Elements for a National Strategy to Implement Biorefineries in Brazil

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Elements for a National Strategy to Implement

Biorefineries in Brazil

Brasília, April 2025

TECHNICAL SHEET

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The diagnosis, mappings, and proposals presented in this document were developed with the collaboration of various entities and bioeconomy experts, whose contributions were essential in advancing the understanding of opportunities for the sustainable valorisation of biomass in the country.

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FOREWORD

Brazil holds a prominent position on the global stage when it comes to bioeconomy. With its vast biodiversity, extensive agricultural areas, and renewable energy grid—among the most advanced in the world—the country possesses unique potential to develop a thriving bioindustry rooted in a systemic vision of biorefining.

In addition to showcasing national and international experiences, this publication examines technological innovation, public policies, and business models that can drive growth in this sector. It aligns fully with the New Industry Brazil (*Nova Indústria Brasil—NIB*) framework—particularly Mission 5, "*Bioeconomy, Decarbonisation, and Energy Transition and Security for Future Generations*", launched in December 2024—and with the national bioeconomy and circular economy strategies.

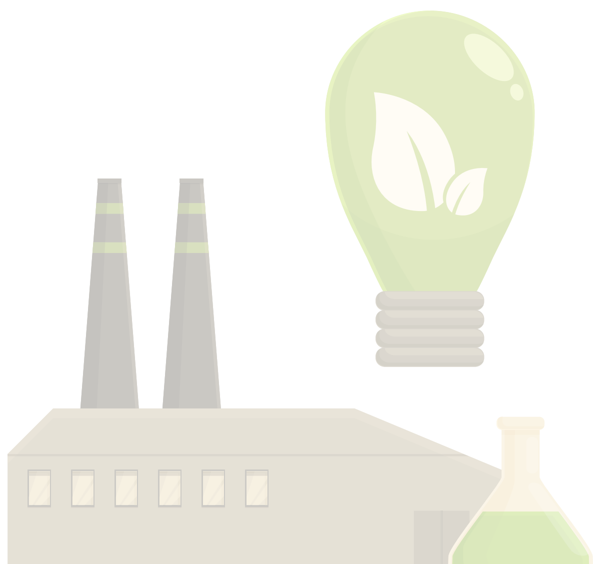
As one of the outcomes of Project BRA/18/023—*Modernisation of the Economy and Qualified Expansion of Brazil's Trade Insertion*, this publication highlights the importance of cooperation between the United Nations Development Programme (UNDP Brazil) and the Ministry of Development, Industry, Trade and Services (MDIC) in advancing Brazil's development on strategically significant issues related to sustainability and the country's 2030 Agenda.

More than merely a repository of knowledge, this publication serves as a call to action. Companies, researchers, policymakers, and society at large have the opportunity to contribute to a more sustainable and competitive future, with bioindustry playing a leading role in a new cycle of development.

MDIC and UNDP Brazil extend their gratitude to all those who contributed to this initiative—collaborators, partners, industry representatives, and members of academia. May this publication provide enriching insights, inspire action, and strengthen Brazil's commitment to an innovative and sustainable bioindustry.

Ministry of Development, Industry, Trade and Services

United Nations Development Programme Brazil



SUMMARY

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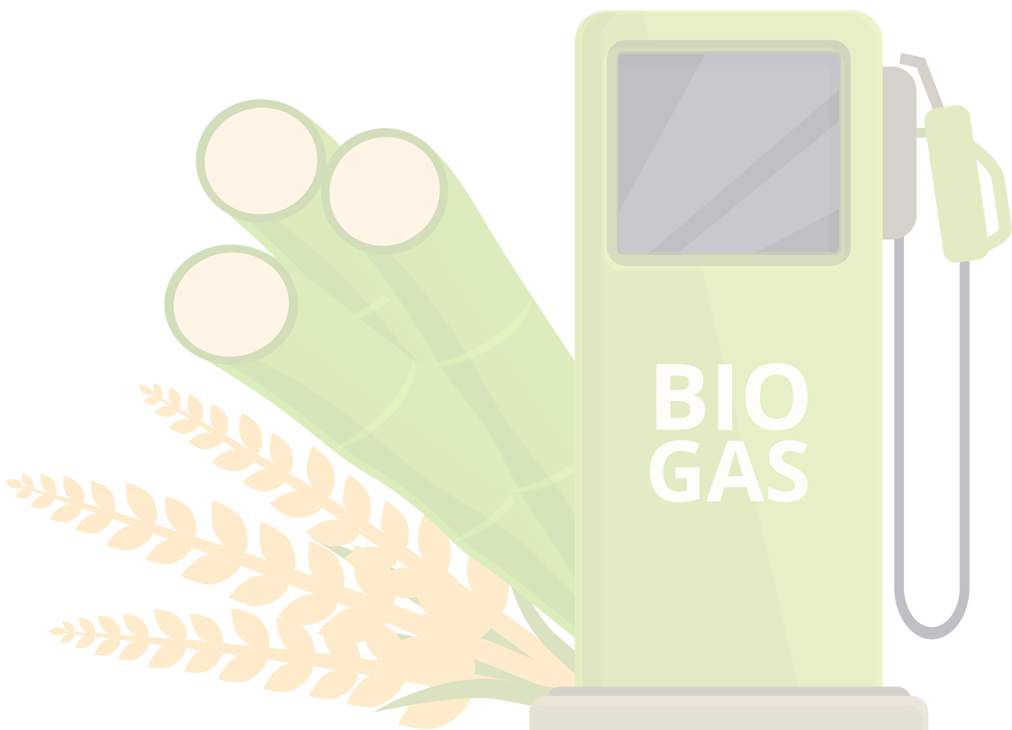
ACRONYMS

ABC+	Low-Carbon Emissions Agricultural Plan (Brazil)
ADEME	French Agency for Ecological Transition (France)
BETO	Bioenergy Technology Office (USA)
BIOEN	FAPESP's Bionenergy Research Programme (Brasil)
BNDES	Brazilian National Economic and Social Development Bank(Brasil)
CE	Circular Economy
DOE	Department of Energy (USA)
EMBRAPA	Brazilian Agricultural Research Corporation
FAPESP	São Paulo Research Foundation
FINEP	Brazilian Funding Authority for Studies and Projects
IACGB	International Advisory Council on Global Bioeconomy
IAR	Industrie et Agro-ressources (France)
IEA	International Energy Agency
IICA	Inter-American Institute for Cooperation on Agriculture
ILPF	Programme for the Integration of Agriculture, Livestock, and Forestry (Brazil)
IPAM	Amazon Environmental Research Institute (Brazil)
ISPN	Institute for Society, Population, and Nature (Brazil)
VAT	Value-added Tax
MAPA	Ministry of Agriculture and Livestock (Brazil)
MCTI	Ministry of Science, Technology, and Innovation (Brazil)
MIDR	Ministry of Integration and Regional Development (Brazil)
MMA	Ministry of the Environment and Climate Change (Brazil)
OECD	Organisation for Economic Co-operation and Development (Brazil)

PAISS	Support Plan for Industrial Technological Innovation in the Sugar-Energy and Sugar-Chemistry Sectors (Brazil)
RD&I	Research, Development, and Innovation
PDE	Energy Expansion Plan (Brazil)
RENOVABIO	Brazilian National Biofuel Policy
SAF	Sustainable Aviation Fuel
SAP	System, Applications, and Products for Data Processing
SISGEN	National System for the Management of Genetic Heritage and Associated Traditional Knowledge (Brazil)
USDA	Department of Agriculture (USA)



EXECUTIVE SUMMARY

The relevance of biorefining and biomass-based biorefineries lies in the opportunities they offer for the sustainable valorisation of Brazil's diverse biomass resources. The aim of this report is to assess the current stage of biorefinery development in Brazil and based on this assessment, provide insights to support the formulation of biorefinery strategies for the country.

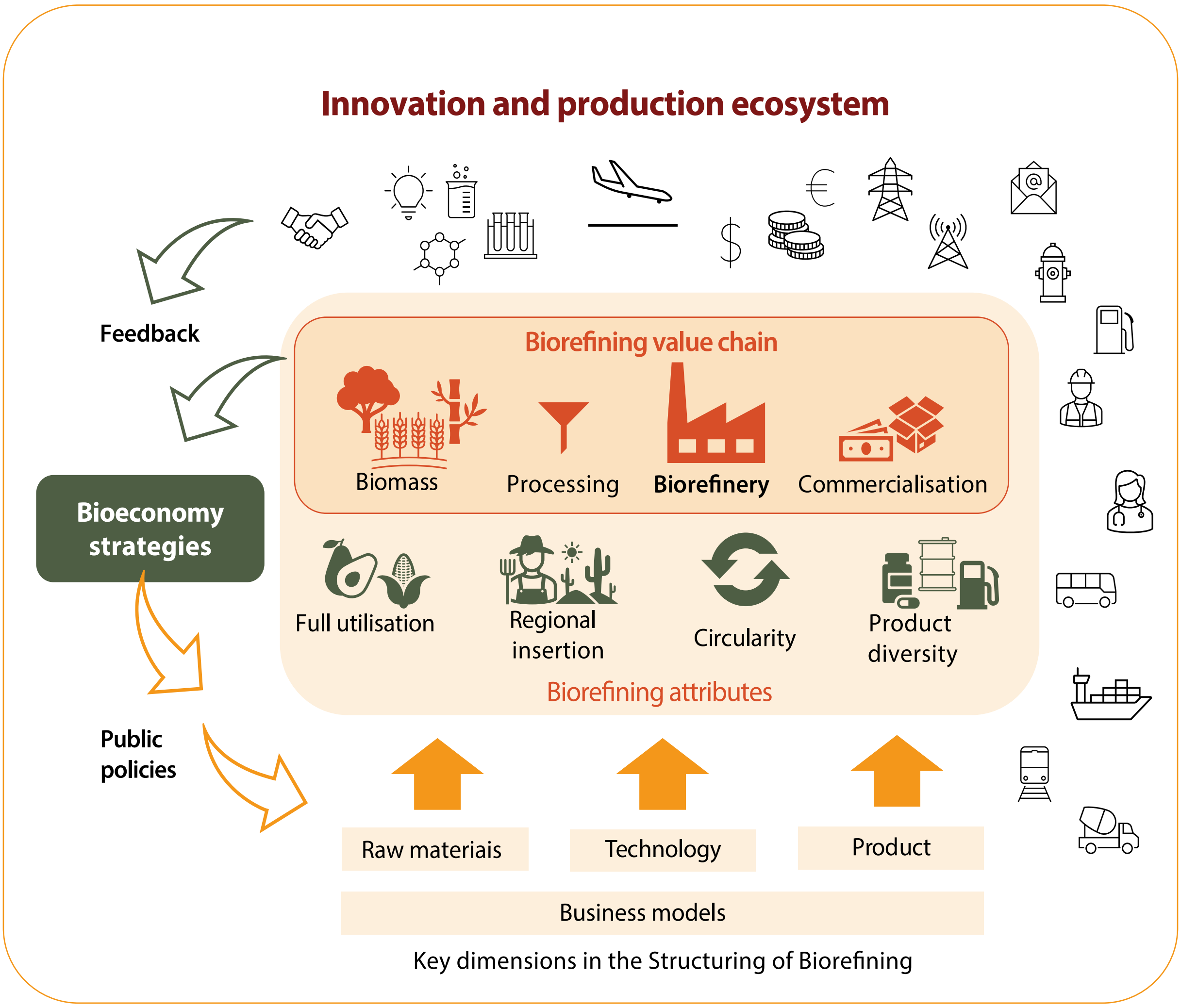
This study is grounded in the perspective of sustainably valorising Brazil's natural resources to generate economic, social, and environmental benefits. As such, it serves as a key contribution to advancing the objectives and outcomes of Project BRA/18/023—*Modernisation of the Economy and Qualified Expansion of Brazil's Trade Insertion*, a partnership between the United Nations Development Programme in Brazil (UNDP Brazil) and the Ministry of Development, Industry, Trade and Services (MDIC) of the Brazilian government.

This report is also aligned with Mission 5 of the New Industry Brazil Plan (*Plano Nova Indústria Brasil*), led by the MDIC: *"Bioeconomy, Decarbonisation, and Energy Transition and Security to Guarantee Resources for Future Generations"*. Among other initiatives, this Mission aims to achieve a 50 per cent increase in the use of biofuels within the transportation energy matrix. Accordingly, the report presents a comprehensive assessment of the current stage of biorefinery development in Brazil and offers insights to support the formulation of biorefinery strategies in the country.

To this end, the paper proposes a systemic view of biorefining that extends beyond the industrial unit or biorefinery itself. This systemic vision can be summarised as follows:

Biorefining: Biorefinery + Production Chain + Innovation and Production Ecosystem

To address the challenges of the bioeconomy, biorefining must aim to achieve four key attributes: product diversification, full utilisation of biomass, circularity, and regional/territorial integration. The figure below illustrates the systemic vision of biorefining and its connection to these attributes.

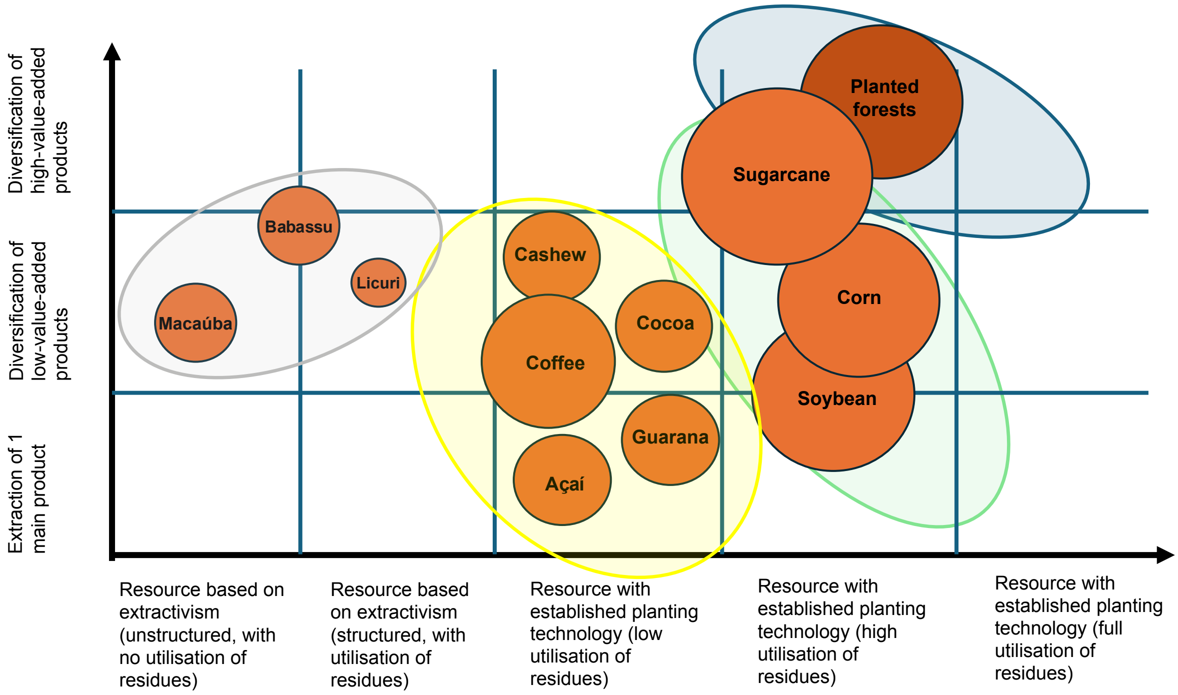


Source: Elaborated by the consultant.

The diversity of biomass available in the country must be understood in relation to the variety of products, the level of added value, the degree of utilisation of the biomass, and the biomass supply model (extraction or cultivation). These parameters allow for the identification of four distinct biomass groups, each with its own internal logic regarding exploitation and valorisation. The groups identified in the study were: planted forests (Group 1), sugar cane (Group 2), coffee and *açaí* (Group 3), and babassu and *macaúba* (Group 4).

