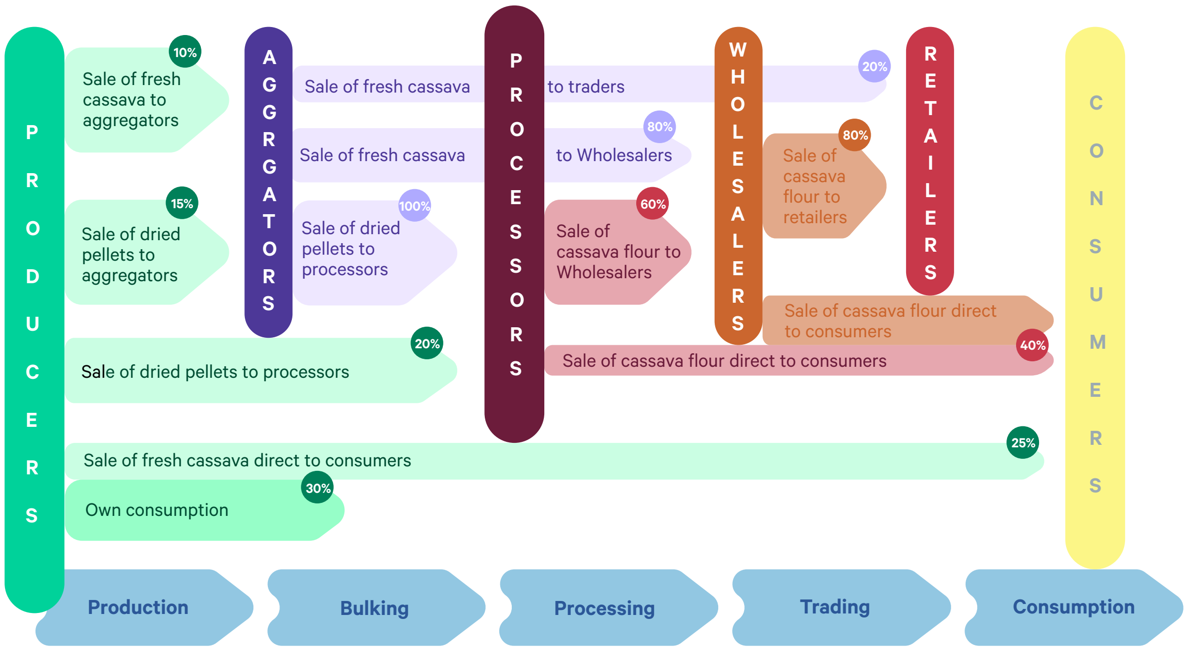
Kenya

In Kenya, cassava is grown on approximately 90 394 ha, with an annual production of 775 000 tons and an average yield of 8.3 tons/ha (Emongor et al., 2023). It is the third most important food root crop in Kenya and supports the livelihood of over 2.5 million people. It is a major food security crop and an income-generating crop for millions of smallholder farmers (KALRO, 2020).

Cassava farmers tend to be smallholders who mostly intercrop the cassava with other crops, e.g. beans, in farms that range from less than half to 1 ha. Approximately 70% of farmers grow local cassava varieties, with farmers most often getting their plantings from neighbours and, in a few cases, from the national Kenya Agricultural and Livestock Research Organization (KALRO).

In Kenya, cassava is primarily consumed at home by those who grow it, with surplus sold locally or to aggregators who supply millers. It is grown mainly for its tuberous roots as food and eaten either raw, after boiling or in a processed form. The roots are peeled, sun-dried and milled to flour for better storage. Large-scale milling is rare; small and informal flour processors predominate. Flour is used to make porridge, ugali (a staple in Kenyan food cuisine), local brews or mixed with wheat flour for home baking. Young cassava leaves provide protein and vitamins (Emongor et al., 2023) and are used in vegetable dishes among many communities. The variety of human consumption options grants cassava high potential to alleviate food shortages and energy deficiencies (KALRO, 2020).

Figure 3. Cassava value chain in Kenya



Source: Adopted from (Osumba, 2019)

The cassava value chain in Kenya (see Figure 3) employs 30% of the population indirectly and directly (KALRO, 2020). These value chains exemplify the broader bioeconomy concept (Tirra, 2019), including various input and output channels serving multiple markets. They encompass auxiliary services such as inputs, capital, knowledge and technical assistance.

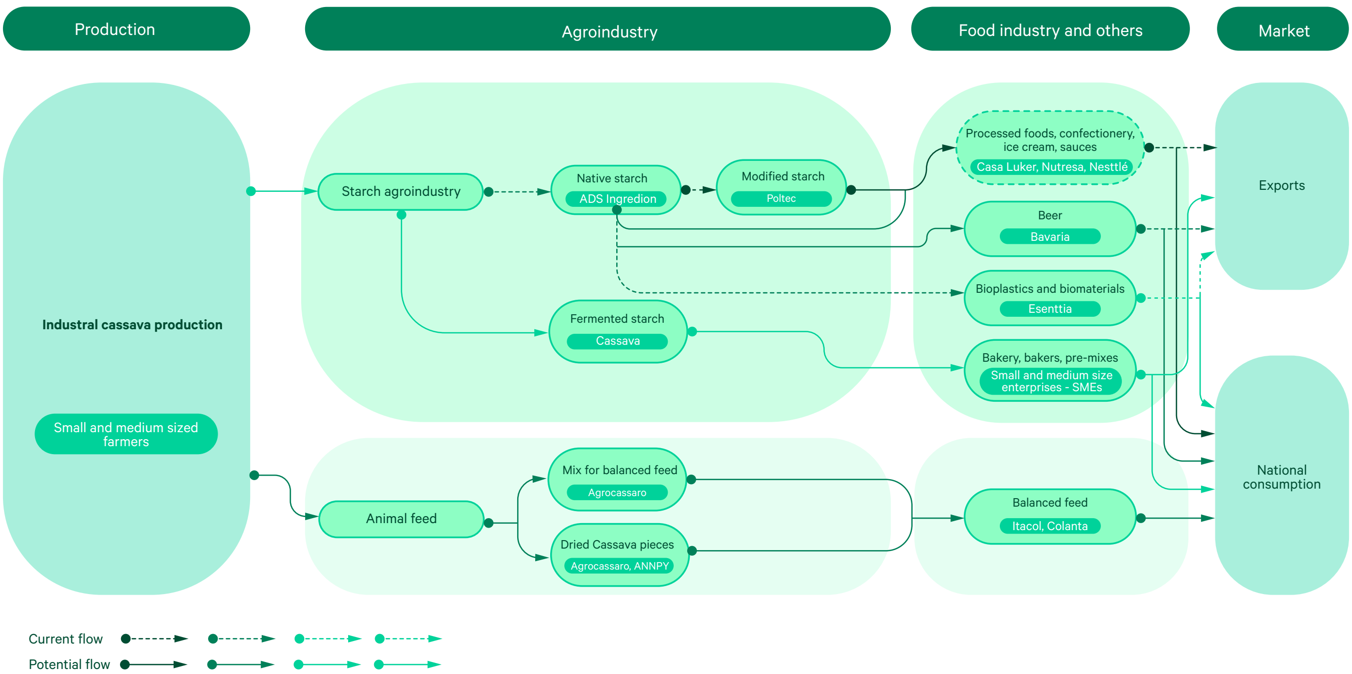
Support services play a pivotal role in bolstering Kenya's cassava value chain. Investing in these services is imperative to empower actors with essential information, expertise and resources needed for effective development (Government of Kenya, 2019a).

As high-value cassava markets increasingly demand quality and safety standards, intricate supply chains have emerged to manage product movement within distribution channels (Kleih et al., 2019). Private sector involvement becomes crucial in enhancing connectivity within the cassava supply chain, especially in addressing market inefficiencies that hinder access for marginalized communities. Collaborations between the public and private sectors can strengthen stakeholder capacities, enabling them to produce marketable products and earn substantial revenue, thereby expanding operations and production scale (Awuor et al., 2021).