The figure below presents a situational analysis of biorefining in Brazil, highlighting the four distinct biomass groups.

Biorefining situational matrix in Brazil



Source: Elaborated by the consultant.

The proposed integrated vision for biorefining highlights that the development of industrialisation through biorefineries depends on overcoming challenges present at the early stages of production chains, which vary in their level of structuring. Advancing the industrialisation phase within the biorefining production chain requires addressing challenges related to primary processing—considered the pre-industrialisation stage—for both resources derived from Brazilian biodiversity and lignocellulosic biomass.

The following key points emerge from the situational diagnosis of biorefining in Brazil:

As a general rule, Brazilian biorefining does not achieve full utilisation of available resources.	Product diversification is limited, with a tendency toward low-value products and infrequent production of high-value-added goods.
Many types of biomass are exploited for the extraction of a single main product and would be more accurately described as pre-biorefineries.	The supply of biomass involves both extraction (structured and unstructured) and cultivation, each presenting distinct challenges for the development of biorefineries.
Industrialisation must be carefully examined, particularly to understand the development of dynamic biomass-based sectors, such as planted forests and sugar cane.	The evolution and maturity of biorefining processes based on biodiversity must be studied in depth, as the future of Brazilian biorefining may rely on the pillars of both agribusiness biomass and biodiversity biomass.

This publication presents a comparative study of the main instruments identified and the policy orientations observed in six selected countries (Australia, China, the USA, Finland, France, and Thailand). Overall, the strategies and policies identified are diverse, reflecting various approaches to bioeconomy and biomass valorisation. One of the study's key conclusions is that the countries analysed lack a systemic vision of biorefining. Of the references examined, the vision and structuring of the Biomass Board in the USA stands out as the best example of a systemic approach to biorefining.

Regarding the cross-cutting policies examined in this study, important lessons emerge concerning weaknesses in Brazilian public policies, particularly in the areas of programme and call-for-tender development, coordination and governance, and the integration of policies and processes.

Key conclusions of the report include:

The systemic vision of biorefining (Biorefining = biorefinery + production chain + production and innovation ecosystem) is crucial for the formulation of effective public policies.	
Regarding biomass, the study outlines 15 recommendations. The implementation of each recommendation is influenced by the production chain—covering biomass supply, processing, industrialisation, and marketing—as well as key business dimensions in the bioeconomy, including raw materials, technology, products, and business models.	All recommendations and the policy instruments used to implement them must always consider the key attributes of biorefining: product diversification, full utilisation of biomass, circularity, and regional/territorial integration.
Both the systemic vision and the attributes of biorefining are concepts that are not yet widely disseminated in academic, industrial, and government circles. Efforts should be made to promote and discuss these concepts, as this could lead to a better understanding of the opportunities and challenges associated with biorefineries.	Public policy proposals for the development of biorefining must consider the different stages of biomass supply chain development and incorporate sustainable production models that prioritise environmental and social aspects.
Policies and strategies for developing biorefining in Brazil should consider international benchmarks in two key areas: governance and coordination, and the processes for designing and monitoring programmes and calls for tenders.	The establishment of a coordination body, similar to the Biomass R&D Board in the USA, capable of guiding initiatives involving government, research, and industry through integrated programmes, appears to be a crucial first step toward fostering the development of biorefining in Brazil. Given the strong connection between biorefining, the bioeconomy, and the circular economy, establishing links between these agendas and their respective coordination and governance bodies is essential.

1. Introduction

The importance of biorefineries and biomass-based biorefining[1] is closely linked to the sustainable valorisation of Brazil's diverse biomass resources. The country has successfully developed bioenergy policies and strategies, as evidenced by the long-standing trajectories of ethanol and biodiesel. The recent enactment of the Future Fuel bill (Law No. 14.993, dated 8/10/2024, and published in the Official Gazette on 9/10/2024)[2] further reinforces national efforts to sustain and, more importantly, advance these initiatives.

However, despite consistent progress in biofuel production, many valorisation opportunities remain untapped in Brazil. Biomass resources already used for biofuel production still offer potential for product diversification and more efficient utilisation of sub-products and co-products. Additionally, many other biomass resources, which may have limited potential for biofuel production, present opportunities for innovation in resource efficiency, generating economic, social, and environmental benefits.

In the sugar-energy sector, for example, the potential for valorising vinasse and other residues for biogas and biomethane production is beginning to emerge. Within 10 years, this could result in a volume of 6.1 billion Nm3 (equivalent to 11.2 billion Nm3 of biogas), assuming full utilisation of vinasse and filter cake and 20 per cent utilisation of sugar cane trash (EPE 2023). Additional opportunities for product diversification can be explored, such as new valorisation pathways for sugar cane trash, including second-generation ethanol, cellulose, and lignin. Furthermore, opportunities for the valorisation of straw and CO2 would still remain.

There is similar potential in the paper and cellulose industry, particularly for lignin derivates. Likewise, large biomass resources and well-established industrial supply chains—such as planted forests, soy, and corn—could create opportunities for biorefinery development, leading to the production of diverse bioproducts.

The potential of biomass is often underutilized. This is particularly true for production chains focused on extracting food components—such as coffee and fruits—as well as Brazilian biodiversity chains[3] such as *açaí* and *babassu*. In these cases, the current scenario can be summarised in two key points: the extraction of a single primary product, which represents only a small fraction of the biomass, and the generation of large volumes of subproducts and coproducts that are discarded.

1. The study was conducted in collaboration with researchers Flávia Alves, Fábio Oroski and Carlos Corrêa from the Bioeconomics Study Group (GEBio) at the School of Chemistry, Federal University of Rio de Janeiro (UFRJ).

2. https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/L14993.htm.

3. From this point forward, whenever 'biodiversity' is mentioned, it refers to Brazilian biodiversity.

In the case of coffee, only 5 per cent of the harvested biomass is ultimately consumed, while the remaining 95 per cent consists of husks, off-specification beans, and coffee grounds (Arya, Venkatram, and More 2022). Similarly, açai pulp production generates approximately around 1.6 million tonnes of pits. While this waste can be viewed as an environmental challenge, it also presents an opportunity for biorefining, which could convert these byproducts into high added value bioproducts, as identified in previous studies.

Babassu, a traditionally extracted product, exemplifies another case: while its full potential remains underutilised—estimated at 4 per cent of available resources (Porro 2019)—various valorisation initiatives have emerged. The formation of cooperatives and the development of industrial exploration models have demonstrated a strong capacity to valorise biodiversity, generating positive economic, environmental, and social outcomes.

This study adopts the perspective of sustainably valorising Brazilian natural resources to achieve these benefits. As such, this report serves as a key outcome to advancing the objectives of Project BRA/018/023—**Modernisation of the Economy and Qualified Expansion of Brazil's Commercial Insertion**, a partnership between the United Nations Development Programme (UNDP) in Brazil and the Brazilian Ministry of Development, Industry, Trade and Services (MDIC). It also aligns with Mission 5 of the *New Industry Brazil* plan, led by MDIC: *Bioeconomy, decarbonisation and energy transition and safety to ensure resources for future generations*. Among other initiatives, this Mission aims to increase the share of biofuels in Brazil's transportation energy matrix by 50 per cent.

This report provides comprehensive assessment of Brazil's biorefinery sector, offering insights to inform future strategies. It is structured as follows: Section 2 explores conceptual frameworks and assessments of biorefining and biorefineries; Section 3 outlines the methodology; Section 4 presents a diagnostic of Brazil's biorefining landscape; Section 5 reviews international experiences in formulating public policies for biorefining; Section 6 offers recommendations based on the study's findings; and, finally, Section 7 provides the conclusion.

> **"In these cases, the current scenario can be summarised in two key points: the extraction of a single primary product, which represents only a small fraction of the biomass, and the generation of large volumes of subproducts and coproducts that are discarded."**

2. Biorefineries and biorefining: Conceptual aspects and analytical dimensions

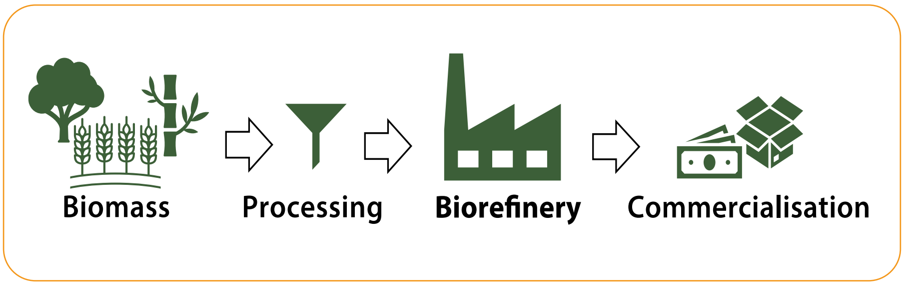
2.1 Definitions of biorefining and biorefineries

There are various definitions for biorefinery in the literature and from interviews with stakeholders in the bioeconomy. These definitions typically centre around the "industrial unit that transforms and/or deconstructs biomass." However, this perspective does not fully capture the broader process involved in developing sustainable businesses based on biomass processing.

This report proposes adopting a definition that considers the biorefining process in a systemic manner. From this perspective, the definition proposed by Task 42, IEA Bioenergy (2022) seems appropriate: "Biorefining is the sustainable processing of biomass into a spectrum of marketable products and energy."

Therefore, biorefining must encompass agents and processes that extend beyond physical biorefinery installations but are crucial for achieving sustainability and adding value. The entire production chain—from input supply and biomass production to transformation and delivery to end markets—is an integral part of biorefining (Figure 1).

Figure 1. Biorefining production chain



Source: Elaborated by the consultant.

However, considering the production chain as merely a linear sequence of steps does not fully capture all stakeholders involved. Since biorefining development relies on various capacities and resources—such as basic infrastructure (e.g., water and energy supply), equipment, trained staff, R&D, financing, fiscal incentives, etc.—these elements must be made available. Therefore, the production and innovation ecosystem should also be considered a key aspect of analysis.

The importance of a systemic view of biorefining was strongly emphasised in the study "Innovation Ecosystems in the Bioeconomy" (OECD 2019). The construction of industrial units—biorefineries—is considered the easiest aspect in developing new bioeconomy businesses. The greatest challenges lie creating ecosystems of companies and value chains that can sustain biorefinery activities.

Most value chains and their products still lack a defined economic structure. In addition, markets are not yet fully developed, and products might not even be recognised by consumers.

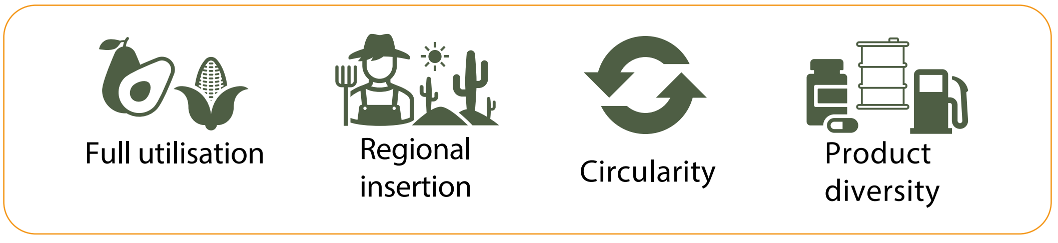
The systemic view of biorefining adopted in this report can be summarised as follows:
Biorefining = biorefinery + production chain + production and innovation ecosystem.

2.2 Systemic attributes of biorefining

A systemic view of biorefining is essential for the development of the bioeconomy in the coming decades, and the efficient use of resources requires that bioeconomy be circular. In addition, the production and utilisation of biological resources must ensure that processes are sustainable from economic, environmental, and social perspectives.

To address these challenges, biorefining must have some ideal attributes. This report, based on the literature—especially bioeconomy reports and strategic plans—highlights four main attributes: product diversification, full utilisation of biomass, circularity, and regional/territorial insertion (Figure 2).

Figure 2. Biorefining attributes



Source: Elaborated by the consultant.

Although these attributes are interconnected, each can be examined individually to highlight its specific characteristics.

Product diversification

Historically, biorefineries have been built with the primary goal of producing a key product that ensures the viability of the enterprise. This has been the case for biofuels such as ethanol and biodiesel, and more recently, sustainable aviation fuels (SAFs). Production scales must be suitable for large-scale commodities, which typically yield lower profit margins.

However, in the past decade, studies—such as those conducted by the US Department of Energy (DOE) in 2015—have introduced a more sustainable perspective for biorefineries, emphasising the integration of bioenergy and bioproducts as a desirable goal (DOE 2015; IEA Bioenergy 2017).

Product diversification can generate positive economic and environmental outcomes, contributing to improved carbon management. The DOE, through the Bioenergy Technology Office (BETO), has explicitly emphasised in its call for tenders and research programmes the need for biorefineries to incorporate a diverse line of products—including bioenergy and bioproducts—during biomass processing. This approach to product diversification, encompassing items with varying volumes and profit margins, should be broadly applied to biorefining.

Product diversification as a key attribute of biorefining has not been explicitly recognised in Brazil's bioeconomy development programmes. While initiatives such as PAISS (BNDES/FINEP 2011) and PADIQ (BNDES/FINEP 2015) aligned with a broader concept of biorefining, they primarily focused on single-product models.

In its BIOEN 2020-2030 plan, FAPESP identifies increasing biomass productivity as a key goal, emphasising the "development of high-productivity plants for the production of bioenergy and bioproducts." This objective clearly prioritises the diversity of both energetic and non-energetic products, which may be achieved in dedicated biorefineries or those serving other purposes.

Full utilisation of biomass

Full utilisation enables the efficient use of renewable resources, potentially minimising environmental impacts and emissions while creating new opportunities for economic gains. Therefore, recognising coproducts, subproducts, and residue as valuable resources can generate both environmental and economic benefits.

Circularity

Biorefining is naturally aligned with the principles of a circular bioeconomy, emphasising the efficient use of resources. The full biomass utilisation is a key aspect of this approach. However, circularity also requires efforts throughout the production chain, including distribution, utilisation, and the management of end-of-life products. Ideally, a biorefinery should evaluate its current and potential levels of circularity.

Regional/territorial insertion

This attribute, in a way, stems from the previous one but extends beyond it by offering regional benefits through integration with other complementary activities. A key driver of circularity in biorefineries lies in opportunities for territorial integration, which can generate not only economic and environmental benefits but also social gains through regional development.

Regional integration can serve as the foundation for building clusters that foster synergies among companies, research institutes, service providers, and other stakeholders. Over time, these interactions can evolve into areas of industrial symbiosis. While industrial symbiosis requires long maturation periods, the starting point is to identify and pursue opportunities for the regional or territorial integration of biorefineries.

Finally, in addition to the four systemic attributes outlined above, it is important to consider the temporal dimension of biorefining. The maturation of biorefineries appears to be an incremental process, driven by successive innovations that accumulate over time. This process is often lengthy, as several examples illustrate.

The Pomacle-Bazancourt biorefinery in France, one of the most renowned integrated biorefineries, has a history spanning more than 70 years, dating back to 1948. In Brazil, Tobasa—a benchmark in biorefining based on Brazilian biodiversity—has been in operation for 56 years. Likewise, the sugar-energy industry, in its bioenergy-focused form, traces its origins to the late 1970s. Thus, the development and maturation of biorefining appear to be measured in decades.

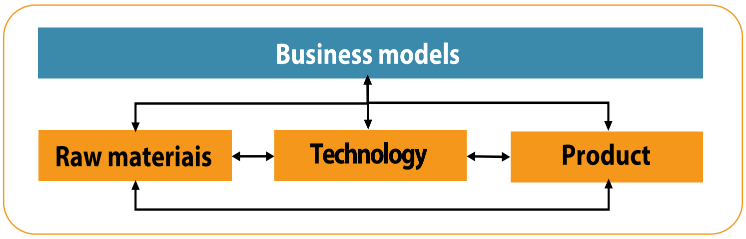
2.3 Dimensions for analysing biorefining businesses

Beyond the systemic level, policies and programmes must address the challenge of structuring businesses. These businesses are often in their early stages, lacking a defined structure and requiring innovation.