Colombia

In Colombia, more than 90% of the cassava production is of sweet varieties suitable for direct human consumption. The rest is for bitter cassava varieties suitable for industrial processing into starch or dry chips for animal feed. Industrial cassava production is carried out mainly by small farmers based in the Caribbean region. Of the growers that are small farmers, most plant on less than 10 ha; 52% are tenants of land owned by ranchers. See Figure 4 for an illustration of the value chain, the actors and their transactions in Colombia.

Figure 4. The cassava value chain, actors and transactions in Colombia



Source: Authors' own

Farmers and starch processors generally do not have practices that promote sustainable use of natural resources, protection of biodiversity or circularity. Industrial cassava production is based on monoculture, and there is very little technological development for fertilization and irrigation. Cassava cultivation has traditionally been recognized as a resistant rustic crop, efficient and adaptable by nature, as it resists low fertility and drought (DANE, 2016). In this way, the mechanization, fertilization practices or irrigation systems implemented by farmers are minimal, especially with sweet cassava, which is part of family agriculture.

There are three large starch processors in the Caribbean region and various artisanal agro-industries that transform cassava into starch, mainly for the food industry. The transactions between small farmers and large starch processors are increasingly mediated by formal contracts (Canales & Trujillo, 2021).

Contracts can be "forward" or "spot". The spot type contract is for immediate purchase, with which farmers sell their harvests quickly and at the price that is in force at the time of the negotiation. Farmers tend to respond to the most attractive offer in the market (Camilo Romero, personal communication, 2023).

The forward contract is established for one year or productive cycle and sets out the conditions of product, volume, price, time and form of payment, among other conditions. The farmer obtains technical assistance during the term of the contract for the best management and yield of the crop (Almidones de Sucre, 2022). Access to credit with financial institutions is also facilitated by the contract. Even so, in Sucre and Córdoba, the two most important cassava-producing departments in the Colombian Caribbean region, only 33% and 10% of the farmers, respectively, sell cassava through contracts (Contreras, 2022).

The specific market situation with regard to contracts has shifted since new artisanal processors arrived in the region and offered higher prices to buy the harvest. This generated an increase in the price of industrial cassava in the region and several cases of non-compliance by farmers with contracts with large processors. Small artisanal agro-industries produce fermented starch that is necessary to make food products typical of Colombian cuisine.

Farmers generally work individually with starch agribusiness or processors but have also formed their own representative associations. In the region, 110 grower associations have been identified (Contreras, 2022). Although initiatives to create a national union and formalize the productive chain have been made, these have not materialized. In terms of gender, the participation of some women as leaders of industrial cassava grower associations in the region is evident, though most growers and members of associations are men.

New starch agribusinesses have arrived in the Caribbean, increasing competition for purchasing industrial cassava with high cash prices (Camilo Romero, personal communication, 2023). This coincides with a trend of high demand for starch worldwide. This situation has favoured the planting of industrial cassava, increasing the preference for immediate transactions based on the market price and indirectly generating non-compliance with longer-term contracts. These trends have boosted the regional economy in the short term; however, price fluctuations are circumstantial and can affect small growers. Table 6 summarizes and compares Thailand, Kenya, and Colombia's cassava business organization, including environmental, social, and economic aspects.

Table 6. Cassava business organization in Thailand, Kenya and Colombia

Cassava Business organization and Sustainability considerations	Thailand	Kenya	Colombia
Production	Predominantly small-scale farmers, less than 4 hectares. There are incentives to register with an association or cooperative.	Small farmers, less than 1 hectare. No incentives for associativity.	Small farmers, less than 10 hectares. In the majority, farmers are tenants of land owned by ranchers.
Formality of transactions	Low formality – no contracts with small producers. Associations negotiate with larger processors.	Informality is predominant. Individual negotiations with processors predominate.	Transactions of bitter or industrial cassava can be done through formal contracts Individual transactions predominate.
Environmental	Sustainable resource utilization, biodiversity conservation, and monitoring standards are influenced by international market demands. Circularity principles, encompassing waste reuse, recycling, and water treatment, are promoted in processing factories including Life Cycle Analysis and Carbon footprint tracking. Environmental certifications lack domestic enforcement.	No environmental considerations in the business organization of cassava value chains.	The industrial cassava business model does not include practices that promote the sustainable use of biodiversity, natural resources, and circularity. The production system is not input-intensive and lacks adequate soil and pest management.
Social	Limited use of formal contracts between farmers and cassava processors. Lack of available data on women's leadership or gender equality within the industry. Absence of reference to green and decent jobs in the context of the sector	Informal business and transactions were found.	Formal contracts between large starch processors and small producers. This allows for certainty in transactions and benefits such as technical assistance and easy access to finance. However, non-compliance with these contracts is recurrent. The gender approach and the inclusion of vulnerable groups remain challenges in the region.
Economic	Challenges related to low yield in the upstream segment, despite advanced technological progress in mid and downstream sectors. Insufficient raw material supply forces processing factories to operate below optimal capacity, making domestic supply unreliable and increasing reliance on imports. Additionally, the industry's heavy reliance on the Chinese export market poses risks, especially as Vietnam and Laos, with more economical transport costs to China, expand their production. Substantial contributions from the private and academic sectors are crucial in fostering industry development and improving technological access and adoption to achieve higher yields.	A favourable environment for the private sector and companies to generate businesses around cassava for the bioeconomy was not found.	The economic dimension is predominant in policies, business models, and technology and innovation, with a focus on increasing productivity and competitiveness in the value chain, linked to employment and income generation. The current economic cycle favors industrial cassava producers due to high root prices driven by global and national factors, including the migration of cassava growers from Cauca to the Caribbean. To mitigate the effects of low productivity and price fluctuations on the entire value chain, it is essential to strengthen business models and the relationship between agro-industries and small producers.

Source: Author's own

2.3 Cassava and technology and innovation structure

While cassava is an agricultural bioresource with a long history of smallholder production for household-level consumption, the diversity of value-added products that can be derived from cassava have prompted an increasing interest in improved technology and innovation within cassava value chains. This section summarizes the technology and innovation landscape related to cassava in Thailand, Kenya and Colombia. Table 7 shows a comparison of the sustainability challenges associated with technological development and innovation in the cassava value chain in the three countries, in summary of the discussion below.

Thailand

Southeast Asia, particularly Thailand, boasts the highest cassava production yields in the world, currently around 23 tons/ha (Kongsil et al., 2024). This productivity results from factors such as advanced agricultural practices, favourable climatic conditions, improved cassava varieties and substantial investments in infrastructure and agricultural technologies. Key initiatives, such as the Cassava Stake Distribution Program, provide farmers with high-yield, high-starch varieties and extension training, significantly enhancing productivity (Arthey et al., 2018). However, experts believe that further strengthening technological transfer to small producers could lead to even higher yields (Phaisa-ard, Rangsee, personal communication, 2023).

Technological advancements in Thailand's mid- and downstream segments of the cassava industry and value chain are well-developed, particularly in circularity practices such as waste reuse, recycling and water treatment to enhance sustainability and productivity. Processing industries have promoted biogas systems for wastewater treatment, using the generated heat for starch drying and electricity and repurposing cassava pulp for animal feed or biogas generation. These innovations highlight the economic importance of the industry (Lilavanichakul & Yoksan, 2023).

The Thai government [Revenue Department] has created a tax incentive to encourage the use of biodegradable plastic products, which are made from agricultural materials such as sugar cane or cassava. Companies in Thailand can deduct more from their taxes when they buy these bioplastics. Specifically, they can deduct 1.25 times the actual cost of the products.

BIOTEC

Thailand is the world's second largest exporter of bioplastic from cassava and sugar cane (Apisitniran, 2023), producing 95 000 tons of bioplastic annually, mainly from polylactic acid (PLA), with 90% of this production exported. The shift towards sophisticated bioproducts, such as biofuels and bioplastic, began in the early 2000s, spurred by a research project by the Thai National Innovation Agency, which focused on productivity, technology transfer, technological development and regulatory reform for bioplastic (Tagliani, 2024). Despite biofuels' initial prominence, bioplastic has since taken precedence.

Effective farm management practices such as water-efficient irrigation, soil enhancement and systematic monitoring of farming activities are crucial for achieving higher yields. Thai research institutions such as the National Center for Genetic Engineering and Biotechnology (BIOTEC), Kasetsart University, Suranaree University of Technology and King Mongkut's University of Technology Thonburi have played pivotal roles in advancing and distributing knowledge about maximizing efficiency, waste reduction, water treatment and resource optimization in the cassava value chain.

Thai academic institutions have worked in partnership with international development agencies such as GIZ (Deutsche Geseelschaft für Internationale Zusammenarbeit) to create key performance indices designed to enhance production efficiency and reduce waste (B. Wattanaruangrong, personal communication, 2023).

Mechanization is essential to address labour shortages in cassava farming, but the high costs often make it unaffordable for low-income farmers. Increased research and better outreach efforts are needed to adapt imported technologies to local conditions. Experts have proposed establishing a cassava farmers' fund, funded by a portion of farmers' sales, to support mechanization and emergency expenses. Still, the president of the Thai Cassava Farmers Association, has highlighted the significant volume of non-performing loans at the Bank for Agriculture and Agricultural Cooperatives as evidence of the financial challenges facing further production level innovation (Phaisa-ard, Rangsee, personal communication, 2023).

Kenya

In Kenya, the bioproducts generated from cassava are flour, starch and snacks for direct consumption. Cassava production declined in the 1990s and early 2000s due to the lack of good quality planting materials, leading farmers to plant diseased cultivars (Karuga, 2024). As maize became the staple amid changing climate conditions, cassava was gradually abandoned. Between 2012 and 2016, cassava production in Kenya declined by 44% due to several constraints attributed to lack of high-yielding varieties, susceptibility to cassava brown streak disease, and cassava mosaic disease (KALRO, 2020).

In response, research institutions have been pursuing advances in disease- and pest-resistant varieties with the promise to revive cassava production. KALRO has released diverse high-yielding varieties, available to smallholder farmers, with fast-maturing options that yield over 49 tons/ha (KALRO, 2024). These varieties are suitable for consumption and processing into starch, flour and animal feed. Additionally, KALRO is working to promote climate-smart technologies that could be the most effective and efficient strategy for reversing the country's declining productivity for cassava (KALRO, 2020).

Cassava is a very important crop for Kenya as it produces more energy per unit area than most cereals and is the most resilient to climate change among major African crops (Jarvis et al., 2012). Cassava can be produced in marginal and drought-prone areas, which constitute over 80% of Kenya's land area (KALRO, 2020). Still, innovation in cassava production and value-adding processing is not as developed in Kenya as in Thailand.

Colombia

Low productivity is one of the most prominent challenges in the industrial cassava value chain in Colombia, currently reported at 17 tons/ha (Agronet, 2023). This depends on the quality of the seed and on the production system. The production, multiplication and distribution of industrial cassava seed is managed by AGROSAVIA in collaboration with the International Center for Tropical Agriculture (CIAT). Currently, the Cassava Country Plan has allowed the production and distribution of improved seeds to different associations of the Caribbean. With the improved seed varieties, productivity of 25 tons/ha is expected (Contreras, 2022).

The industrial cassava production system is carried out as a monoculture with very little technology and maintenance. Experts have highlighted at least two key aspects to increase the productivity of the system: improving soil conditions and pest and disease management (DANE, 2016). Currently, the agricultural extension provided by the municipal agriculture secretariats is minimal, and this function has been delegated to cassava starch agroindustry or processors if the grower has a forward contract (see Section 2.2).

Starch extraction from cassava is a water-intensive process that can create significant groundwater and surface water pollution due to hydrocyanic acid from bitter cassava. The water requirement varies with technology and processing capacity. Artisanal cassava graters can process 4 tons of cassava per day and use 8 to 20 m^3 of water per ton (Torres et al., 2005), often exceeding wastewater discharge limits due to a lack of treatment systems (Resolución 631, 2015). Large agribusinesses such as Almidones de Sucre (known as ADS) have more water treatment facilities, while others in the Caribbean use solid traps and oxidation ponds for wastewater management.

The circularity of waste is a process of great importance to making the most of biomass. Agro-industries generally do not use their waste and by-products in a circular way to generate energy or other new bioproducts. The large starch processors sell the bran to ranchers to feed cattle. Farms seem not to engage in circular waste management (Camilo Romero, personal communication, 2023).

The energy transition also includes the transition in materials. Demand of plastics will continue but from other origins than fossil fuels. A key opportunity lies in bioplastics from waste and raw materials that are not used in food, avoiding competition with food safety.

Manuel Leyva, Esenttia Growth vice president

Transforming cassava residues and starch into biomaterials is an economic alternative that the University of Cauca in Colombia has been researching since 2005, and the university currently holds more than 13 related patents (Hector Samuel Villada, personal communication, 2023). Bioplastic is produced from cassava starch and biomaterials from bran after processing. Since 2020, the University of Cauca has been working with the company Esenttia, a Colombian company that is part of the Ecopetrol Group, which produces conventional plastic, to produce bioplastic from cassava starch (Ortiz et al., 2023). Table 7 summarizes and compares Thailand, Kenya, and Colombia's cassava technology development and innovation challenges, including environmental, social, and economic aspects.

Table 7. Comparative analysis of cassava technology development and innovation challenges in Thailand, Kenya and Colombia

Cassava technology and innovation	Thailand	Kenya	Colombia
Cassava production yields	21-23 tons/hectare (FAO, 2022)	12 tons/hectare (FAO, 2022)	• 17.5 tons /hectare (Agronet, 2022) industrial cassava • 11 tons/hectare (FAO, 2022) sweet cassava
Main bioproducts	Bioplastics (2nd world exporter), bioethanol, pellets for animal feed, starch (1st world producer and exporter), and specialized ingredients for food.	• Flour, starch and cassava snacks. • Direct human consumption of cassava roots and leaves	Native, modified, and fermented cassava starch for the food industry. Direct human consumption of cassava roots for different typical dishes. Recent opportunity: bioplastics from cassava starch.
Environmental	The predominant system is monoculture with low mechanization rates. Farm management practices are lacking, including water irrigation efficiency, soil improvement, and on-farm monitoring systems. Production technologies do not reduce pollution or promote the sustainable use of biodiversity. Production technologies do not reduce pollution or promote the sustainable use of biodiversity. Processors incorporate circularity into their production processes, implementing waste use systems (e.g., generating biogas), and incorporating wastewater treatment.	Self-consumption farming system. Rotation with other crops. No circular or wastewater treatment systems were identified.	The industrial cassava production system is monoculture. Research, development, and innovation for this crop are low, especially in mechanization, fertilization, and irrigation systems. Starch production requires a lot of water, and wastewater treatment systems are not implemented. Circular systems are also lacking in processors' agro-industries and farms.
Social	Technological access and adoption are usually limited to medium and large-scale farmers, as well as processors. Inadequate and inconsistent knowledge sharing from knowledge producers to farmers to enhance farm management practice. Cassava producers are ageing and there is no generational renewal. Technologies, innovation processes, and decision-making are not easily accessible to small farmers and vulnerable and marginalized populations.	KALRO has recently developed more productive and disease-resistant varieties to increase yields for small-scale cassava farmers. These are expected to be easily accessible to small farmers. Factors such as poverty, inequality, and limited access to resources can hinder the participation of marginalized communities in the bioeconomy.	Innovation and technological access for small farmers is low. Relationships between universities, research centers, and public agricultural extension is weak. Cassava producers are ageing and there is no generational renewal. Technologies, innovation processes, and decision-making are not easily accessible to small farmers and vulnerable and marginalized populations. Smallholder farmers are mostly tenant farmers on cattle ranchers' land, which often creates disadvantages due to crop shifts.

Table 7 cont.