An analytical framework (Figure 3) can help identify the different levels of structuring by considering four key dimensions in co-evolution: raw materials/resources, technologies, products, and business models (Bomtempo 2017; Bomtempo and Alves 2014).

Analysing these dimensions and their interrelations provides a clearer understanding of biorefineries, distinguishing their varying levels of structuring. Effective policies and strategies for biorefining development must address the challenges associated with each dimension.

Figure 3. Key dimensions of biorefining analysis

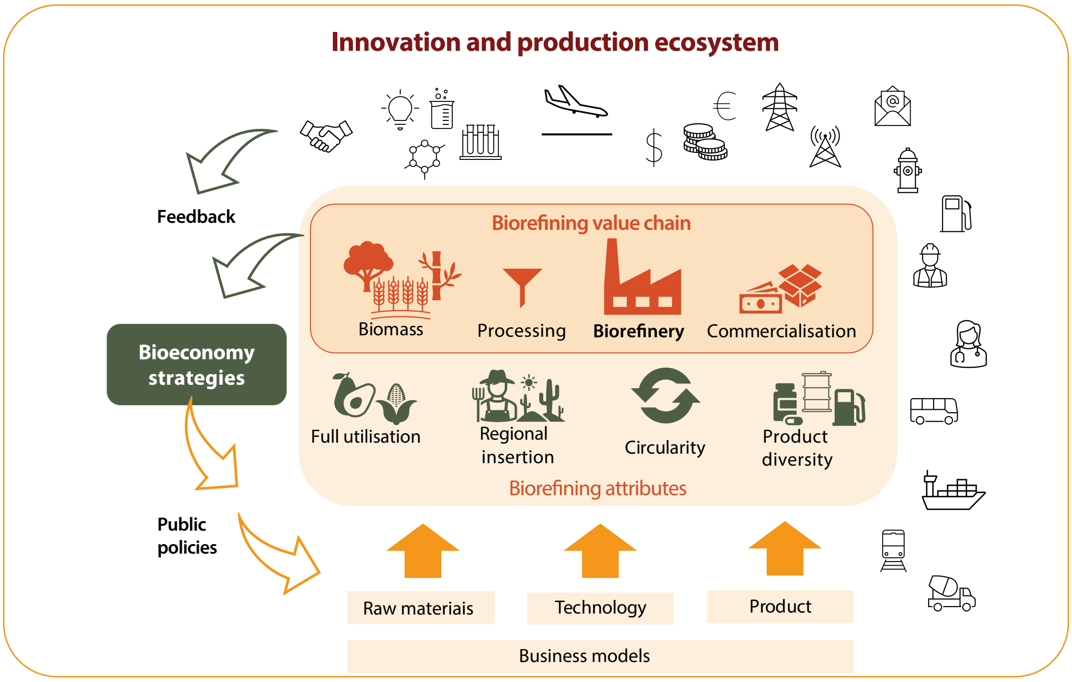


Source: Bomtempo and Alves (2014); Bomtempo (2017).

Business models represent the solutions adopted by biorefineries to integrate opportunities and address challenges related to raw materials, technologies, and products. Beyond economic aspects, this study also considers non-technological factors, such as social dimensions. The exploration of new business models can play a crucial role in the structuring of biorefining.

Figure 4 illustrates the elements involved in the systemic vision of biorefining and the key dimensions for assessing the structural level of businesses.

Figure 4. Systemic vision of biorefining



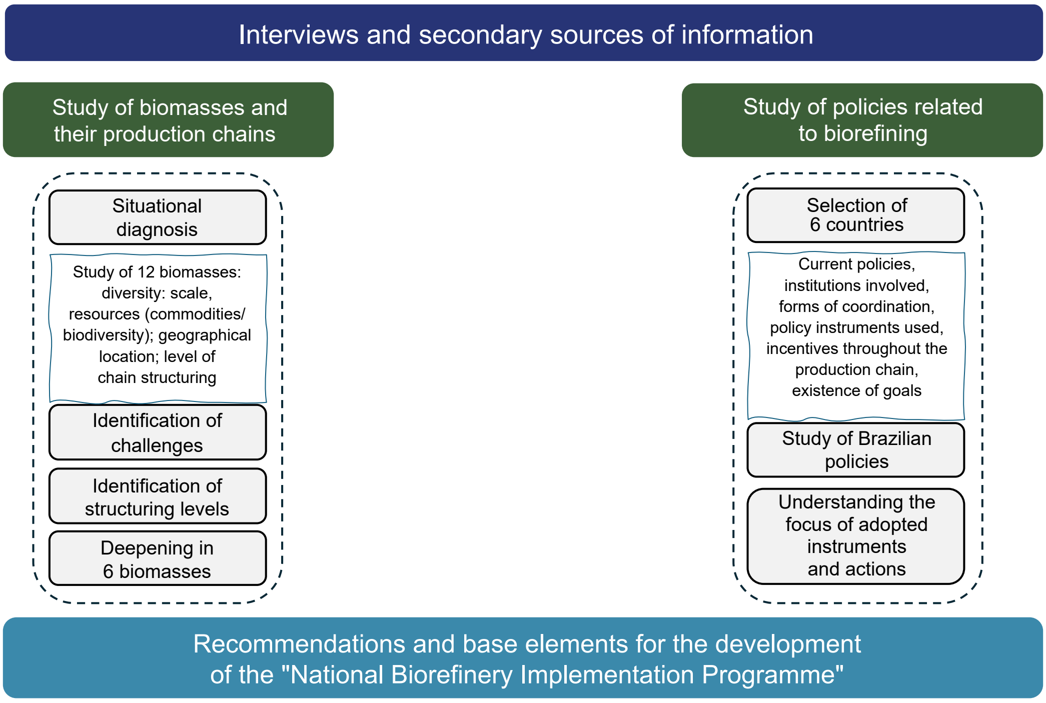
Source: Elaborated by the consultant.

The figure depicts the flow of public policies within the biorefining framework, beginning with macro strategies related to bioeconomy. Each policy is evaluated based on the four key dimensions, considering the attributes of biorefining. Notably, feedback from production chains and the broader ecosystem plays a crucial role in enabling continuous policy review, ensuring alignment with subsequent stages of development.

3. Methodology

This report is based on two studies, as depicted in Figure 5—one focused on biomass and another on policies related to biorefining.

Figure 5. Schematic representation of the methodology



Source: Elaborated by the consultant.

The biomass study provided an assessment of the state of biorefining in Brazil, outlining its current status and the development challenges. Twelve types of biomass and their production chains were analysed to identify both the technological and non-technological challenges, as well as varying levels of structuring. To further explore this diversity, six cases were selected to illustrate different structuring levels, representing the wide range of biomass available in the country.

The study of policies, programmes, and instruments used in the selected countries, as well as in Brazil—reveals that even those not explicitly focused on biorefineries contain elements related to the bioeconomy and circular economy, which may support biorefinery development.

Based on the identification of challenges and gaps in the Brazilian context, along with insights from international experiences and existing policies, programmes, and instruments in the country—both available and in development—a set of base elements were proposed for drafting the National Biorefinery Implementation Programme. These elements will support the creation of action plans aligned with the different structuring levels of biorefining systems in Brazil.

Sources of information

This report draws on secondary sources of information, interviews, and technical visits. For the biomass study, secondary sources included technical and sectoral reports, technical workshop presentations, general news articles, scientific journal articles, and other publications. Additionally, it utilised information from the websites of government agencies, research centres, universities, newspapers, business magazines, and other sources.

The mapping of policies related to selected countries was based on official country documents and websites, studies by international organisations (OECD, IACGB, IEA Bioenergy, among others), scientific articles, and other publications.

Throughout the study, 46 interviews were conducted with stakeholders from the government, research, and industry sectors. These interviews were held in-person or remotely, averaging 60 minutes in duration. A semi-structured survey was used to guide the discussions, allowing for the clarification of questions based on the interviewees' expertise. Priority was given to themes aligned with their experience and areas of work.

The main aspects discussed in the interviews include:

a. The concept of biorefining

b. Challenges in the valorisation of both technological and non-technological biomasses

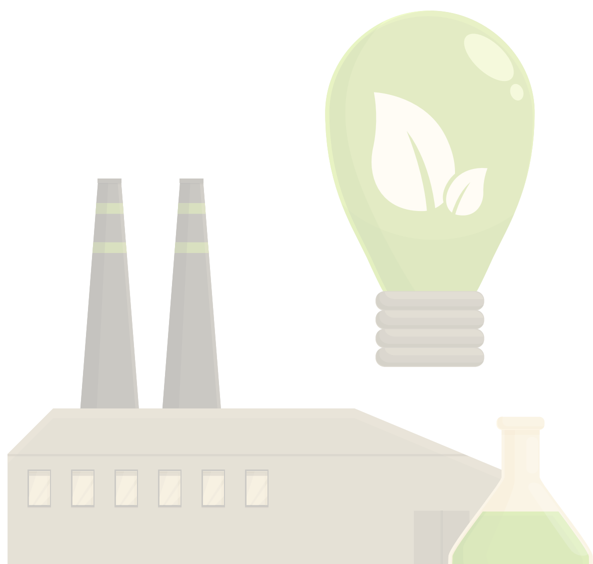
c. Specific challenges for the valorisation of Brazilian biodiversity biomass

d. Stages of production chain structuring

e. Regulatory aspects

f. Public policies and incentive instruments

g. Financing instruments available



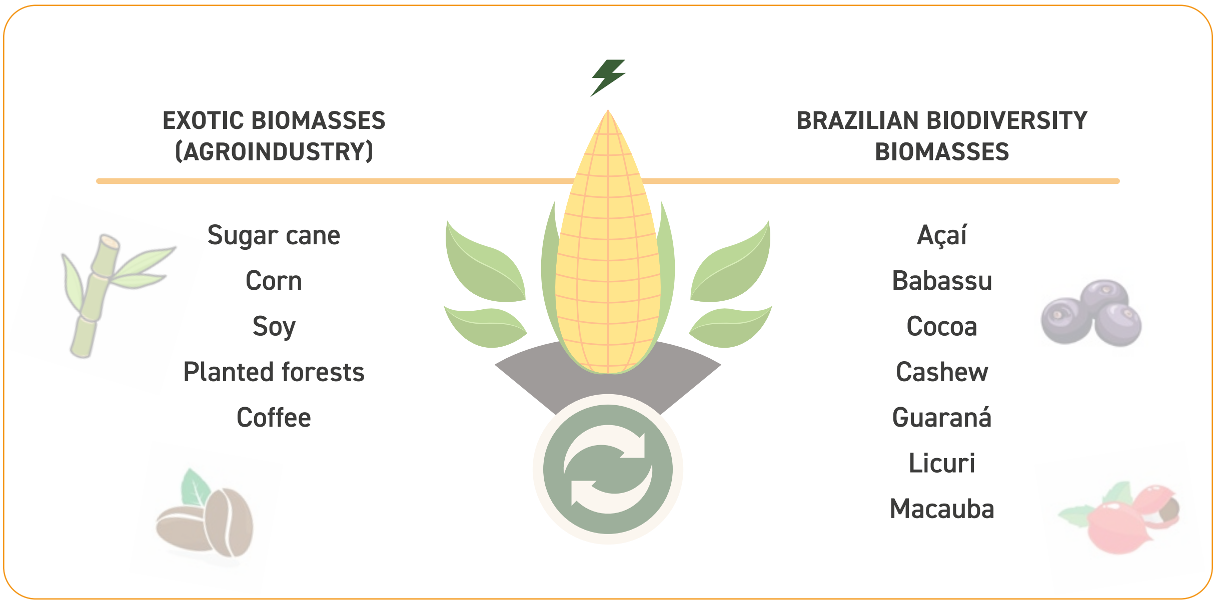
Biomass study

The situational diagnosis of biorefining in Brazil started with exploring a set of 12 biomasses. This was a qualitative and exploratory survey, based on drafting case studies. It sought to identify common and specific challenges related to biomass groups that could inform the proposal of strategies, policies, and instruments for the National Strategy to Implement Biorefineries in Brazil.

For each biomass case, a sheet was developed to examine the current state of biorefining and the challenges— current and future—of adopting a systemic approach.

Biomasses were categorised into two groups based on their origin: agroindustry-derived biomass and Brazilian diversity biomass (Figure 6). In addition, the study aimed to select a representative sample from both groups, considering: (1) production models (extraction or cultivation); (2) biomes and regions; and (3) production chains at different structuring levels. The diversity of cases provided insights into the different factors influencing or determining the challenges in structuring biomass supply and its industrial valuation, making the sample representative. Figure 6 presents the selected biomasses.

Figure 6. List of selected biomasses



Source: Elaborated by the consultant.

The sheets were designed to gather information on production chains and industrial activities related biomass valorisation. Key aspects highlighted included: production scales; geographical location; technological expertise; product diversity; current and potential uses; feasibility of full biomass utilisation; and level of technological maturity.

Cases highlight various challenges related to the valorisation of the studied biomasses, which will be further discussed in Section 4. Four key dimensions of structuring were considered: raw inputs; technologies; products; and business models. This approach enabled a broader understanding of common challenges across different biomasses and their relationship with these dimensions.

The four biorefining attributes outlined in Section 2.2 were used to evaluate the current stage of biorefinery development (Table 1).

Table 1. Assessment of the current state of biorefining in Brazil

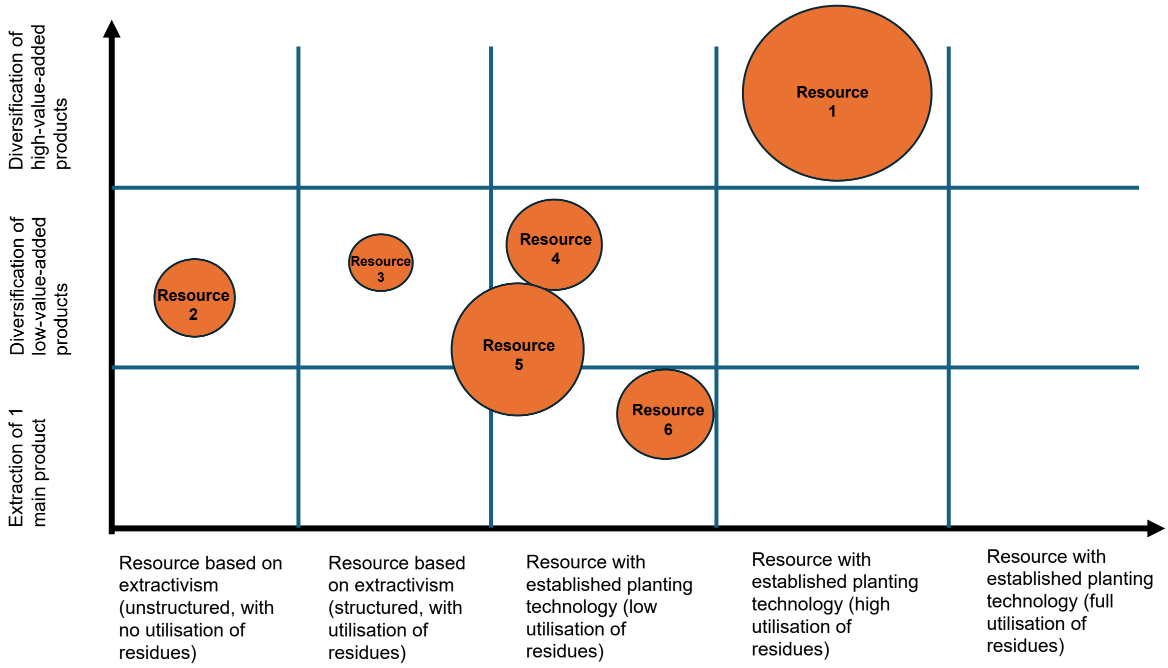
	Biorefining attributes	Key questions
1	Product diversification	What products are currently derived from the biomass resources? How diverse are they?
2	Full use of biomass	What is the current level of biomass utilisation? Which residues remain unused?
3	Circularity	Are there any initiatives related to the Circular Economy? If so, what is their current status?
4	Regional/territorial insertion and industrial symbiosis	Are there efforts to promote regional integration? Are there relationships between companies that indicate industrial symbiosis?

Source: Elaborated by the consultant.

Based on the assessment of the four systemic attributes, each biomass resource was identified in terms of two key aspects: the structuring of its supply and the valorisation of the resource. Figure 6 presents a matrix with two axes. The horizontal axis represents the supply model (extractivism or cultivation), the level of mastery of planting and harvesting technologies, and the degree of utilization of waste generated (low, high, or full). The vertical axis indicates the level of product diversification. Each resource is depicted as a circle, with its diameter representing the order of magnitude of the current supply. Section 4.2 provides further details on the supply magnitude, while the positioning of each resource within the matrix reflects its current stage.

Analytical tables were created to compare the cases and identify similarities and specific characteristics in the structuring of biorefining. The results of this analysis served as the basis for selecting the biomasses studied in greater depth: planted forests, sugar cane, coffee, macaúba, babassu, and açaí.

Figure 7. Matrix of the current state of resources



Source: Elaborated by the consultant.

Planted forests stand out for their high degree of product diversification, advanced mastery of biomass production technologies, and extensive utilisation of residues, byproducts, and co-products—though full utilization has not yet been achieved. These characteristics make this biomass unique and a compelling subject for further study.

A second group identified includes **sugar cane, corn, and soy**, with sugar cane extending beyond the group's boundaries and approaching the characteristics of planted forests. All three biomasses demonstrate technological mastery in resource production.

Despite their competitiveness on an international scale, challenges remain in terms of productivity and sustainability, particularly for sugar cane. Product diversification is most advanced in sugar cane, shows signs of progress in corn, but remains relatively low in soy. Similarly, while there is still significant room for improvement in the valorisation of residues, by-products, and co-products for all three biomasses, sugar cane has already made notable strides in this area. Within this group, sugar cane was selected for a more comprehensive examination.

Another group identified includes **açaí, cocoa, guaraná, coffee, and cashew**. The common characteristic among these biomasses is their low resource utilization, typically limited to extracting a single main product (as in the cases of açaí and guaraná) or, at most, diversifying into low-value products (as seen with coffee, cocoa, and cashew). Cultivation is the dominant production method in this group, with the exception of açaí, which is produced and supplied through various methods, including pure extractivism, managed extractivism, and cultivation.

Within this group, two biomasses were selected for further study: **açaí**, due to its high supply volume—being the primary non-timber extractive resource—and its potential for a diversified biorefining process that could incorporate different business models; and **coffee**, due to the international significance of national production, the regional diversity of its cultivation, and the potential for developing various value chain links.

Finally, the group comprising **macaúba**, **babassu**, and **licuri** represents the predominant extractive production, with limited product diversification (except in the particular case of babassu). Despite announced plans and investments in macaúba, the cultivation model and technological mastery are still under development. However, macaúba's potential as a valuable resource in integrated biorefining schemes, along with numerous initiatives (startups) and project announcements, has made its biomass a recommended subject for detailed study.

Babassu presents an interesting case of extractivism that includes both artisanal extraction and valorisation schemes, though it may face limitations in biomass utilization. A biorefinery focused on babassu aims for full utilization and successfully diversifies its products to a significant level of value. The case of a biorefinery with over 50 years of history offers valuable insights into the development of biorefining from biodiversity resources. Additionally, the production potential of babassu in Brazil's North region provides a basis for exploring different biorefining business models.

For each biomass, the sheets were expanded to include key details. First, the regional particularities of each biomass were highlighted. Next, the challenges associated with biorefining development were outlined. The third section revisits the situational matrix, discussing potential development pathways. Finally, based on the descriptive sheets, regional characteristics, identified challenges, and possible biorefining strategies, recommendations for public policies to address these challenges were presented at the end of each sheet.

Study of policies related to biorefining in different countries

To identify policies, programmes, and instruments already in use in other countries, six countries were selected based on the following criteria:

- The existence of strategies related to the bioeconomy.
- Similarity to the Brazilian context, including the availability of resources with potential for valorisation and the generation of sustainable economic development.
- Experience in formulating and implementing innovation policies and strategies.
- Availability of information to identify the key dimensions of strategies and policies.

Documents from the International Advisory Council on Global Bioeconomy, which identify and characterise countries with bioeconomy strategies, were used as an initial reference for selection criteria. Six countries were chosen: **Australia, China, the USA, Finland, France, and Thailand.**

For France and Finland, strategies and initiatives at the European Union level were also considered. An information sheet was prepared for each country, addressing the key points outlined in Table 2.

Table 2. Topics researched and information mapped

Topic	Information raised
Description	Year of establishment, responsible institutions, main drivers, and key documents
General aspects	Is there an adopted definition of bioeconomy? What are the priority strategy areas? Is there an action plan?
Scope	Are there regional approaches? How are they structured?
Biorefining	Is biorefining explicitly addressed? What concept of biorefining has been adopted?
Circularity	Does it explicitly involve the circular economy?
Institutions involved	Which institutions are involved in the strategy?
Form of governance and coordination	What are the roles of the different institutions?
Policy instruments used	What policy instruments are in place? What mechanisms exist for project selection, incentives, and financing follow-up?
Incentives along the production chain	Are incentives provided throughout the entire value chain?
Approach regarding raw inputs	Are priority raw inputs defined? Is there a policy for residue reuse? Is biodiversity considered?
Approach regarding technology	Are priority technologies identified?
Approach regarding products	Are priority products identified? What types of products (commodities, specialties)?
Approach regarding stakeholders	Are key sectors or production chains identified? Are the stakeholders in the chains/ecosystems identified?
Goals	Are there explicit goals?

Source: Elaborated by the consultant.

A brief description is provided of the main policy orientations related to the bioeconomy, with a particular focus on biorefining, as observed in the policy instruments of the countries studied. These policy orientations can be directly linked to the key analytical dimensions of innovation structuring in the bioeconomy—raw materials, technology, products, and business models—or they may be cross-cutting, not specific to any single dimension.

4. Situational diagnosis—Analysis of Brazilian biorefineries

This section aims to construct a situational diagnosis of biorefining in Brazil based on information gathered from case studies and interviews. Following the methodology outlined in Section 3, the analysis is conducted in three stages. The first stage identifies and describes the challenges facing the development of biorefining in Brazil. In the second stage, these challenges are examined in relation to the key dimensions of bioeconomy development—raw materials, technologies, products, and business models. Finally, in the third stage, the studied biomasses are positioned within a matrix that considers product diversification, supply model (extractivism or cultivation), mastery of cultivation and harvesting technologies, and levels of waste utilisation.

4.1 Stage 1: Identified challenges

Analysing the case studies and interviews revealed a diverse set of challenges affecting the development of biorefining in the country. The challenges outlined in Table 3 encompass both technological and non-technological bottlenecks, spanning the entire process—from structuring biomass supply to processing and industrialisation (biorefinery) and ultimately, marketing the resulting products.

The proposal for an integrated vision of biorefining highlights that the industrial development of biorefineries depends on overcoming challenges present at the early stages of various production chains, each with different levels of structuring.

A key finding of this research is that promoting the industrialisation of resources—particularly those derived from biodiversity (listed in Table 2, Section 3)—requires addressing challenges related to primary processing, which can be understood as a pre-industrialisation stage.

From a policy perspective, as well as in terms of actions and strategies for developing biorefining, it is essential to relate the identified challenges to the analytical dimensions proposed for biorefining. Determining whether a particular challenge pertains to raw materials, technology, products, business models, or a combination of these dimensions is a crucial step in this process.

As noted in Section 2, using analytical dimensions provides a structured and integrated perspective on creating opportunities in biorefining, helping to prevent fragmentation in policy recommendations.

Based on insights from case studies, supplemented by interviews, 17 key challenges related to the development of biorefining were identified. Table 3 presents the main challenges common to most of the cases analysed, along with a brief description. It is important to note that the case studies also highlighted challenges specific to the context of each biomass.

Throughout the research, these challenges were, whenever possible, linked to the broader systemic issues affecting biorefining.

Table 3. Identification of challenges and brief description

Challenges identified	Brief description
1. Ensuring the environmental sustainability of extraction and cultivation practices	Limited adoption of sustainable extraction and cultivation techniques that reduce water consumption, prevent deforestation, and preserve biodiversity.
2. Increasing technological integration in harvesting and processing stages	Encourage the use of (a) technologies, machinery, and equipment to optimise harvesting, minimising losses and damage to harvested crops; (b) technologies that improve the quality of fractions and products obtained in the initial processing stage, reducing waste, adding value, and enhancing the quality of resources for subsequent industrialisation.
3. Increasing productivity	Increase productivity per hectare through various factors, including the need to renew crops and improve farming techniques.
4. Maximising biomass utilisation	Enhance the efficiency of biomass use, aiming for full utilisation, value enhancement, and waste reduction.
5. Increasing the added value of generated products	Implement strategies to enhance biomass valorisation towards higher-value-added products.
6. Ensuring positive social impacts	Promote the participation of producers and primary processors in revenue generation, as well as fostering local development in biomass-producing regions.
7. Improving cultivation, harvesting, and storage processes	Implement better practices, infrastructure, and technologies to enhance cultivation, harvesting, and storage processes, thereby increasing yield, improving product quality, and reducing losses.
8. Advancing applied knowledge on biomass fraction characterisation	Support R&D activities to expand scientific understanding of resource characterisation and chemical composition.
9. Increasing the efficiency of the processing stage	Introduce practices, processes, and technologies to enhance processing efficiency, increasing yield and product quality while facilitating downstream industrialisation.
10. Developing new products and applications	Strengthen R&D efforts to drive the development of new products and applications.
11. Organising the supply chain and minimising the influence of middlemen	Support socio-productive organisations that facilitate product commercialisation, promote best practices, and encourage the adoption of new technologies.
12. Improving logistics for resource access and product distribution	Implement solutions to address access to raw materials and waste management at different supply chain stages, ensuring efficient product distribution.
13. Advancing industrialisation	Enhance biomass valorisation through industrialisation by integrating advanced processing technologies (e.g., extraction, pre-treatment, conversion) and new business models.

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Desafios identificados	Breve descrição
14. Developing mechanisms to strengthen demand for 'green' products, particularly those deriving from biodiversity	Implement incentives to boost demand for bioproducts beyond biofuels, particularly those derived from Brazilian biodiversity. Examples include promoting public procurement of biodiversity products and tax reductions.
15. Scaling up to pilot and demonstration production	Establish financial support and technological infrastructure to provide access to equipment and resources for scaling up new processes and products—addressing a key barrier to the full utilisation of biomass, diversification, and value addition.
16. Providing data and information on resource availability in terms of quantity, detailed georeferenced location, access to logistical infrastructure, etc.	Foster research, technology, and initiatives to generate data on resource availability, including quantity, detailed georeferenced locations, and logistical infrastructure access.
17. SISGEN registration: Genetic heritage—challenges in using Brazil's biodiversity resources for businesses	Despite legal modernisation, some companies report difficulties in registering biodiversity resources within their internal systems (e.g., SAP) or complying with certain legal requirements. As a result, some companies appear to have abandoned the use of Brazilian biodiversity resources.

Source: Elaborated by the consultant.

4.2 Stage 2: Relationship between challenges and key dimensions

The relationship between the identified challenges and the four dimensions of analysis is presented in Table 4. The mapping reveals that these challenges impact all four key structuring dimensions—raw materials, technology, products, and business models. Consequently, developing opportunities in biorefining requires more than an isolated focus on each dimension; it necessitates a comprehensive approach that addresses the linkages between them.

Table 4. Linkages between identified challenges and dimensions of analysis

Challenges identified/Dimensions of analysis	Raw materials	Technology	Products	Business models
1. Ensuring the environmental sustainability of extractivism and cultivation practices	X	X		X
2. Increasing technological integration in harvesting and processing stages	X	X		
3. Increasing productivity	X	X		
4. Maximising biomass utilisation	X	X	X	X
5. Increasing the added value of generated products		X	X	X
6. Ensuring positive social impacts	X	X	X	X
7. Improving cultivation, harvesting, and storage processes	X	X		

→

Desafios identificados/ Dimensões de análise	Matéria-prima	Tecnologia	Produtos	Modelos de negócio
8. Advancing applied knowledge on biomass fraction characterisation	X	X	X	
9. Increasing the efficiency of the processing stage	X	X	X	
10. Developing new products and applications		X	X	X
11. Organising the supply chain and minimising the influence of middlemen	X			X
12. Improving logistics for resource access and product distribution	X	X		X
13. Advancing industrialisation	X	X	X	X
14. Developing mechanisms to strengthen demand for 'green' products, particularly those deriving from biodiversity			X	X
15. Scaling up to pilot and demonstration production		X		
16. Providing data and information on resource availability in terms of quantity, detailed georeferenced location, access to logistical infrastructure, etc.	X			
17. SISGEN registration: Genetic heritage—challenges in using Brazil's biodiversity resources for businesses	X			X

Source: Elaborated by the consultant.

In Figure 5, the identified challenges are mapped to the different stages of biorefining—biomass supply, processing, industrialisation, and commercialisation.

Understanding where these challenges occur within the production chain is crucial for identifying the necessary interventions at other points in the chain that impact industrialisation.

Table 5. Challenges by dimensions of analysis and biorefining stages

STAGES OF THE BIOREFINING CHAIN / ANALYTICAL DIMENSIONS	RAW MATERIAL SUPPLY	PROCESSING	BIOREFINERY	COMMERCIALISATION
RAW MATERIALS	1, 2, 3, 6, 7, 11, 12, 16	2, 4, 8, 9, 11, 12	4, 8, 9, 13	
TECHNOLOGY	1, 2, 3, 6, 7, 12, 16	2, 4, 5, 6, 9	4, 5, 8, 10, 13, 15	5, 6, 10, 12
PRODUCT	2, 3, 7, 8	2, 4, 6, 9	4, 5, 8, 10, 13	5, 10, 14
BUSINESS MODEL	1, 6, 11, 12	4, 5, 6, 11, 12	4, 5, 6, 13	5, 6, 10, 12, 14

Source: Elaborated by the consultant.

4.2.1 Raw materials

From the cases studied, many of the challenges outlined in Table 4 are linked to the raw materials dimension. These challenges span various stages of the production chain, as illustrated in Table 5. From harvesting to processing, technical and operational bottlenecks can hinder both production and the availability of suitable raw materials for industrialisation. These issues will be explored further through examples from the cases analysed.

These case studies highlight the need to balance biomass supply with sustainable extraction and cultivation practices. Implementing sustainable models can involve, for instance, protecting biomes and restoring degraded land. The case of açaí exemplifies the risks of unregulated demand growth, which has driven an expansion of açaí monocultures in the Pará region. This trend may negatively impact local biodiversity, particularly in floodplain ecosystems (IPAM Amazônia, 2021).

The large-scale exploitation and destruction of native licuri palm plantations have led to a rapid decline in natural populations (Guimarães et al. 2021). Similarly, access to babassu groves has decreased due to agricultural expansion and restricted entry to private lands (ISPN, 2023).

> **“There is a need to balance biomass supply with sustainable extraction and cultivation practices.”**

However, integrating resource exploitation with sustainable practices can mitigate environmental impacts and aid biome restoration. For instance, macaúba extraction, when combined with sustainable methods, supports ecosystem preservation. Its cultivation can help restore degraded areas, and when integrated with other crops in agroforestry systems, it provides valuable ecosystem services (Favaro and Rocha 2022).