Cassava technology and innovation	Thailand	Kenya	Colombia
Economic	Research is extensively conducted in Thailand to improve production management, especially at the factory level. This results in resource maximization and, therefore, higher margins. Technologies and innovation processes generate added value for cassava bioproducts such as bioplastics, animal feed, bioethanol, and specialty food.	Kenya and the cassava sector lack the technology and innovation to generate added value for cassava.	The new cassava varieties being distributed in the country are more productive, more resistant and have higher starch content, which will generate better yields and profits for producers. The University of Cauca plays a fundamental role in generating technologies for the transformation of cassava starch into bioplastics and the processing residues into biomaterials. The Ministry of Science, Technology and Innovation is funding bioeconomy calls that promote this technology transfer.

Source: Authors' own

2.4 Challenges for the cassava bioeconomy

A comparative analysis of the institutional, business organizational and technological environments provides several useful insights that could be of potential interest to relevant actors looking to promote the use of this bioresource as an engine for the bioeconomy in tropical countries.

The bioeconomy policies in the countries and regions analysed here have been launched recently: 2020 in Colombia, 2021 in Thailand, and 2022 in East Africa. In general, these policies are very similar and seek to harness agricultural biomass and biodiversity together with biotechnology and innovation to advance sustainable development. However, because they are so recent, the practical delivery of sustainability impacts in the three main areas is minimal, especially in environmental impacts and social demands.

Although cassava originated in the Amazon, Thailand has maximized its potential for high-value transformation and commercialization, driven by private initiatives since the 1970s, later supported by public policies, research and development. Thailand has established itself as a world leader in the cassava industry by developing sophisticated bioproducts such as bioplastic, bioethanol and specialized food and feed ingredients. However, this is not enough to achieve a sustainable bioeconomy if key issues such as soil degradation, better utilization of biodiversity and opportunities for smallholders are not addressed.

In Colombia and Kenya, cassava is primarily used for food security rather than industrial transformation into starch and flour. Colombia's cassava starch industry is growing, with opportunities in specialized ingredients for the food industry, bioplastic and animal feed, but it faces challenges related to business organization, among other sustainability challenges. Kenya's cassava industry is nascent, with low yields, disease issues and a high level of informality, and mainly produces flour for human consumption. Specific public policies related to incentivizing the expansion of potential uses will likely need to be established to realize the additional value-added related to these new uses.

Public policies in all three countries have focused on increasing productivity in different levels and ways, which is essential to business competitiveness.However, cassava policies have not addressed environmental sustainability or social inclusion.

From an environmental perspective, public entities or policies are lacking to promote sustainable production systems as alternatives to conventional monocultures for growing industrial cassava, which degrade soil quality and biodiversity. Policies could better support digitalization, mechanization and crop management practices, including efficient irrigation water management, soil management and monitoring systems.

From a social perspective, despite cassava being mainly produced by smallholders, few policies support their welfare, such as encouraging cooperatives, training, land ownership, generational succession, mechanization and adoption of new technologies. Yield increases will likely emerge from various sources, including improved cultivars, improved production systems and improved access to required inputs and services – for which smallholders need to be considered, in terms of their capacities and training. Assessing whether existing innovation structures can generate the required productivity – and adapting them if they are not – also needs to be a priority.

In general, informality prevails in commercial transactions with small-scale cassava producers. However, some experiences can be strengthened as good practices. For example, there are incentives to organize into associations or cooperatives in Thailand, which improves the bargaining power of small producers; in Colombia, there are formal contracts between agribusinesses and small producers, but they are made individually, which is positive in terms of certainty but discourages participation in associations. This instead could be encouraged, and formal contracts between small producer associations and agribusinesses could be managed by associations. To improve competitiveness, it is also necessary to strengthen the entrepreneurial capacities of small producers' associations, agricultural extensions, technology transfer, and the permanent support of public institutions and research centres for small producers.

Realizing value addition that goes beyond conventional supply chains for human consumption will require the entry of new actors and enterprises into the sector, particularly in the areas of processing, transformation and commercialization. These new enterprises likely will seek more secure business arrangements than those typically found in current cassava supply chains, many of which are informal. Developing standard contracts that will facilitate the entry of these actors should be a priority.

Circularity practices that promote environmental sustainability in the industrial processing of cassava starch have been adopted more widely in Thailand than in Kenya or Colombia. Environmental sustainability is more driven by international market demand than by Thailand's environmental regulations, but it generates good practices worth replicating. Water and waste reuse in Colombia and Kenya were not found at similar levels to Thailand's. In general, no elements of green jobs or criteria for including vulnerable populations such as youth or women were found. Imports of cassava for industrial processing were found in Colombia and Thailand, i.e. processing plants are not operating at total capacity. Thus, the room for growth that exists could favour rural development in these countries.

Mainly large producers and processing companies have access to and are able to adopt new technologies. There is very little knowledge sharing and technology transfer with smallholders.

The problem of ageing producers and few young people in the field is present in all three countries, with no clear strategies on how to deal with it – generational transfer. One option that emerges from the vision in Thailand is mechanization and the development of new technologies in agriculture; these could make this business more interesting for younger generations. Public policies and the articulated work between government, academia, companies and small producers must be strengthened to manage these challenges for sustainability in the framework of the transition to the bioeconomy.

3. Assessing sugarcane

We used the discrete structural analysis framework outlined in Section 1.2, which examines institutional, business and technological environments. Our analyses in these three categories provide valuable insights addressing sustainability needs for a large-scale agricultural commodity.

Sugar cane has always been a crucial commodity in Thailand's agricultural economy. Thailand produced more than 105 million tons of sugar cane (Statista, 2023) and it is currently the third largest sugar producer globally, after India and Brazil, with nearly 15 million tons of sugar produced. In addition to sugar production, sugar cane is the second largest raw source of ethanol worldwide and is used as a solid fuel in an efficient cogeneration system to produce bioelectricity (Karp et al., 2022).

3.1 Institutions and public policies

Due to its economic importance over the past half century, sugar cane is heavily regulated. In Thailand, the first regulation of sugar production and consumption was codified in 1961 and eventually evolved into the Cane and Sugar Act of 1984 (B.E. 2527). This act stabilized the sugar cane industry by controlling production and sales quotas and ensuring profitability for growers and millers through a revenue-sharing scheme. It established the Office of the Cane and Sugar Board (OCSB) in 1963 under the Ministry of Industry and required the formation of growers' and millers' organizations. The act was revised in 2022 in response to the development of bioeconomy ambitions in Thailand and concerns regarding unfair regulatory practices expressed with the World Trade Organization. The revisions included removing regulatory barriers, providing investment incentives, and supporting technological research to accelerate bioeconomy growth; the revisions also led to restructuring of the cane and sugar sector to incorporate the value of sugar cane co-products such as ethanol and electrical power into the revenue-sharing system.

After reviewing the sustainability criteria associated with the promotion of the bioeconomy, it seems that policies and actionable measures related to sugar cane focus mainly on economic growth. There are some measures of environmental safeguarding, but they are secondary. The industrial pathway of sugar cane production lacks consideration for alternatives to the mainstream primary production models. While circularity is regulated and incentivized partly by law and external product standards, millers usually employ it to increase cost efficiency. Thus, at the micro level related to public policies that promote sugar cane bioresource development, Thailand lacks a comprehensive framework to promote sustainability.

3.2 Business organization and value chain

The cane and sugar industries account for 21% of Thailand's agricultural sector's GDP and 48% of the food industry's GDP. Because Thailand is the second largest exporter of sugar globally (and third in production volume), the industry is a major source of income for the rural population and local employment (Preecha et al., 2017).

Under the Cane and Sugar Act (1984), the Cane and Sugar Board allocates cane production quotas to registered millers, who then allocate quotas to their registered growers. Growers and millers, the primary private sector actors in the supply chain, enter direct or indirectly (subcontractual relationships), ensuring cane supply to mills (Preecha et al., 2017). Growers receive partial payment, credits and essential means of production, with costs deducted from their cane sales. In direct contracts, larger growers are contracted directly to millers, while in subcontracts, smaller growers are linked to millers through larger growers or "quota heads" who provide similar support and additional informal social safety nets. This contract farming system reduces market risk for both parties, provides social support, and makes growers eligible for various government benefits.