Large-scale crops are also facing these challenges. Soya, corn, and sugar cane must meet the rising demand for biofuels while contending with increasing pressure against non-food land use and deforestation.

In planted forests, monoculture plantations remain dominant. However, research into agroforestry and silvopastoral systems, such as Crop-Livestock-Forest Integration (CLFI), has advanced, offering economic, environmental, and social benefits (MAPA 2018).

The cases studied highlight that industrialization through biorefining requires not only resource availability but also the development of a sustainable and regenerative supply chain. Extractive activities must be monitored and adapted to balance economic resource use with biome conservation. The transition from extractivism to cultivation must align with growing demand, ensuring that expansion is conditioned by the productive system's capacity to supply resources sustainably.

Scale is another key factor that can limit the use of certain biomasses in industrialization. Crop sizes vary widely, from small-scale crops like licuri and guaraná to intermediate crops such as cocoa and açaí, and large-scale commodities like sugar cane, corn, soy, and coffee.

The development of new products and applications must align with resource availability. For emerging biofuel crops like macaúba, scaling up biomass production while maintaining quality and cost efficiency is a significant challenge. Achieving the necessary production levels often requires long maturation periods, which investors and public policies may overlook.

For some crops, increasing productivity per hectare is crucial for resource supply. This is particularly true for sugar cane, where projected yield gains may be insufficient to meet future demand without expanding the planted area.

The challenge of productivity also affects smaller-volume crops like guaraná and cashew, which are experiencing the depletion of guaraná plants and cashew trees, respectively (Tricaud et al. 2016; Figueiredo Junior 2010). It is important to note that the economic viability of biorefining activities is closely tied to productivity.

A significant obstacle to resource valorisation through industrialization is the low level of technology in harvesting and processing. These challenges are particularly pronounced in biodiversity biomass but are also present in structured crops like coffee.

In several of the biomasses studied, harvesting is carried out manually or the fruit is collected from the ground, jeopardising the quality of the products obtained during processing. In the case of coffee, the use of harvesting machines among small producers remains limited (Conceição et al. 2020). Similarly, collecting açaí is a labour-intensive, costly, and challenging process due to the height of the palm trees, posing risks to farmers' safety and health (Bittencourt, Potiguar, and Fernandes 2024).

The lack of infrastructure and limited financial capacity to invest in equipment for primary processing have hindered producers' ability to obtain higher value-added products. One example is guaraná, where producers carry out primary processing steps such as pulping, washing, and roasting. The roasted grains (guaraná *em rama*) are then sold to intermediaries and/or secondary processors to produce powder, sticks, or syrup—products with greater added value (Silva et al. 2018).

“There is significant variation in scale, ranging from small-scale cultivars such as licuri and guarana to medium-sized cultivars such as cocoa and açai, and large-scale commodities such as sugar cane, corn, soy, and coffee.”

In cashew farming, investment in equipment is needed to improve nut processing in so-called mini-factories or small-scale processing units (da Silva 2024; Brainer 2022).

In the case of licuri and macaúba, oil extraction from the pulp is considered inefficient, as it is typically carried out by pressing, resulting in significant oil loss in the residual cake. This oil is a valuable product for various applications or compound extraction (Favaro and Rocha 2022; Guimarães et al. 2021).

In poorly organised or minimally structured production chains, middlemen often act as intermediaries between producers and the market, as seen in the guaraná, cashew, cocoa, and açaí industries. These middlemen exploit producers' difficulties in commercialising their products, imposing prices that undermine profitability.

The presence of socio-productive organisations, such as cooperatives, is a positive factor in structuring supply chains, as they enable marketing at fairer prices and facilitate access to technical assistance and financing for producers. The lack of organisation within the chain prevents industries from replacing their current inputs with those from renewable sources, due to the uncertainty surrounding the supply of these resources. Therefore, initiatives aimed at improving growing, harvesting, and processing conditions are likely to become viable only if these socio-productive organisations collaborate with Brazilian biodiversity crops.

The level of biomass utilisation is low, with processing often focused on one or a few key products, while waste is either discarded or underutilised in low value-added applications. This is evident in cashew nut production, where the focus is on the nut, and the stalk, which accounts for 90 per cent of the fruit, is rarely used (da Silva 2024; Embrapa 2022).

In the case of açaí, the focus is on the pulp, and the use of the stone and waste streams from the pulping process (such as lees, stones, and fibres) presents a challenge for the sustainability of the açaí supply chain. In coffee production, waste is generated in large quantities from the field to industrialisation, with most of it being underutilised in low-value applications (IICA 2020).

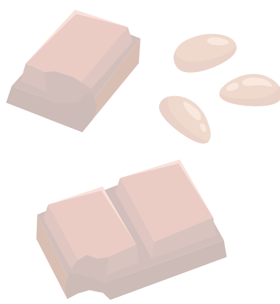
In the cocoa supply chain, only 8 per cent of the fruit is utilised for processing into fruit derivatives, while the remaining 92 per cent is classified as waste with no effective commercial use (MAPA 2024; Veloso 2020). In the artisanal exploitation of babassu, utilisation is often limited to the kernel, which is rich in oil but accounts for less than 9 per cent of the coconut (ISPN 2012).

These cases highlight the opportunities for fully utilising resources through an expanded biorefinery concept aligned with the principles of circularity.

Another major challenge is the lack of data and information regarding the availability of resources, such as quantity, location, and other relevant factors, which hinders the development of opportunities and the attraction of investors. The lack of reliability in the supply of raw materials, compounded by the challenges inherent in poorly structured supply chains, creates a bottleneck for the industrialisation of resources. Perishability, as well as inadequate transport and storage conditions, also need to be addressed.

It is also important to emphasise that regulatory issues can be crucial to business development. In addition to international concerns related to the sustainability of biomass—particularly sensitive in markets like Europe—two other key regulatory frameworks for biorefining development should be highlighted at the national level: biosafety and access to genetic heritage.

In particular, the law on access to genetic heritage, despite the acknowledged modernisation of the legal framework, has been seen as a barrier to the use of Brazilian biodiversity resources. Some companies report challenges in registering these resources within their internal systems. Difficulties with operating the SISGEN registration system are causing companies to abandon the use of biodiversity resources altogether. The payment structure for access, which is made in the final product, as well as formal difficulties in registering it within companies' supply systems (e.g. SAP), are deterring potential stakeholders from engaging with biodiversity products.



4.2.2 Technologies

The low level of technology integration in the initial stages of the analysed supply chains was identified as a significant bottleneck for both the supply of biomass and its subsequent industrial valorisation. The technological agenda for biorefining development is broad, encompassing multiple areas of expertise.

The search for more sustainable extraction and cultivation systems requires RD&I activities. The case of macaúba exemplifies the significant technological effort underway to make the transition from extractivism to cultivation viable. Characterising and selecting species with higher oil yields is considered one of the critical stages in advancing the domestication of species chosen by companies interested in their development (Junqueira et al. 2019).

An example illustrating the role of technology is the genetic improvement programme carried out by Embrapa Agroindústria Tropical, which has developed small cashew clones with greater resistance to pests and water stress. By replacing the giant cashew tree with the dwarf cashew tree, greater productivity in the field and more efficient harvesting will be possible, enabling the valorisation of the stalk for the production of the cashew fruit, jams, jellies, or juices, thus minimising losses (da Silva, 2024).

The low adoption of technological packages by small producers has had negative consequences for productivity in the field, as well as in harvesting and processing. In general, there is limited use of machinery in the harvesting/collecting process, and in some cases, research, development and innovation (RD&I) efforts are still needed to develop equipment that meets the specific needs of each situation.

The mechanisation of harvesting is proving to be a challenge, particularly in lowland areas for açaí. Although farmers have developed rustic equipment, such as harvesting poles that eliminate the need to climb palm trees, traditional harvesting methods remain dominant (Embrapa 2021).

It was also found that the low technical capacity of producers can be an obstacle to the adoption of new technologies, as well as the financial limitations associated with acquiring machinery for the processing stage. As discussed above, rudimentary equipment and inadequate extraction techniques generally limit the yield and quality of products.

In processing, technology can be seen as a crucial first step towards industrialisation. For example, a key challenge with macaúba is optimising the process of extracting oil from the pulp and kernel, which has led to efforts to develop various technological solutions (Favaro et al. 2018). One solution is aqueous extraction, in which the fruit is processed fresh, without the need for drying, using equipment similar to that used for olive oil extraction. It is important to note that, in many cases, some of these improvements depend on the adoption of simple technologies with a high level of technological maturity.

Technology plays a crucial role in maximising the use of biomass and converting it into higher value-added products, a process made possible by the advancement of industrialisation in production chains. In this context, a broad spectrum of technologies can be observed, including: (1) the search for technologies to optimise the extraction of specific fractions of the fruit (for example, oil from the pulp of certain fruits, which is currently extracted mechanically); (2) advances in more efficient and sustainable compound extraction technologies (such as microwave-assisted extraction and ultrasound-assisted extraction); (3) advances in pre-treatment technologies for the release of sugars in lignocellulosic materials; and (4) chemical, biochemical, or thermochemical conversion technologies.

In the case of projects aimed at producing second-generation ethanol, for example, a major R&D effort was required to develop technologies for pre-treating and converting lignocellulosic biomass (such as sugar cane straw/bagasse and corn straw/waste) into ethanol. Various pre-treatment methods have been developed to release cellulose and hemicellulose molecules, which are then subjected to new enzyme cocktails to release fermentable sugars. Researchers also had to investigate the action of yeasts, as the enzymatic hydrolysis stage produced not only C6 sugars, as in first-generation ethanol production, but also C5 sugars (Correa et al. 2023).

> **“Although farmers have developed rustic equipment, such as harvesting poles that eliminate the need to climb palm trees, traditional harvesting methods remain dominant.”**

The search for new products and raw materials requires the development of processes on a larger scale, in partnership with equipment manufacturers. This process involves conducting various tests to adapt existing equipment to new functions. These are slow steps that require relatively high investments, as well as process modelling using phenomenological and hybrid technologies.

The case of second-generation ethanol illustrates the technological challenges in developing equipment. Most of the equipment in the feed systems for the pre-treatment stage operated well below the designed capacity and without continuity, due to issues such as clogging, incrustation, and material build-up, as well as erosion and corrosion problems in the equipment (ibid.).

The cases revealed that biomasses can face different technological challenges or be at various stages in addressing these challenges. For some biomasses, there is already extensive scientific knowledge regarding the physical and chemical characterisation of biomass and waste, such as agro-industrial biomass.

However, in the case of biodiversity biomass, this level of knowledge can vary. For example, with guaraná, technical reports highlight gaps in scientific understanding of the composition of residues such as bark and shells. In contrast, for macaúba, there is a growing effort in research and publications to characterise the different fractions of the fruit in order to identify potential products and applications.

Another important point in the discussion of technology is understanding that sectors and industries can have different patterns of technological innovation. While the planted forest sector, particularly the pulp and paper industry, is recognised for significant investment in RD&I, the sugar cane sector, for example, generally relies on equipment suppliers and other stakeholders as sources of innovation.

Large pulp and paper companies have invested considerably in developing technologies to convert planted forest residues and industrial waste into new, value-added products. In contrast, few companies in the sugar cane sector have invested in advanced technologies, such as those related to second-generation ethanol.

In less structured chains, progress towards industrialisation will depend on attracting players capable of introducing or developing these technological skills through partnerships. In the cases studied, technology-based start-ups, universities, and research institutes were identified as key contributors to these developments. Therefore, technological progress will rely on fostering an innovation ecosystem that encourages collaboration among various stakeholders.

Finally, it is worth noting that recent technologies—such as those used for product traceability, data processing, logistics, and transport—should also be considered when structuring the production chains involved in biorefining.

4.2.3 Products

The first key observation from the case studies is the low diversity of products generated. Açaí, for example, is primarily focused on pulp, while in the case of cashew, nuts are the main commercial interest. In the cocoa sector, the primary product is its seeds, which serve as raw material for chocolate and its derivatives.

This observation is most evident in biodiversity biomass but can also be applied to agro-industrial biomass such as coffee, corn, soya, and sugar cane. In the case of coffee, the seed (bean) is the primary product; for sugar cane, the main products are ethanol and sugar; corn is primarily used for animal feed; and soya beans are the main product, with bran and oil as by-products.

In addition to low diversity, the current landscape consists mainly of low value-added products, resembling commodities, which presents a challenge for value generation within the chains. Coffee serves as an illustrative example. The diversity of products currently derived from coffee remains limited compared to the potential identified in the literature and the significant volumes of waste generated. The pulp and bark, for instance, can be utilised to produce a wide range of products, from commodities such as ethanol, biofuels, biochar, and biochemicals to higher value-added products like caffeine, chlorogenic acids, lipids, and antioxidants for use in the food, cosmetics, and pharmaceutical industries.

Several opportunities have been identified for developing a broader range of higher value-added products. Investors in corn industrialisation have highlighted not only the production of first-generation ethanol and animal feed but also the significant potential for utilising crop residues to produce biomethane, bioplastics, or 'green' hydrogen, which can be converted into SAF. Additionally, the CO_2 generated during fermentation could be used to produce green methanol.

Sugar cane also shares some of these opportunities. Macaúba presents particularly promising prospects, with studies exploring its potential for biofuel production (green diesel, SAF), the development of chemicals and cosmetics from its oil, and the utilisation of its pulp cake—rich in fibre and protein—for food products, animal feed, biogas, biofertiliser, and biochar. In most cases, addressing these opportunities requires tackling the challenges of increasing biomass utilisation, advancing RD&I to characterise its fractions, and furthering industrialisation efforts.

The potential products derived from the full utilisation of biomass range from commodities to specialised products. Opting for commodity-type products has implications for business models, which must be designed to enable larger scales that ensure cost competitiveness.

On the other hand, higher value-added products, particularly non-drop-in[4] products for the pharmaceutical, cosmetics, and food industries, require efforts to develop market applications. This often depends on capabilities that are either absent or insufficiently developed in many companies.

In this case, the challenges arise at the commercialisation stage and demand business models that incorporate partnerships with players who possess the necessary expertise. It is important to highlight that public policies for the development of biorefining should not only promote the adoption of bioproducts but also support business models that foster skills related to product development and market applications.

There are, therefore, opportunities to obtain both drop-in and non-drop-in products, commodities, and specialised products, catering to diverse markets—many of which lie outside the traditional competitive environment of companies, ranging from fuels to cosmetics. However, as illustrated by the examples presented, progress in diversifying products and developing higher value-added applications hinges on increasing biomass utilisation, advancing RD&I to characterise its fractions, and driving industrialisation forward.

Without these advances, the current situation of low product diversity and low added value is unlikely to change. It can also be stated that progress in product diversification will depend on the organisation of the chains at the upstream stages. Industries are unlikely to alter their products and formulations to include bioproducts unless there is reliability in the supply and quality of the raw materials used.

4.2.4 Business models

The business model dimension is closely linked to the other dimensions, as structuring the supply and ensuring the availability of resources with the required quality for subsequent processes is the starting point for the development of biorefining.

Additionally, business models must provide solutions to the challenges encountered across the various stages of biorefining, including biomass supply, processing, industrialisation, and product marketing. Developing opportunities that consider the systemic attributes of biorefining—such as product diversification, full utilisation of biomass, circularity, and regional/territorial integration—requires the proposal of innovative business models.

4. Drop-in products are those equivalent to fossil-based products, possessing the same chemical structure and therefore identical technical properties, allowing them to be used without alterations down the production chain (Oroski, Bomtempo, and Alves 2014).

For nearly all biomass from biodiversity, a low degree of organisation within the production chain was observed, characterised by significant fragmentation between links and a strong influence from middlemen.

In the cases of açaí, cocoa, and guaraná, the conflict between producers, middlemen, and processors over the low prices paid to the former was evident. The intermediaries (middlemen) dominate the market, retaining the margin that would otherwise go to the producer. One way to organise production could be through socio-productive organisations. In many cases, the lack of organisation within the production chain remains a barrier to progress in accessing markets, adding value to production, and obtaining training and technical support.