In the quota head system in Thai sugar cane farming, 80% of growers are small-scale, operating on less than 9.6 hectares, which reflects the demographics of the sector, where 20% of growers are large-scale operators or quota heads (Narathip Anantasuk, personal communication, 2023). While this system provides income and social safety nets, quota heads often exploit their power and influence by offering means of production at higher prices and deducting coordination costs from sales. This, combined with low yields and sugar cane prices, can lead growers into debt, forcing them to continue unprofitable cane cultivation. To counteract this, some growers form cooperatives or community enterprises for better negotiation power (Narathip Anantasuk, personal communication, 2023), with some bypassing quota heads to deal directly with mills. However, these organizations do not legally ensure equity among members, including gender equality or representation of vulnerable groups.

In terms of environmental sustainability, it is recognized that monocultures can be a threat to biodiversity. Additionally, the burning of sugarcane biomass is a pollutant. However, there is no significant incentive to change; the premium price for a sustainable and safer standard is very low. On the other hand, one of our biggest challenges is the ageing population and the shortage of manpower to cut cane.

A representative of the thai sugar millers corporation (tsmc) in 2023

Cane cutters are crucial but often overlooked; these workers have a high impact on the quality and availability of sugar cane and its products. Despite agriculture employing one-third of Thailand's workforce and contributing 6% to GDP (International Trade Administration, 2024), farm workers are among the poorest. Although cane cutting can be mechanized, 90% of harvesting in Thailand relies on manual labour due to the high cost and limited availability of imported machines (Manivong & Bourgois, 2017). While some mills offer rental machines, the demand significantly exceeds the supply. Imported machinery for cane cutting in Thailand is unsuitable for local landscapes and farming practices, due to small plot sizes and inconsistent row distances. Consequently, cane cutting, a labour-intensive and time-sensitive task, is outsourced to seasonal workers. Labourers burn the cane leaves to facilitate quicker harvesting, and this practice contributes significantly to severe haze pollution in Thailand and neighbouring countries (Marks, 2022). Burning cane for harvest also negatively affects the quality of the final sugar produced.

The labour shortage and limited access to appropriate harvesting technology promotes burning, impacting the quality and supply of sugar. This complex interaction highlights the challenges faced by small-scale growers compared to medium and large-scale operations that benefit more from value addition (Choonhawong, personal communication, 2023).

Despite the high demand for sugar cane, Thailand struggles due to low productivity and risks a sugar cane supply shortage (Choonhawong, personal communication, 2023). Consequently, larger millers may acquire more land to ensure a steady supply of raw materials.

The lower profits for sugar cane growers, driven by drops in global sugar prices, climate uncertainties, labour shortages, higher operational costs and limited mechanization, motivate them to seek a larger share of revenue from downstream products. According to the original Cane and Sugar Act (1984 B.E. 2527), net revenue from the sale of sugar and molasses is allocated to growers and millers at a 70:30 ratio.

The amended Cane and Sugar Act (2021 B.E. 2565) included the residues from processing. For example, bagasse (fibres left after crushing) is included under the act in the revenue-sharing system, recognizing its value for use as fuel in mills and for packaging materials, even though it was previously considered waste. Some mills have power plants to generate energy from cane leaves and bagasse, and some produce fertilizer from vinasse and filter cake for their contracted small-scale growers.

Millers are motivated internally and externally, complying with Thai laws on wastewater treatment and international sustainable sugar production standards (Bonsucro, 2023). However, at the farm level, enforcement of environmental and social regulations is inadequate, particularly concerning health, safety and ecological impacts (Manivong & Bourgois, 2017).

3.3 Technology development and innovation

Thailand's sugar cane industry has made regulatory advancements to promote value addition, but the production of raw materials still needs improvement. Key challenges affecting the industry's sustainability and competitiveness include reliance on conventional farming practices, low mechanization levels, insufficient use of modern technology, poor agricultural management practices and limited capacity to adapt to climate change.

Traditional farming practices imply reliance on rainfall, manual harvesting and burning, with low mechanization and limited use of technological solutions. Growers and millers recognize that mechanization and technology – such as irrigation systems, precision agriculture tools or harvesting machines, can reduce costs and improve efficiency. Still, socio-economic factors such as age, income and affordability impact growers' and millers' access and adoption of these tools (Choonhawong, personal communication, 2023). The gap in technology adoption hampers the industry's potential. This gap and suboptimal agricultural management are in part due to insufficient government intervention in agricultural knowledge transfer, lack of government support for precision farming and mechanization, and lack of government incentives for younger labour to join the industry.

Consistent and widespread input is still needed from academia on plant variety, pest management and optimal fertilizer use. Knowledge access depends on group memberships, leading to uneven distribution. The government supports growers through regulations that facilitate access to credit from financial institutions and millers for irrigation and technology development. However, the challenge of low productivity is likely to persist without addressing underlying socio-economic issues (Choonhawong, personal communication, 2023).

Climate change poses a significant threat to the cane and sugar industry, with extreme weather events such as droughts and floods set to shift. Historically, these events have impacted global sugar supply and prices.

To sustain the Thai sugar cane industry and its bioeconomy, building capacity in climate knowledge, optimal agricultural management practices, mechanization and policy support is essential. These measures are crucial for adopting necessary knowledge and practices to ensure the industry's future sustainability. Moreover, diversifying into new bio-based products and processing systems, thereby modernizing the sugar cane bioeconomy, can be a means to hedge against climate change risks.

4. Biodiversity products and the bioeconomy

Efforts to support emerging bioeconomies often involve exploring various potential bioresources to achieve value addition and sustainability. The bioeconomy extends beyond traditional principles of agriculture or forestry management or conservation; it means viewing biodiversity, when used sustainably, as a means for adding value and engaging in cross-cutting innovation.

The development of non-timber forest products (NTFPs) promoting the sustainable use of biodiversity is gaining increased interest and attention for the bioeconomy (IACGB, 2024). Here, we analyse the sustainability challenges of more specialized non-agricultural bioresources such as croton and açaí, both NTFPs.

4.1 Croton in Kenya: what are the opportunities for NTFPs in the bioeconomy?

The croton tree, scientifically known as Croton megalocarpus Hutchinson, is native to eastern and southern Africa (Kedir et al., 2022). The nuts of the tree are an example of NTFPs that are a wide variety of natural bioresources derived from forests (CIFOR, 2011). The seeds within the nut have high oil content (30%) and possess notable levels of protein (50%) (Aliyu et al., 2010), though they are inedible. The oil can be extracted through mechanical means or with the use of chemical solvents. The oil has been documented as a viable fuel source for diesel stationary engines, including generators and irrigation pumps (Mutemi, 2021). Additionally, the oil can be utilized for medical applications, and the byproduct of crushed seeds made into seedcake can be used as a feed for poultry.

Biomass sources such as croton offer valuable feedstocks to produce bioenergy as biogas or biofuels alongside other value-added products (Virgin et al., 2022). Biofuels can help address both climate change and energy security challenges by reducing greenhouse gas emissions, enhancing energy diversity, and fostering sustainability (Jha & Schmidt, 2021).

Institutions and public policies

Kenya committed to international agreements such as the Paris Agreement and the SDGs, and the country actively promotes renewable energy advancement, as outlined in different policy documents (Energy Act, 2006) (Sessional Paper No. 04 of 2004 on Energy, 2004), which promotes biofuel development. The Kenya Bureau of Standards oversees biofuel quality and environmental impact assessments. The Bioenergy Strategy (2020–27) focuses on sustainable bioenergy production to reduce greenhouse gas emissions by 30% by 2030. Many biofuel technologies and systems are still in the early development stages.

In Kenya, biofuel management and regulation involve multiple government ministries, leading to coordination and enforcement challenges. The Ministry of Agriculture and

The government of Kenya is aware of the transformative potential of the bioeconomy, including the conservation, protection, restoration and management of the environment and forest ecosystems, climate change adaptation and mitigation, agroforestry and commercial forestry development.

Linda Kosgei, Ministry of Environment and Climate Change, Kenya

Environment handles tree cultivation, while the Ministry of Energy oversees processing and utilization. Different departments manage transportation and marketing. Current policies lack a clear regulatory framework, causing project authorization uncertainty, land use conflicts, and difficulties in enforcing environmental and social regulations. Despite acknowledging the importance of technological innovation, the strategy lacks provisions for technology transfer and adoption, hindering the implementation of advanced bioenergy technologies. Thus, although there is an opportunity to generate biodiesel from croton nuts, public policy falls short of taking advantage of this opportunity.

Business organization and value chain

Eco Fuels Kenya Ltd. (EFK), now known as EcoFix (EFK), is the only company in Kenya successfully generating bioenergy from tree products, specifically croton oil. EFK conducts research and development on bioproducts derived from croton oil and explores markets for these products. The company purchases croton nuts from subsistence farmers, providing them with additional revenue through contractual arrangements. EFK handles the collection and transportation of the fruits, which are then dried and husked. The oil extracted from the nuts is marketed as biofuel for various machines, while the residual cake is processed into chicken feed. The shells and cake are also composted to produce organic fertilizer.

EFK markets organic fertilizer produced from croton oil by-products to local vegetable and flower producers (Jacobson et al., 2018). The residual compost undergoes pyrolysis to produce vinegar, which is sold as a biopesticide. EFK's business model includes a croton tree planting initiative in Kenya. As the sole global processor of croton nuts, the company is expanding its operations to meet the growing demand in East Africa for organic biofuel, animal feed and organic fertilizers.

EFK employs two distinct business models involving agents (aggregators) and farmers (collectors) (Diaz-Chavez, 2020). In the first model, agents gather dried croton fruits from multiple farmers and transport them to the factory, with EFK providing transportation. EFK compensates the agents, who then pay the farmers. In the second model, a group of collectors sells to a lead collector who operates on a commission basis. EFK trains all farmers on specific requirements for the fruits, including size, adequate drying, and freedom from fungal infection, ensuring quality control.

This business model integrates interesting elements for the bioeconomy. On one hand, it works with subsistence rural communities, strengthening their incomes and organizing new value chains from forest products. On the other hand, it generates new bioproducts from the use of the nut and its residues, including biodiesel, animal feed and bio inputs, among others. Ensuring environmental sustainability in the croton bioeconomy means avoiding monoculture systems and favouring virtuous replication of innovative production models that rely on croton as a natural bioresource, without conventional agricultural settings.

Technology development and innovation

To drive the bioeconomy, practical engagement with the private sector is essential, requiring catalytic funding support. Supporting initiatives that enhance capacity building and linking theoretical knowledge to the real world by involving students in practical innovation and invention, as well as bridging the gap from laboratories to markets, is vital.

Shira Mukiibi, BioInnovate Africa

The oil can be extracted mechanically or chemically and used directly as a diesel substitute in engines or processed into biodiesel (Diaz-Chavez, 2020). It also has applications in leather tanning, paint, soap and cosmetics. The residual seedcake is suitable for chicken feed, and the nitrogen-rich husks can be used as organic fertilizer or to produce agricultural waste briquettes.

EFK produces liquid biofuel, organic fertilizers, briquettes and chicken feed using a sustainable manufacturing process that minimizes waste from croton. To enhance productivity, support is needed for identifying and cultivating high-quality croton trees through the establishment of germplasm resources, including the collection of naturally occurring seeds. Additionally, capacity development initiatives, such as training sessions on croton planting and management for smallholder producers, are essential.

4.2 Açaí in Colombia: how can a forest-grown "super fruit" be turned into a sustainable business for the bioeconomy?

Açaí is a fruit from a wild palm tree species, Euterpe oleracea, that is located in northern South America's humid, flooded forests. Brazil is the world's largest producer of açaí and accounts for 85% of world production, producing 1.5 million tons from 233 000 ha in 2022 (IBGE, 2022). This palm is also part of the tropical forests of Colombia, Ecuador and Bolivia, among others. In Colombia, it is also called naidí in the Pacific region of the country, and in 2022, the country produced 23 000 tons from 4600 ha (Agronet, 2022b).

The potential of açaí as a NTFP stems from its high antioxidant activity. The fruit has high proportions of anthocyanins, especially delphinidin, cyanidin and ferulic acid, which are potent antioxidants that protect cells from oxidation (Avila-Sosa et al., 2019). These characteristics mean that açaí is considered a "super fruit", from which functional foods, biocosmetics and pharmaceuticals can be made.

Institutions and public policies

In Colombia, the sustainable use of wild flora and forests is conceived as a strategy for their conservation and management (Decreto 1076 de 2015, 2015). In the national legislation, NTFPs are goods of biological origin other than timber and fauna, obtained from wild flora. In 2021, Colombia approved a regulation regarding the sustainable management of wild flora and NTFPs such as flowers, fruits, seeds and roots (Decreto 690 de 2021, 2021). The decree promotes sustainable biodiversity use, ecosystem conservation, and the balance of traditional and cultural values and provides the legal framework to use NTFPs.

While individuals can use natural resources freely for basic needs, commercial use requires a permit and a technical study. With the support of international cooperation, management protocols have been established for six priority species (including the açaí) to facilitate the evaluation by regional environmental authorities. In some cases, micro, small and medium-sized community enterprises are known to have gained access to permits through the support of international cooperation projects (P4F, 2022). In general terms, despite being a significant step in promoting the sustainable use of biodiversity, the decree lacks detailed guidelines for technical studies and poses economic challenges for community enterprises in complying with the law.

Although there is already a bioeconomy strategy in Colombia, there is still a need to move from diagnosis to action. It is necessary to generate more instruments to promote entrepreneurship, for the incorporation of science, technology and innovation, to encourage investment and thus consolidate the bioeconomy in Colombia.

Claudia Betancur, Director, Biointropic

In Colombia's bioeconomy strategy, biodiversity and ecosystem services play a central role. The country's geographical and bioclimatic conditions make it one of the most biodiverse countries on the planet.

Business organization and value chain

Functional foods and cosmetics are the two interconnected value chains that currently generate the highest volume and value of açaí fruit transactions in Colombia. In the food sector, two markets were found: açaí palm heart and fruit. Between the late 1970s and early 2000s, the main use of the açaí´s palm tree was the extractive exploitation of palm heart for export markets; this has been the most significant business in terms of volume and value associated with the açaí, led by foreign companies.

Initially, this exploitation generated concern among the environmental authorities, as it involved cutting down the entire palm; at that time there was a lack of information and research to ensure that the population would not be depleted. Despite this initial exploitation, some studies show that the Pacific populations were maintained due to factors such as the species' reproduction vigour, its abundance, its invasive nature, and the participation of Afro-descendant communities in the management of the species (Vallejo Joyas, 2013).

Commercial use of the açaí fruit in Colombia has been more recent, starting in the mid-2000s, and currently is the fastest growing market. In contrast to the commercial use of palm hearts, cutting the whole palm to harvest the fruit is unnecessary. One company that has led the value chain of functional foods is Corpocampo, which started as a small Colombian company from Putumayo (a department in the Colombian Amazon) and has been growing, expanding markets with Amazonian fruits and consolidating a sustainable business model. The company combines the harvest of açaí in natural forests and agroforestry systems; it won the Business for Peace Award in 2018, an international award highlighting inclusive business models.

Other value chains with potential regarding açaí are associated with ecological restoration and "nature tourism" with local communities. Interviewees identified the trees' potential for ecological restoration, especially in flooded ecosystems along riverbanks. Ornamental use was identified as a potential, based on knowledge of the species' propagation techniques, which are still experimental and under investigation. These uses involve providing conditions for natural regeneration, ecosystem restoration and planting the species on riverbanks.

Maintaining the açaí ecosystem in a good state of conservation attracts wildlife that is valuable in terms of nature tourism, especially birdwatching, and also for Indigenous and Afro-descended communities' identities; traditional uses of these ecosystems include hunting for food security. Açaí is a fundamental part of the daily life, culture and historical roots of the territory of the local communities.

Business models with biodiversity products require a different approach in terms of investment. Impact funds and credit lines are needed with longer terms that respect the timeline of the forest and the market return. Entrepreneurs need patient, not short-term investments.