It was observed that, despite the new opportunities for work and income generation arising from the sustainable exploitation of biodiversity biomass, much remains to be done to ensure its proper utilisation. Many family farmers either do not understand the potential of the economic chain or lack the necessary resources to invest in organised production or access better markets.

The opportunities surrounding waste are even less recognised by these players, which makes it difficult to structure this offering. The preservation of the different residual fractions for later utilisation is crucial to advancing industrial waste utilisation processes. This requires business models to propose solutions for the primary processing stage.

To generate positive social impacts, issues such as better income distribution along the chain, increased primary processing capacity among producers, and the development of local productive arrangements are important and must be considered when drafting the biorefining development plan.

The case of cocoa presents an interesting perspective. Most producers still do not carry out the fermentation stage, which is responsible for adding value by influencing the aroma and flavour of the seed. As a result, they produce lower-quality seeds that are marketed as a commodity, affecting the prices paid by middlemen and, consequently, the income of these producers.

> **“One way to organise production could be through socio-productive organisations. In many cases, the lack of organisation within the production chain remains a barrier to progress in accessing markets, adding value to production, and obtaining training and technical support.”**

Structuring biorefineries using biomass from Brazilian biodiversity requires creating an interface between the processing stage and industrial valorisation, i.e., bringing the different links in the chain closer together. From this perspective, the case of macaúba presents an interesting dynamic. Exploiting the opportunities surrounding this biomass has opened up possibilities for innovative business models driven by startups that propose structuring the chain—from supply (cultivation and harvesting) to industrialisation with oil extraction and the full use of the fruit under the concept of biorefining.

In the case of planted forests, sugar cane, maize, and soya, the challenges for business models centre on advancing industrialisation, attracting new companies to take advantage of opportunities for using biomass, and developing new technologies.

Coffee is an interesting case because, despite having a structured supply, it still presents challenges similar to those faced by biodiversity biomass. The sale of green coffee from small producers to roasting companies occurs through co-operatives or intermediaries. These are primarily small businesses (64 per cent are micro-enterprises), many of which are family-run.

Despite this, there are large companies, some controlled by foreign capital. The instant coffee industries are larger, with multinational companies operating in a concentrated market. Co-operatives have played an important role in organising the chain and mediating between small producers and the industry. This context suggests that new players should be introduced into the chain to connect the production of beans to their processing, industrialisation, and marketing stages.

In the case of planted forests, large volumes of waste are concentrated in large-scale industrial facilities, but they are not yet utilised or are underused to generate higher value-added products, such as black liquor and lignin, presenting an opportunity for the sector. A similar situation arises with soya, corn, and sugar cane.

Improving logistics for resource access and product distribution emerged as a central issue in the case studies and interviews. The development of logistical infrastructure is a common challenge for all the biomass companies studied, whether in transporting raw materials to processing sites or moving waste and products to the final market.

Infrastructure plays a decisive role in location choices, influencing the industrialisation model—whether production units are established closer to raw material sources or consumer markets. In the case of babassu, one company has developed a business model that relies on intermediaries to organise collectors. The company accredits, trains, and supervises these intermediaries through field supervisors to ensure the proper functioning of the supply chain, providing collection and transport infrastructure.

In the case of macaúba, one of the start-ups involved in its development plans to adopt a model of mobile processing units. These units will be transported to locations near farms to address the logistical challenge of accessing waste during processing.

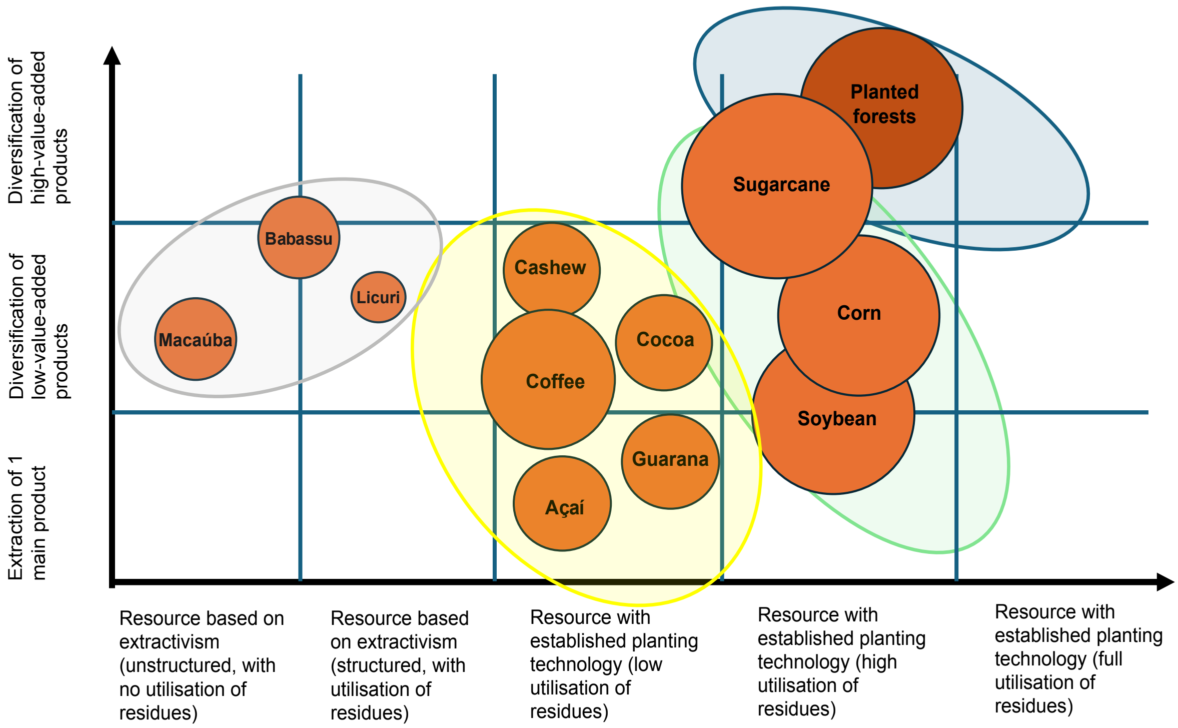
Finally, as opportunities shift toward diversification and the development of higher value-added products and applications, business models must facilitate partnerships with players who possess the necessary complementary skills. Developing new applications can be an even greater challenge for small companies and start-ups that lack direct access to markets.

4.3 Stage 3: Current state of biorefining in Brazil

The case study exploration revealed that resources can be at different stages of development concerning the attributes of the proposed biorefining concept. Figure 8 presents the Biorefining Situational Matrix, which identifies four distinct groups (I, II, III, and IV) representing the biomass studied in relation to key biorefining attributes:

- Level and quality of product diversification.
- Extraction or cultivation, where cultivation may be well-structured with established technological expertise or still in development.
- Level of utilisation of waste, by-products, and co-products, or the extent of full biomass utilisation.

Figure 8. Biorefining situational matrix in Brazil



Source: Elaborated by the consultant.

The differentiation of resources between biodiversity and commodities, which is common in the literature, doesn't seem to address all the challenges of structuring biorefining, as it doesn't allow for the recognition of the differences between resources, both in the set of biodiversity resources and commodities in relation to various aspects that dialogue with the attributes of the biorefining concept adopted in this study, such as: scale, level of organisation of the chain, full use of resources and diversification of products, as shown in Table 6.

Table 6. Aspects related to biorefining attributes across the four biomass types

	RAW MATERIAL SUPPLY MODEL	RESIDUE UTILISATION	DEGREE OF PRODUCT DIVERSIFICATION	
GROUP I	CULTIVATION	HIGH	HIGH WITH THE PRESENCE OF HIGH VALUE-ADDED PRODUCTS	COMMODITIES
GROUP II	CULTIVATION	HIGH	VARIED, WITH FEW HIGH VALUE-ADDED PRODUCTS	COMMODITIES
GROUP III	CULTIVATION	LOW	LOW WITH EXPLORATION OF A SINGLE PRODUCT OF INTEREST	COMMODITIES / BIODIVERSITY
GROUP IV	EXTRACTION WITH DIFFERENT STRUCTURING LEVELS	LOW TO NONEXISTENT	LOW WITH LOW VALUE-ADDED PRODUCTS	BIODIVERSITY

Source: Elaborated by the consultant.

The first key observation concerns the volumes of biomass involved, represented by the varying sizes of the circles. The major crops—sugar cane, maize, soya, and planted forests—process more than 100 million tonnes per year. The second group, with volumes between 500,000 and 5 million tonnes per year, includes coffee and açaí. In the 100,000 to 500,000 tonne per year range are cashew, cocoa, and macaúba. Finally, guaraná, licuri, and babassu account for less than 50,000 tonnes per year.

The variation in biomass volumes highlights the need for different business models in terms of scale, supply chain organisation, and decisions regarding technological and product opportunities and applications.

The second observation is that biomass supply involves both extraction and cultivation. In the case of extractivism, the examples studied demonstrated varying levels of organisation. Extractivism remains the current method of supply for macaúba, licuri, and babassu, whereas the other biomass sources come from cultivated crops with well-established technological mastery.

An exception is açaí, which combines both cultivation and extraction. Notably, macaúba stands out, as meeting the required biomass volumes will necessitate overcoming the challenge of advancing technological mastery in its cultivation.

Regarding the utilisation of waste and by-products, Brazilian biorefining remains in its early stages. There is no full utilisation of biomass, and efforts to valorise resources are more advanced in large-scale crops, particularly planted forests and sugar cane. Maize appears to be following a similar development trajectory, whereas soya remains largely underutilised in terms of biomass valorisation.

Babassu presents a unique case, as it is exploited through two extractivist models—artisanal and industrial—both of which have shown progress in biomass utilisation. In the artisanal processing model, co-operatives have developed some degree of product diversification and are working towards better waste utilisation. The industrial model, by contrast, achieves full utilisation, with certain products considered to be of higher value.

Macaúba is also noteworthy, as discussions are ongoing regarding potential future exploitation models. There is strong interest in its oil for biofuel production, along with some emerging opportunities for utilising other fractions. However, it remains unclear to what extent biomass utilisation and product diversification will be achieved by companies looking to develop biorefining from this resource.

Most biomass is exploited to produce a single product or, at best, a low-value product. Even in cases where greater diversification exists, there remains significant potential for developing higher value-added products.

The situational representation of Brazilian biorefining offers a broad perspective, highlighting four distinct biomass groups and their respective approaches to exploitation and valorisation.

To further refine the situational analysis of these four biomass groups in relation to biorefining attributes, six types of biomass were selected for a more in-depth case study: planted forests, sugar cane, coffee, açaí, macaúba, and babassu. These detailed case studies provided deeper insights into the challenges initially identified.

Table 7 summarises the main challenges and recommendations identified through interviews and literature review. In Groups I and II, the recommendations focus on incentives for scaling up, the development of specialised equipment, and support for research, development, and innovation (RD&I) in product development. These cases already feature industrialisation, with the main challenges centred on improving waste and by-product utilisation and advancing the development of higher value-added products.

It is important to highlight that among the recommendations proposed for addressing the challenges of Group III and IV resources, specific measures include structuring the production chain for biomass supply by strengthening cooperatives and improving logistics for accessing waste and by-products.

Additionally, there are recommendations for creating mechanisms to encourage the adoption of products derived from biodiversity. This analysis underscores the need for biorefining development policies to account for the varying levels of maturity across different stages of the supply chain, from biomass production to industrialisation.

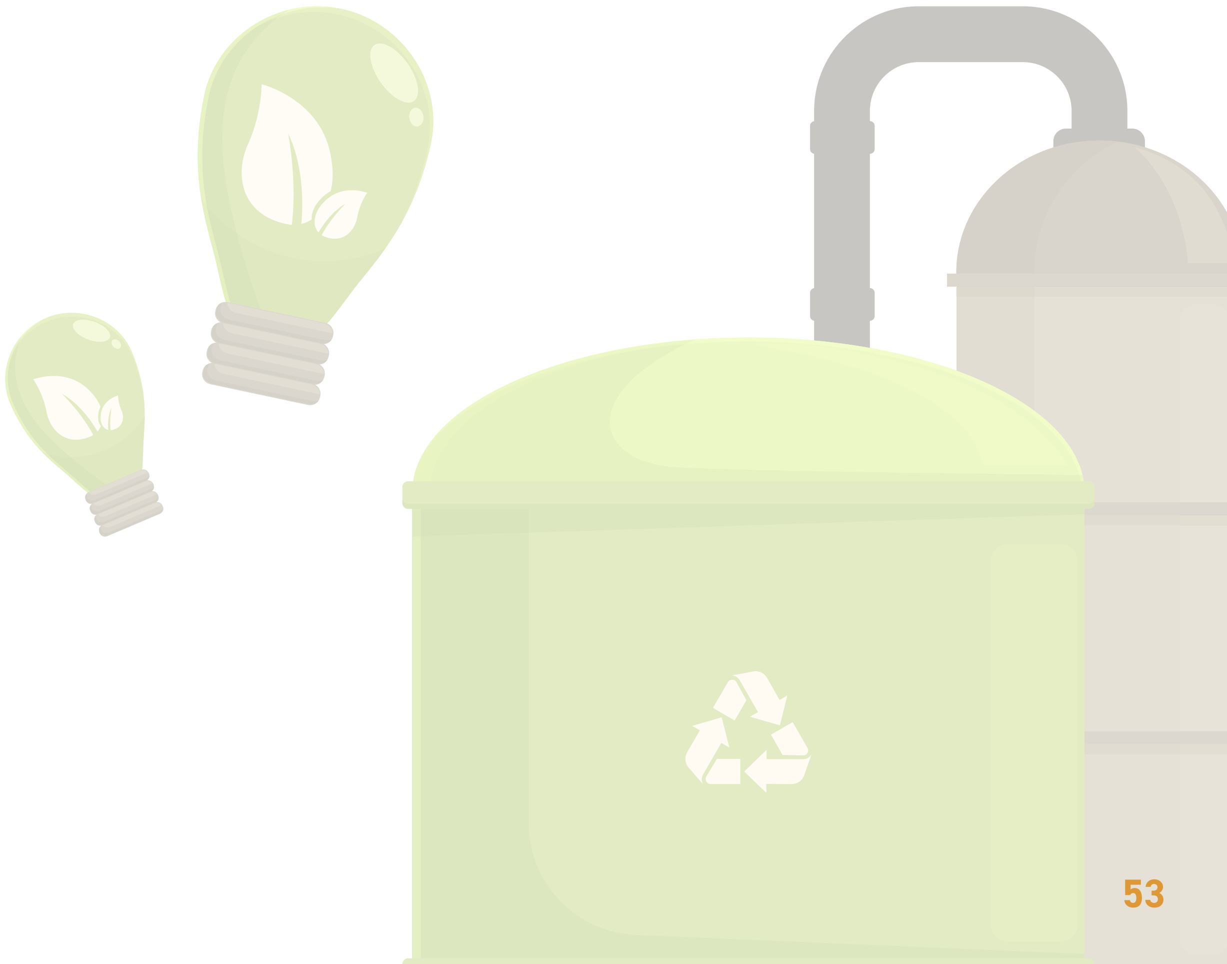
Table 7. Challenges and recommendations

Groups/ biomass	Current stage in relation to biorefining attributes	Key recommendations
Group 1 Planted forests	Varying levels among companies in terms of full biomass utilisation and product diversification	• Support for scaling up projects (pilot and demonstration stages) • Development of equipment to process different types of biomass • Incentive mechanisms for the adoption of "green" products
Group 2 Sugar cane	High utilisation of residues but low product diversification and limited production of higher-value-added products	• Support for scaling up projects (pilot and demonstration stages) • Development of equipment to process different types of biomass • Specific incentives for the development of new products derived from sugar cane
Group 3 Coffee	Low utilisation of residues and no product diversification	• Strengthening cooperatives to improve early-stage chain structuring and technological integration • Mechanisms to attract companies for innovation development in the coffee industry • Specific incentives for developing new products from coffee residues
Group 3 Açaí	Low utilisation of residues and no product diversification (focus solely on açaí pulp)	• Incentives for structuring the supply chain and waste logistics • Support for scaling up bench projects to pilot stage • Specific incentives for developing new products from açaí residues • Incentive mechanisms for the adoption of biodiversity-based products
Group 4 Macaúba	Unstructured extractivism, no utilisation of residues, and no production of value-added products	• Incentives for projects focused on full biomass utilisation and product diversification • Creation of mechanisms that reward ecosystem service provision • Support for scaling up bench projects to pilot and demonstration stages
Group 4 Babassu	Two extractivism models: one cooperative-based and another structured by industry. Residue utilisation and value-added product development tend to be more challenging for cooperatives	• Mechanisms for strengthening and training cooperative • Mapping babassu groves and assessing their exploitation potential • Support for scaling up projects • Incentive mechanisms for the adoption of biodiversity-based products

Source: Elaborated by the consultant.

The following points can be highlighted in conclusion of this diagnostic:

- Generally, Brazilian biorefining does not achieve full utilisation of resources.
- Product diversification is limited, primarily focused on low-value products, with high added-value products being rare.
- Biomass supply includes both structured and non-structured extraction, as well as cultivation, each presenting distinct challenges for biorefining development.
- Levels of structuring vary between Brazilian diversity-based biomass and commodity biomass, requiring tailored approaches to address their unique challenges.
- Industrialisation must be carefully assessed, especially in dynamic biomass sectors such as planted forests and sugar cane. It is also crucial to understand the evolution and maturity of biorefining processes based on biodiversity. The future of biorefining in Brazil appears to be built on these two pillars.



5. International experiences of biorefining policies

5.1 Overview of reference countries

To explore pathways for developing biorefining strategies and policies, this section presents a comparative study of key instruments and policy directions identified in six analysed countries: Australia, China, the USA, Finland, France, and Thailand. The main policy approaches and frameworks will be discussed in relation to the Brazilian context. The analysis does not assess the implementation or outcomes of these policies but focuses on their strategic orientation.

The identified strategies and policies identified vary widely, reflecting the diverse pathways for bioeconomy development and biomass valorisation. While concepts such as product diversification, circularity, full utilisation, and regional insertion are mentioned, they have yet to be fully embedded in the technological dynamics and innovation of the business models.

This establishes two starting points for a comparative discussion of the six countries studied: (i) bioeconomy activities, particularly those related to biorefining, are still in development; and (ii) the pathways for this development are largely shaped by each country's specific conditions and context.

However, these six countries offer a range of experiences that can provide valuable insights for Brazil's biorefining focus.

In Australia, bioeconomy policies and initiatives are located at the state level (notably in Queensland), rather than at the country level. These initiatives, were updated in 2022, are primarily focused on biofuels, especially SAF in Queensland. The concepts of biorefining and biorefineries are not explored. While Queensland and New South Wales have experience with demand-side biofuel policies, there has been no sustained policy continuity. No reference is made to other bioproducts beyond biofuels, and there is no record of efforts to structure the biomass supply.

China's engagement with biorefining is relatively recent, first appearing in a structured form in the 14th Five-Year Plan (2021-2025). As is typical, the plan outlines action strategies and targets. Policy coordination is highly centralised, and initiatives related to the bioeconomy largely align with broader developments in renewable energy. However, there is no specific reference to biorefineries or the concept of biorefining.

There have been initiatives in the field of Circular Economy (CE) since 2005-2006, marked by the launch of several programmes. In 2009, China's National People's Congress (NPC) enacted the Circular Economy Promotion Law of the People's Republic of China, establishing a structured system that fosters co-evolution between science and policy, incorporating two-way feedback and continuous adjustments.

A literature review reveals that Chinese studies on CE have increased rapidly since 2005, whereas this growth only began overseas around 2014-2015. Bioenergy appears to be the next frontier, with policies in place to support the development of green fuels.

In the USA, the first national document explicitly referencing bioeconomy policies dates back to 2012. Advanced biotechnology is considered the foundation for the development of various fields of action. Although significant updates were made after 2022, biotechnology and biomanufacturing have remained the primary focus.

The development of bioenergy has been supported by the US Department of Energy (DOE) since the 1970s through the Bioenergy Technologies Office (BETO). These efforts were reinforced and updated throughout the 2000s. BETO promotes the concept of biorefining, with an emphasis on product diversification, linking bioenergy and bioproducts.

The structuring of biomass supply is supported by the Billion Ton Programme, managed by the DOE since 2005, with updates in 2011, 2016, and 2023. Additionally, a public procurement and bioproduct labelling initiative—the Biopreferred Programme, managed by the US Department of Agriculture (USDA)—has been in place since 2002.

The responsibility for policies and strategies are defined through the appointment of agencies and departments task with coordination and oversight.

Supported projects undergo periodic public presentations, where they are discussed by invited specialists external to BETO. The presentations, expert feedback, and project responses are publicly disseminated.

Finland pioneered the launch of a National Bioeconomy Strategy in 2014, with several update documents published since. A key milestone was the National Bioeconomy Strategy in 2022, which prominently incorporates CE principles and aligns with related policies at both national and European levels.

For each of the four priorities established in the national strategy, the responsible institution and involved stakeholders are clearly defined. Those priorities focus on: added value; technological competence; competitive environment; and sustainable use of biomasses.

Biorefining is approached systemically, with measures spanning entire production chains and engaging various stakeholders. Finland places particular emphasis on forest biomass, and recent policies highlight financing for demonstration plants to advance the country's bioeconomy.

France's national strategy, launched in 2018, was developed through a bottom-up approach, involving key stakeholders from across the bioeconomy sector. While no official updates to the document have been recorded, numerous initiatives have emerged in recent years, many under the coordination of the French Agency for Ecological Transition (ADEME).

Various ministries are involved, with no explicit coordination between them. Regional integration is a trademark of French bioeconomy, with the Pomacle-Bazancourt biorefinery serving as a benchmark for integrated biorefining.

In the early 2000s, competitive clusters were created, including *Industrie et Agro-ressources* (IAR), a hub focused on the non-food valorisation of agricultural resources. Now known as Bioeconomy for Change (B4C), the cluster has approximately 500 members and presents itself as a key network for bioeconomy development in France, Europe, and abroad.

Thailand does not explicit reference bioeconomy in official documents, although bioeconomy-related initiatives have been recorded since the 1980s. These initiatives primarily focus on biotechnology, which the country considered as the foundation for its bioeconomy development.

Various Thai institutions launch programmes and policies, but there is no clear indication of coordination between them in individual documents. A key highlight is the priorisation of bioplastics, with sugar cane and cassava defined as key feedstocks for bioplastic production. This focus is regarded as a success, reflecting efforts to build an innovation ecosystem that engages multiple stakeholders, including bioplastic manufacturers, the plastic industry, universities and research institutes, government bodies, and others.

> **“In 2009, China's National People's Congress enacted the Circular Economy Promotion Law of the People's Republic of China, establishing a structured system.”**

Table 8 synthesises the orientations identified in studied countries, based on the key dimensions of analysis.

Table 8. Bioeconomy-related policies

Key dimensions	Perceived policy orientations
Raw materials	In some countries, such as Australia and the USA (1 Billion Ton Programme), there is a focus on mapping biomass potential. In France, development practices include both innovative agricultural practices value creation through forestry resources.
Technology	All studied countries have established programmes for financing, tax benefits, or financial support for R&D activities, pilot plant projects, demonstration plants, and even industrial-scale plants. In Australia, grants support research institutions and projects focused on synthetic biology and biotechnology. In China, there is a dedicated programme for developing non-grain biofuels. In Thailand, companies can access matching funds to facilitate R&D projects.
Products	All studied countries have mandates for biofuel blending. In Australia, there is a complete exemption from consumption taxes on domestically produced ethanol and biodiesel. In the USA, the Biopreferred Programme has two components: a mandate for federal procurement of biobased products and a labelling programme to certify bioproducts.
Business models	Financial support for bioeconomy business development is a common feature across all studied countries. In Australia, a carbon credit system supports projects that reduce greenhouse gas emissions. China prioritises pilot projects for biodiesel promotion and aviation biofuel demonstration in suitable areas within a cluster-based model. Finland fosters partnerships between research institutions and companies to develop business models and products that incorporate reuse and recycling potential. Additionally, Finland streamlines permitting processes for designing and constructing bioproduct manufacturing plants.

Source: Elaborated by the consultant.

Supply policies rely on traditional incentives. Regarding demand policies, despite the success of bioplastics, there are few initiatives, such as tax reductions for the purchase or use of bioproducts.

As the six countries studied, Brazil also has programmes and policies related to the bioeconomy, particularly with a focus on bioenergy. From the creation of the National Alcohol Programme (Proálcool) in the 1970s to recent initiatives such as the Fuel for the Future Law and the BNDES/FINEP call for business plans for investments in low-carbon aviation and shipping fuels, various bioeconomy-related initiatives can be identified. Other notable programmes include PAISS (BNDES/FINEP 2011) and RENOVABIO (2017).

The main policy orientations observed in the strategies, programmes, and instruments identified in the studied countries can be directly linked to the key dimensions of innovation structuring in the bioeconomy—raw materials, technology, products, and business models—or they can be cross-cutting, not specific to any single dimension.

5.2 A cross-cutting overview of policies and programmes

A cross-cutting overview of the policies and programmes identified in the six countries studied is presented below, categorised into five thematic groups: biorefining vision, policy mix, governance and coordination, supply and demand policies, and policy and programme development processes. In the discussion of each theme, aspects related to the Brazilian case are highlighted.

Biorefining vision

The vision of biorefining and biorefineries varies significantly among the countries studied. A systemic vision of biorefining is rarely presented explicitly. The Biomass Board's approach in the USA stands out as perhaps the best example of a systemic vision of biorefining among the cases studied. This initiative is notable for its comprehensive effort to structure biomass supply at the municipal level.

In this regard, the Brazilian case, with its vast and diverse resources, can look to the Billion Ton project as an interesting benchmark for advancing the structuring of biomass supply for industrialization.

Regarding technology choices, most countries focus on biotechnology, indicating that they view advanced biotechnology as the foundation for resource valorisation technologies. In some cases, there is an emphasis on capacity building for RD&I, including incentives for training specialised labour.

There is a lack of references to the development of technologies for biomass handling equipment, particularly with regard to equipment used in processing stages (such as milling, drying, cleaning, etc.) and for feeding biomass into continuous processing plants. This absence may suggest that, despite the challenges faced by recent industrial plants—such as the pioneering second-generation ethanol production facilities—the issue has not been adequately identified or addressed by policymakers.

Regarding products, while bioenergy remains the primary focus, particularly with the demand for advanced biofuels in applications such as aviation and shipping, there are noteworthy visions and strategies in place. For instance, Thailand has prioritised bioplastics produced from two selected raw materials: sugar cane and cassava. The efforts in this area appear to be successful.

In the case of Finland, the focus in terms of products is on the pursuit of higher value-added products. In the US, product diversification is emphasised through the combination of bioenergy and non-energy bioproducts. BETO regularly issues funding calls for projects that consider product diversification.

Brazil has extensive experience with biofuel mandates, which were renewed and reaffirmed in the recent Fuel for the Future (*Combustível do Futuro*) programme. The RENOVABIO programme is another initiative that offers additional benefits for biofuels as they meet environmental performance standards. However, the programme is limited to biofuels.

Another important dimension related to biorefining is the valorisation of the attribute of circularity. Circularity forms the basis of the Chinese Industrial Parks, which may suggest that the bioeconomy in China will be circular from the outset. In Europe, the bioeconomy is increasingly viewed as a circular bioeconomy, as clearly emphasised in the Finnish strategy. In Thailand, circularity is seen as an opportunity to valorise waste from the sugar cane industry.

However, based on the sample of the six countries studied, it is evident that although circularity is recognised in some documents, it remains an attribute yet to be fully integrated into national strategies.

“In Thailand, a key highlight is the priorisation of bioplastics, with sugar cane and cassava defined as key feedstocks for bioplastic production.”

In Brazil, there are initiatives to formulate a national circular economy policy, but the format of these initiatives seems to be developing in parallel with the bioeconomy, without fully integrating circularity into the bioeconomy.

Although the biorefining model considered in this study has not yet been fully observed, Brazil is moving in that direction, particularly within the sugar and alcohol mills and companies in the pulp and paper sector.

In various interviews with professionals from these sectors, numerous studies and developments were discussed, focused on better utilisation of biomass, product diversification, and the pursuit of circularity. These experiences are reflected in the results of this work.

Policy mix

The cross-cutting nature of the bioeconomy is reflected in a highly complex production and innovation ecosystem, involving multiple and diverse stakeholders. In this context, it is important to pay attention to the mix of policies related to the topic. This is particularly recognised in the Finnish documents, though it appears to be somewhat less emphasised in the other cases studied.

The concept of extended biorefining proposed in this study suggests that policies targeting biorefineries must consider those policies, whether existing or to be created, that are involved in other links of the supply chain. Policies focused on bioenergy and biofuels, as well as those centred on the circular economy, for example, form a policy mix that cannot be overlooked. Additionally, the policy mix must account for aspects such as workforce training, capacity building, and service infrastructure, alongside the key attributes necessary for the biorefining concept: full utilisation of biomass, circularity, product diversity, and regional integration.

In the Brazilian case, a structured set of policies aimed at centralising the bioeconomy has not been observed. It has been noted that programmes and instruments are often created without considering the experiences of previous initiatives or other ongoing efforts, suggesting a challenge in aligning agendas.

Supply-side and demand-side policies

Supply-side policies are common across all the countries studied. Generally, the classic instruments of tax exemptions, favourable loans, and grants are utilised. One distinguishing feature of the policies in some countries is the provision of grants for demonstration plants, with grants typically being offered for bench and pilot research. In the case of the US, continued support for grant-funded projects may depend on periodic monitoring and evaluations.

Demand-side policies, however, are much less developed. This remains an area in need of policy innovation, particularly regarding non-energy bioproducts. Aside from biofuel mandates, few instruments are aimed at stimulating demand.

The only established example is the Biopreferred Program in the US, a system for public procurement and labelling of products with renewable content. Managed by the USDA, this programme has been in operation for over 20 years, although it has yet to produce results that suggest a clear shift towards increasing the consumption of bioproducts.

Brazil has experimented with the implementation of supply-side policies, such as the PAISS 2011, which significantly contributed to the establishment of two pioneering second-generation ethanol production plants in the country. Other initiatives, like the 2024 SAF production call and the development of RENOVABIO, have proven to be valuable for promoting environmental performance, though RENOVABIO remains limited to biofuels.

Governance and coordination

In the study of the selected countries, the cross-cutting nature of the bioeconomy was evident, involving various government agencies and bodies in the planning and implementation of policies and strategies. This presents a challenge for the coordination and governance of these strategies. In the cases studied, references can often be made to the bodies responsible for specific initiatives.

However, the leadership of the processes and the roles of the participants are not always clearly defined. It seems that while the countries lack clear coordination and governance protocols, they do make an effort to involve most of the relevant bodies.

China and Thailand demonstrate clear central government coordination in policy formulation, whereas in Finland, the Ministry of Economic Affairs and Employment is responsible for developing the National Bioeconomy Strategy in collaboration with various other bodies and ministries. In Australia, the development of roadmaps serving as 'guides' for public policies is particularly noteworthy, outlining scenarios and actions needed to achieve desired objectives.

Both France and the United States have established dedicated entities to oversee bioeconomy-related initiatives. In France, the Ecological Transition Agency, a public institution linked to multiple ministries, plays a key role in bioeconomy-related actions. In the US, since March 2024, the National Bioeconomy Board has been responsible for initiatives related to biotechnology and biomanufacturing.