Edgar Montenegro, Founder and CEO, Corpocampo

Community-based enterprises make the sustainable bioeconomy a reality in the territories. These enterprises should be promoted to sustainably use and add value to biodiversity in remote areas. Procedures for rural agro-industrial ventures must be facilitated, and this also implies access to capital for financing, knowledge transfer and specialized market access.

Technology development and innovation

Two harvesting systems were identified: one wild one, which generates the most significant volume of product, and the other based on domesticated cultivation in agroforestry systems. Approximately 95% of the current harvesting is wild, which implies an essential logistical effort to access the açaízales (the açaí palm complex that is formed in the ecosystem) and bunches when the fruit is in optimal ripening conditions and to transport the fruit in the shortest possible time to the processing plant. To access the natural forest to harvest açaí for commercial use, a management plan and a permit from the environmental authority are required. This permit includes technical requests that rural community enterprises cannot meet. International cooperation projects generally support MSMEs to meet these requirements. Some interviewees mentioned that if the location of the açaízal is more than 35 km away, it is no longer profitable because of the difficulties in accessing the natural forest.

The cultivation of açaí is an option that has been used in Colombia because of the innovation of some companies, such as Corpocampo, among a few others. Nonetheless, rural extension services that include agroforestry systems based on açaí targeting tropical forest-dwelling communities are currently minimal. The agroforestry systems found with açaí include different Amazonian fruits such as camu-camu and copoazú, among others, as an alternative to conventional crops in regions such as Putumayo (Amazon region of Colombia). Entrepreneurs argue that if the palm were domesticated, productivity would multiply and facilitate access to markets. These systems are considered beneficial for restoring land that has been transformed into cattle pastures, used in conventional agricultural systems or for cultivation of illicit crops (Agrosavia, 2020).

Corpocampo has innovated in the way it harvests açaí in the natural forest. It has generated a geo-referenced information system and satellite information with drone images to monitor the state of the forest on a daily basis, identifying the precise moment to harvest the fruit (Corpocampo, 2023). This allows for more efficient access to the natural forest and early warnings to prevent deforestation.

Innovation in harvesting and post-harvest technologies is fundamental to promoting biodiversity-based businesses. Management plans and harvesting protocols should include monitoring and harvesting technologies that facilitate the procedure and technologies that extend the shelf life of fresh pulp and meet the needs of consumers and industry, such as freeze-drying.

More research is needed on the productivity of the species to strengthen the bio-based value web of the açaí. Scientific expeditions that allow the collection and analysis of wild material are considered necessary for the conservation of the species and its possible domestication for agroforestry use. Research into knowledge of the species and technologies for high altitude harvesting, more significant proportion of pulp in each fruit, larger fruit per bunch, lower palms, among others, are aspects mentioned by the entrepreneurs for research. Agroforestry crops promoted by companies and institutions should be ensured as part of the transition from conventional farming systems to more sustainable ones with native species to foster the local economy.

5. Challenges and recommendations for bioresources management within emerging bioeconomies

The bioeconomy can have different forms of expression in tropical and subtropical countries. One bioeconomy may be based on larger-scale agricultural commodities and another type of bioeconomy may be based on small-scale biodiversity. This requires differential changes and adaptations in terms of public policy, regulation, business organization and technological advancement. The following are some general insights useful to guide this differentiation.

Government support through clear policies, incentives and international agreements will play a crucial role in transitioning to more innovative and sustainable practices in Colombia's agricultural sector.

Angelica Herrera, Director, Bichopolis

Agricultural commodities have been developed in environments where institutional, business organization and technological structures were established before the overarching bioeconomy concept was clarified. This means that significant intention and patience will be required to adapt these environments to new bioeconomy objectives that are more cross-cutting and innovative. Sugar cane's sustainability challenges are very similar to those of cassava; thus, it seems that agricultural commodities face common challenges in the transition to the bioeconomy. Increasing yields at the smallholder level and improving monoculture management with circular and sustainable alternatives must be priorities. Incentivizing and facilitating access to new technologies that minimize pollution is essential in the case of sugar cane, where burning must be a priority for cultural and technological change.

Smallholders are being squeezed out of traditional commodity systems, with negative social impacts. Efforts to expand value chains related to these bioresources as part of emerging economies should prioritize opportunities to strengthen the position of smallholders, including younger people, to participate. A better relationship between smallholders, universities and research institutes is required to improve technology transfer and advance more innovative and sustainable production systems.

The institutional, business organization, and technological environments related to NTFPs are nascent, and where they exist, they have generally responded to small-scale, artisanal opportunities. Connecting these systems to emerging opportunities such as biofuels and emerging functional food trends will require investment and incentives to allow MSMEs and these bioresources to scale within emerging bioeconomies.

Pioneers in NTFP systems are key to developing the innovations needed to bring these bioresources to scale. It is important to attract and maintain anchor companies in NTFP value chains because they play a very important role in opening markets and territorial development (CORDIS, 2011). Encouraging rural entrepreneurship and partnerships with local communities is essential to better connect them to value chains that access better markets. Regulation must guarantee the sustainable use of biodiversity and generate economic and business opportunities for the population. This should be a priority for biodiversity conservation.

Natural bioresources are typically regulated under different authorities than agricultural bioresources. These authorities are often charged with biodiversity protection first and foremost, creating challenges for promoting value addition in emerging economies. Procedures for regulatory compliance need to be clarified and streamlined.

Cases related to commodities and non-timber forest products NTFPs have been presented throughout the paper. The recommendations for both stem from the three different categories of analysis of the bioeconomy and sustainability, using the framework above. See Table 8 for all recommendations. Recognizing the differences in the two worlds, the table presents recommendations on policies and incentives, business organization and technology development for commodities and for biodiversity products. These include enhanced coordination at different governance levels, incentives for best sustainability practices and circularity, collaboration across many sectors in the value chain – and especially collective actions for smallholders – and more research and development of technologies and advances that are made available for users of all kinds, especially small-scale farmers.

Table 8. Recommendations for commodities and biodiversity products for the bioeconomy

Levels of analysis	Commodities in the bioeconomy: sugarcane and cassava	Biodiversity products - NTFP
Institutions and public policies	• Incentivize sustainable practices in production systems to replace traditional monocultures, including practices to address soil degradation, biodiversity loss, water efficiency and waste circularity. • Support smallholders, encouraging the formation of cooperatives, providing training, knowledge exchange, supporting generational succession and mechanization for small producers. • Fostering strong collaborations between government, academia, companies, and small producers to address challenges and enhance sustainability in the bioeconomy transition must be a priority. • Research centers, universities, public agencies, producer associations, and enterprises must invest in research to develop improved cultivars and more sustainable systems.	• Enhance coordination between the different public authorities that manage these bioresources, their ecosystems, and the products and services of their processing. • Strengthen an articulated work between government, universities, research centers, communities, and companies to develop technologies for the harvesting and sustainable production and transformation of timber and non-timber forest products. • Implementing non-agricultural rural extension services focused on the sustainable use of biodiversity with timber and non-timber forest products should be a priority in tropical countries. • Policies should also encourage the business environment for MSMEs and promote transfer technology for innovation and productivity with NTFP. • Incentives to achieve compliance with the requirements for accessing permits, procedures, and biodiversity management plans, avoiding disincentives for businesses associated with biodiversity are needed.
Business organization	• Value chain organizations and policies must ensure smallholders can access necessary inputs and services to boost productivity and innovation, adding social and environmental values. • A coordinated work between actors of the value chain must encourage associativity and entrepreneurial capacities, promoting the organization of small producers into SME´s such as cooperatives or associations to enhance their bargaining power. • Promoting standard contracts between small producer associations and agribusinesses to secure business arrangements and facilitate value addition must be a priority of value chain organizations	• MSMEs related to NTFP, in the bioeconomy, need support to meet legal requirements, improve technological adoption, innovation processes and strengthen sustainable business models. • Rural communities' capacities in entrepreneurship, private initiative, and business management should be strengthened to favour their positioning and negotiation in scaling-up processes and connection to more sophisticated value chains. • Structures for local innovation and social inclusion in these differentiated value chains should be promoted. • Market intelligence is essential for these businesses to start and consolidate in the market, especially with MSMEs. • Sustainability agreements along the value chain are needed to meet the purposes of the bioeconomy.

Table 8 cont.

Levels of analysis	Commodities in the bioeconomy: sugarcane and cassava	Biodiversity products - NTFP
Business organization	• Developing strategies to formalize commercial transactions with small-scale producers to improve competitiveness and sustainability is also needed • New contracts should integrate elements of green jobs and criteria for including vulnerable populations such as youth and women in bioeconomy strategies. • Sustainability agreements at the value chain are needed to meet the purposes of the bioeconomy. These agreements should be generated in participatory processes, including smallholders, MSMEs, large companies, processors, clients, local governments, universities, and research institutes, among other critical actors in the value chain. These agreements should include the environmental, social, and economic aspects that need to be addressed to guarantee the objectives of the bioeconomy.	
Technology development and Innovation	• Supporting technological adoption and increasing access to modern agricultural technologies among smallholders through government support and collaboration with academia and the private sector • Joint work with academia, the private sector, and smallholders should promote mechanization and digital technologies to attract younger generations to farming and develop value-added processes to enhance market access. • Encourage the adoption of water and waste reuse in processing, ensuring sustainable industrial processes.	• Research centers and academia should encourage technology transfer for harvesting NTFP in the forest avoiding difficulties in natural ecosystems • Provide technological packages with sustainable production systems such as agroforestry, when a domestication process is needed to achieve higher production and productivity. • Promote technologies to add value and transform raw material in the forest, taking into account the logistical difficulties of rural areas in natural ecosystems. • The development and transfer of these technologies to small-scale producers, rural harvesters and MSMEs should include strategies for circularity in the use of waste.

Source: Authors' own

6. Concluding thoughts

The case studies presented here illustrate how large and mid-scale commodities (sugar from cane and cassava), and small-scale biodiversity products NTFPs (açaí and croton) can be motors of emerging and established bioeconomies. The framework used here shows how institutions and public policies, business organization and value chains, and technology development and innovation can drive these motors. Our assessment also shows where three emerging bioeconomies – Thailand, Kenya and Colombia, with these different crops – have had success and failures that each can learn from each other.

A necessary condition for any bioeconomy, sustainability is not necessarily guaranteed simply by increasing the use of bioresources. Sustainability is a social construction that requires proper governance. Sustainability requires the state's leadership with the permanent accompaniment of public policies that encourage innovation, technological development and the collaborative work of the private sector, academia and civil society. That is why the implementation of bioeconomy requires an active role from the state.

Bioeconomies in tropical and subtropical countries may have similar elements related to biodiversity and the social inclusion of vulnerable populations such as small producers, Indigenous Peoples and other social groups with particular needs. Public policies must incentivize sustainable production practices to replace traditional monocultures, addressing soil degradation, biodiversity loss, water efficiency and waste circularity. Support for smallholders is crucial, including promoting cooperatives, providing training, knowledge exchange and mechanization.

At the value chain level, the organization and relationships between actors are fundamental, especially between small and large ones. Strengthening contracts between these actors, including standards to improve environmental management, biodiversity conservation and social inclusion, is essential. Strengthening the capacities of small rural producers and collectors in sustainable rural entrepreneurship for better negotiation at the chain level is also a priority.

The methodological framework used for the analysis described here was useful. However, efforts to monitor sustainability in public policy and value chain relationships need to be strengthened. Strong collaboration between government, academia, companies and small producers is essential to enhancing sustainability in the bioeconomy transition.

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Annex 1. List of interviewees

The following table lists the names of the organizations that were interviewed through a representative.

Chapter	Representative from organization	Country / Region
1	ASEAN Cassava Centre	South East Asia
1	Som Za local community in Phitsanulok	Thailand
1	ASEAN Center for Biodiversity (ACB)	South East Asia
1	Corpocampo	Colombia
1	Bioingred Tech	Colombia
1	Naturela	Colombia
1	Acai Palmito del Chocó (Planeta CBH SAS)	Colombia
1	Crepes & Waffles	Colombia
1	Naidi Pacifico SAS	Colombia
1	Fondo Acción	Colombia
1	PMA	Colombia
1	Droguería Rosas	Colombia
1	Selva Nevada	Colombia
1	Naturesse	Colombia
1	Agencia presidencial de Cooperación internacional	Colombia
1	Swiss Contact	Colombia
1	SIPPO	Colombia
1	Asoprocegua	Colombia
1	Agrosavia	Colombia
1	Bichopolis	Colomba
2	Ministerio de Ciencia, Tecnología e Innovación	Colombia

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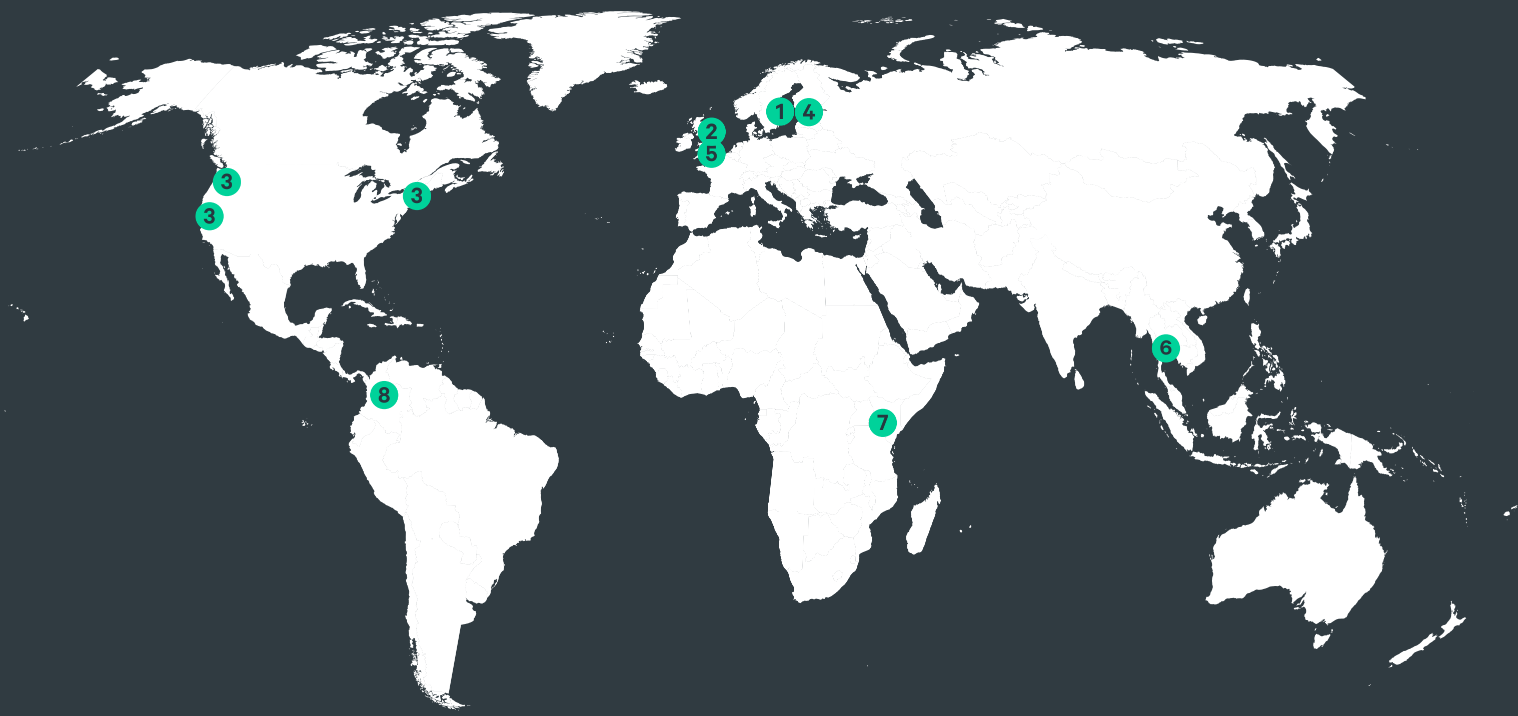

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