Brazil lacks centralised coordination for the issuance of bioeconomy-related instruments, unlike Finland's National Bioeconomy Strategy. Instead, various ministries oversee actions within their respective areas of expertise. The Ministry of Mines and Energy, for instance, manages bioenergy initiatives such as RENOVABIO and the Ten-Year Energy Expansion Plan (PDE 2034). The Ministry of Agriculture and Livestock (MAPA) is responsible for the ABC+ Plan (Low Carbon Agriculture) and promoting sustainability in rural areas.

Conceptually, the Ministry of Science, Technology, and Innovation (MCTI) supports technological innovation in biomass utilisation, while the Ministry of the Environment and Climate Change (MMA) oversees carbon market management and sustainability incentives. Additionally, the Ministry of Integration and Regional Development (MDR) is tasked with promoting regional integration in initiatives related to the use of biomass from Brazilian biodiversity (Pinto 2024).

The formation of the National Bioeconomy Board in the United States stands out as a model that could serve as inspiration for Brazil. Every new initiative or body is presented to the Board, which designates the components responsible for governance and coordination. Additionally, representatives from other agencies and departments who will participate as institutional representatives are clearly identified. From that point forward, all official documents are signed by the Board and its representatives, ensuring a coordinated approach.

This governance structure has been in place since 2002, when the Biomass Research and Development Board was established. In the US, initiatives related to biomass and biorefineries are well-organised and centralised within the Departments of Energy (DOE) and Agriculture (USDA), which co-direct the Biomass Research and Development Board.

Processes in programme and policy development

In most of the cases studied, it was not possible to find details about the processes for drawing up programmes and policies. It is believed that these processes, as part of the internal mechanisms of agencies and ministries, are generally not disclosed in official documents. Even so, it is possible to highlight some points based on the research carried out.

The first point is the effort to favour bottom-up processes. In the case of France, the national strategy was built using this approach. The work of the Bioeconomy for Change cluster, with hundreds of members with different profiles and interests, also helps to bring together the discussions of a large number of stakeholders. In the case of the USA, it is worth highlighting the open consultation mechanism - the RFI, request for information - launched whenever a new topic is to be considered in an upcoming call or funding opportunity.

Another key aspect of programme development in the United States is the emphasis on the scientific qualifications of the team. These teams comprise highly skilled professionals with cutting-edge expertise in relevant fields, who are specifically invited to provide technical insights. This is a particularly relevant consideration for Brazil, where a similar approach could enhance future calls for proposals for biorefinery development.

In Brazil, programme implementation has relied on professionals from organisations such as BNDES and FINEP. While these staff members are well-qualified, their expertise tends to be more generalised in relation to the specific themes of the calls for proposals. In an emerging and unstructured field like biorefining, a deeper understanding of scientific and technological aspects would be highly beneficial.

Finally, the importance of monitoring supported projects cannot be overstated. Here too, the US model offers a valuable reference. In the US, projects undergo periodic public presentations and are reviewed by panels of external experts. The presentations, expert feedback, and responses from project leaders are all made publicly available, ensuring transparency and accountability.

6. Recommendations

Based on the study of biomass and the challenges identified, 15 recommendations have been proposed for biorefining development policies in Brazil, as outlined in Table 9. These recommendations also incorporate insights gathered from interviews.

The table further presents potential policy approaches and instruments that can be used to implement each recommendation, drawing on the framework proposed by the OECD (2018). For instance, the first recommendation—"stimulating demand for biorefining-derived products"—**can** be implemented through various measures, such as prioritising biorefining-derived products in public procurement, running public awareness campaigns, and developing labelling systems to clearly communicate the characteristics of bioproducts, among others.

It is essential that all recommendations and the policy instruments used to implement them consistently consider the key attributes of biorefining: product diversification, full utilisation of biomass, circularity, regional/territorial integration, and industrial symbiosis.

The recommendations address various aspects, including infrastructure and logistics, regulation, technology development, and demand creation, among others. This underscores that advancing biorefining requires coordinated efforts across multiple domains, as well as interaction among the entities responsible for shaping public policy. Adopting this systemic approach is crucial to developing a coherent policy mix that effectively promotes biorefining in the country.

Table 9. Recommendations for biorefinery development models in Brazil

Recommendations	Examples of approaches/instruments to be used (Based on OECD 2018)
1 - Stimulating demand for biorefining-derived products	• Targets and quotas • Mandates • Certification • Awareness and labelling • Public procurement
2 - Incentives for the development of biomass handling equipment across the entire production chain	• Tax incentives for industrial R&D • Improved investment conditions
3 - Streamlining regulatory approval for new products and processes	• Standards and regulations • Certification
4 - Credit and incentive restrictions for companies using fossil fuels or fossil-based products	• Fossil carbon taxation • Removal of fossil fuel subsidies
5 - Encouraging the establishment of pioneering plants	• Support for pioneering plants • Tax incentives for industrial R&D

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Recommendations	Examples of approaches/instruments to be used (Based on OECD 2018)
6 - Promoting the establishment of demonstration plants	• Support for pilot and demonstration plants
7 - Training and capacity building for a skilled workforce	• Education and training programmes
8 - Developing infrastructure for the distribution and use of biofuels and bioproducts	• Improved investment conditions • Enhancements in infrastructure and logistics
9 - Encouraging the production of bioproducts from waste	• Regional clusters • Direct financial support for bioproducts • ax incentives for bioproducts • Improved investment conditions
10 - Incentivising R&D for waste and by-product utilisation, with a focus on partnerships	• Subsidies for R&D (focused on waste and by-products) • Incentives linked to GHG emissions reduction • Carbon credit purchase for research • Tax incentives for industrial R&D • Improved investment conditions • Technology clusters
11 - Supporting the creation of startups	• Technology clusters • Improved investment conditions • Tax incentives for industrial R&
12 - Incentives for structuring the supply of waste materials	• Resource development/access • Infrastructure and logistics • Regional clusters
13 - Mapping data on biomass availability and its production chain	• Knowledge-based capital • Resource mapping
14 - Enhancing clarity on legislation for biodiversity access and benefit-sharing	• Governance and regulation
15 - Encouraging new agricultural production models (to increase biomass productivity, mitigate environmentally harmful agricultural practices, and support ecosystem restoration projects, e.g., CLFI for degraded land regeneration)	• Resource development/access • Governance and regulation

Source: Elaborated by the consultant.

Table 10 presents the policy recommendations in relation to the dimensions analysed.

Regarding the raw material dimension, resource mapping can be understood as the foundation for biorefining development. Identifying the availability, location, quantity, and quality of raw materials is essential for structuring supply chains, mobilising stakeholders, and attracting participants to the innovation and production ecosystem to capitalise on biorefining opportunities.

Similarly, regulatory aspects related to access to genetic heritage and traditional knowledge must be clearly defined for all stakeholders in the ecosystem. Additionally, policies that promote the development of new agricultural production models—encouraging sustainable, high-productivity approaches—are essential to ensuring the environmental, social, and economic benefits of biorefining.

Workforce training, equipment development, and R&D focused on characterising different biomass fractions are crucial for enabling product diversification, increasing value-added outputs, and ensuring the full utilisation of biomass.

Incentives for structuring the supply of residues and by-products are essential to promoting their use, particularly given the logistical challenges related to access and transport. Focusing on the initial stages of the supply chain is also crucial to ensuring fair income distribution for biomass producers and fostering regional economic development.

Regarding technologies, the recommendations highlight the need for policies that support R&D and innovation at all stages of technological maturity, from bench-scale research to pilot projects, demonstration plants, and full-scale industrial implementation.

The international experiences examined underscore the importance of supporting the development of demonstration and pioneering plants to address the challenges of scaling up innovative production processes.

Additionally, mechanisms to foster partnerships and encourage the creation of start-ups are essential for strengthening the innovation and production ecosystem by attracting diverse stakeholders. Equally important are investments in workforce training and policies aimed at enhancing production and distribution infrastructure.

Table 10. Relationship between policy recommendations and analytical dimensions

Recommendations	Raw materials	Technology	Products	Business models
1 - Stimulating demand for biorefining-derived products			X	
2 - Incentives for the development of biomass handling equipment across the entire production chain	X	X		
3 - Streamlining regulatory approval for new products and processes			X	
4 - Credit and incentive restrictions for companies using fossil fuels or fossil-based products			X	
5 - Encouraging the establishment of pioneering plants		X		X
6 - Promoting the establishment of demonstration plants		X		
7 - Training and capacity building for a skilled workforce	X	X		X
8 - Developing infrastructure for the distribution and use of biofuels and bioproducts		X	X	X
9 - Encouraging the production of bioproducts from waste	X	X	X	X
10 - Incentivising R&D for waste and by-product utilisation, with a focus on partnerships	X	X		X
11 - Supporting the creation of startups	X	X	X	X
12 - Incentives for structuring the supply of waste materials	X	X		X
13 - Mapping data on biomass availability and its production chain	X			
14 - Enhancing clarity on legislation for biodiversity access and benefit-sharing	X			
15 - Encouraging new agricultural production models (to increase biomass productivity, mitigate environmentally harmful agricultural practices, and support ecosystem restoration projects, e.g., CLFI for degraded land regeneration)	X			X

Source: Elaborated by the consultant.

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The technology dimension requires particular focus on RD&I to ensure the full utilisation of biomass. This is crucial to prevent biorefining from generating excessive waste or exacerbating environmental issues by relying on only one or a few biomass fractions.

When examining the recommendations related to the product dimension, it becomes evident that a broad set of policies is needed to stimulate demand for bioproducts. These policies should address regulatory frameworks for product approval and support the development of diverse markets.

As discussed above, preferential public procurement, awareness campaigns, and restrictions on the use of fossil-based products are effective ways to stimulate demand for biorefining products.

Regarding the business models dimension, the recommendations focus on creating a favourable environment for the development of the innovation and production ecosystem. This includes connecting stakeholders, fostering partnerships, and promoting innovation while addressing various issues already discussed in other dimensions. Incorporating business model perspectives into Brazil's biorefining strategies is essential, as it enables experimentation, encourages innovation, and strengthens relationships between players across different stages of the biorefining value chain.

Table 11 presents the recommendations based on the stages of the biorefining production chain—biomass supply, processing, industrialization, and marketing—while also considering the analytical dimensions of raw materials, technologies, products, and business models.

This integrated approach demonstrates that a single recommendation can be relevant to multiple stages of the biorefining chain as well as various analytical dimensions, highlighting its cross-cutting nature. For example, recommendations 2 (incentives for the development of biomass handling equipment across the entire production chain), 7 (training and capacity building for a skilled workforce), 9 (encouraging the production of bioproducts from waste), 11 (supporting the creation of startups), and 12 (incentives for structuring the supply of waste materials) all span multiple stages and dimensions.

It is therefore crucial to design policy instruments with this interconnected perspective in mind. Workforce training and education should not be limited to preparing individuals for the industrialization stage. Instead, it must encompass training from the very beginning of the chain, including raw material supply and processing. Only with this comprehensive approach can the challenges identified in Section 4.1 be effectively addressed, ensuring the incorporation of key biorefining attributes.

Similarly, fostering the creation of start-ups must consider opportunities across the entire biorefining chain, particularly in the utilization of waste and by-products. This requires a mix of policies addressing raw materials, technologies, products, and business models—encouraging the integration of new players into the innovation and production ecosystem.

Another key point is the importance of considering the different biomass groups, as shown in Figure 6. These groups are at varying stages of development in terms of biorefining attributes (Table 2), meaning their public policy needs will also differ accordingly.

For example, the challenges for biomass in Groups I and II are concentrated in the industrialisation and marketing stages. Therefore, policy recommendations aimed at these stages will be most relevant in encouraging biorefining development. In contrast, Groups III and IV generally require the building of supply chains, with particular focus on structuring the supply of raw materials and processing stages. Consequently, policies should be based on recommendations related to these stages before addressing those aimed at industrialisation and marketing. Focusing only on the final stages is unlikely to be effective in fostering biorefining development for these types of biomass.

Table 11. Recommendations for biorefining development policies in Brazil, by dimensions of analysis and biorefining stages

STAGES OF THE BIOREFINING CHAIN / ANALYTICAL DIMENSIONS	RAW MATERIAL SUPPLY	PROCESSING	BIOREFINERY	COMMERCIALISATION
RAW MATERIALS	2, 7, 9, 10, 11, 12, 13, 14, 15	2, 7, 9, 10, 11, 12	2, 7 ,9 ,10	11, 12
TECHNOLOGY	2, 7, 9, 10, 11, 12	2, 6, 7, 9, 10, 11	2, 5, 6, 7, 8, 9, 10	8, 11, 12
PRODUCT	9, 11	9, 11	8, 9, 11	1, 3, 4, 8, 11
BUSINESS MODEL	7, 9, 10, 11, 12, 15	7, 9, 10, 11, 12	5, 7, 8, 9, 10, 11	8, 11, 12

Source: Elaborated by the consultant.

7. Conclusions

The main points to highlight as results of this report can be grouped into four categories: (i) conceptual vision of biorefining; (ii) situational diagnosis of biorefining in Brazil; (iii) international experiences; and (iv) recommendations.

Regarding the concepts of biorefining:

- A systemic view of biorefining is proposed that goes beyond the industrial unit or biorefinery. This systemic vision can be summarised in the following proposition: Biorefining = biorefinery + production chain + production and innovation ecosystem.

- To address the challenges of the bioeconomy, biorefining must pursue four key attributes to be ideally achieved: product diversification, full utilisation of biomass, circularity, and regional/territorial integration.

Regarding the situational diagnosis of biorefining in Brazil:

- The diversity of biomass must be understood in relation to the diversity of products, the level of added value, the degree of biomass utilisation, and the biomass supply model (extraction or cultivation). These factors allow for the identification of four distinct biomass groups, each with its own logic for exploitation and valorisation. The groups represented in the research were planted forests (Group 1), sugar cane (Group 2), coffee and açaí (Group 3), and babassu and macaúba (Group 4), as described in Section 4.3.

- The proposal for an integrated vision of biorefining highlights that the industrialisation of biorefineries progresses by overcoming challenges present at the early stages of production chains, which involve resources with varying levels of structural development.

- Advancing the industrialisation stage in the biorefining production chain requires overcoming challenges related to the primary processing phase, which can be considered pre-industrialisation. This applies to both resources from biodiversity and lignocellulosic agroforestry biomass.

- As a rule, Brazilian biorefining does not fully utilise resources.

- Product diversification is limited, typically focused on low-value products, with high-added-value products being rare.

- Many biomasses are exploited to extract only a single main product and would be better described as pre-biorefineries.

- The supply of biomass includes both extraction (structured and unstructured) and cultivation, which presents very different challenges for structuring biorefineries.

- Industrialisation needs to be studied carefully, particularly to understand the evolution of biomass-based sectors that have proven to be dynamic, such as planted forests and sugar cane. It is also crucial to understand the evolution and maturity of biorefining processes based on biodiversity. Ultimately, the future of Brazilian biorefining appears to rest on these two pillars.

Regarding international experiences:

- Diversity of international experiences studied across six countries: Australia, China, USA, Finland, France, and Thailand.

- A systemic vision of biorefining does not appear explicitly in the countries studied. Among the cases examined, the vision and structuring of the Biomass Board in the USA stands out as the best example of a systemic approach to biorefining, which could serve as inspiration for Brazil.

- The experiences with cross-cutting policies offer important lessons regarding weaknesses in Brazilian public policies, particularly in relation to the processes for drafting programmes and calls for proposals, coordination and governance, and the policy mix.

Regarding the recommendations:

- Based on the cases studied and the interviews conducted, the study proposes a set of 15 recommendations. The production chain (biomass supply, processing, industrialisation, marketing) and the dimensions of bioeconomy business analysis (raw materials, technology, products, business models) influence the implementation of each recommendation.

- The systemic vision of biorefining proposed in this work (Biorefining = biorefinery + production chain + production and innovation ecosystem) must be considered when formulating public policies.

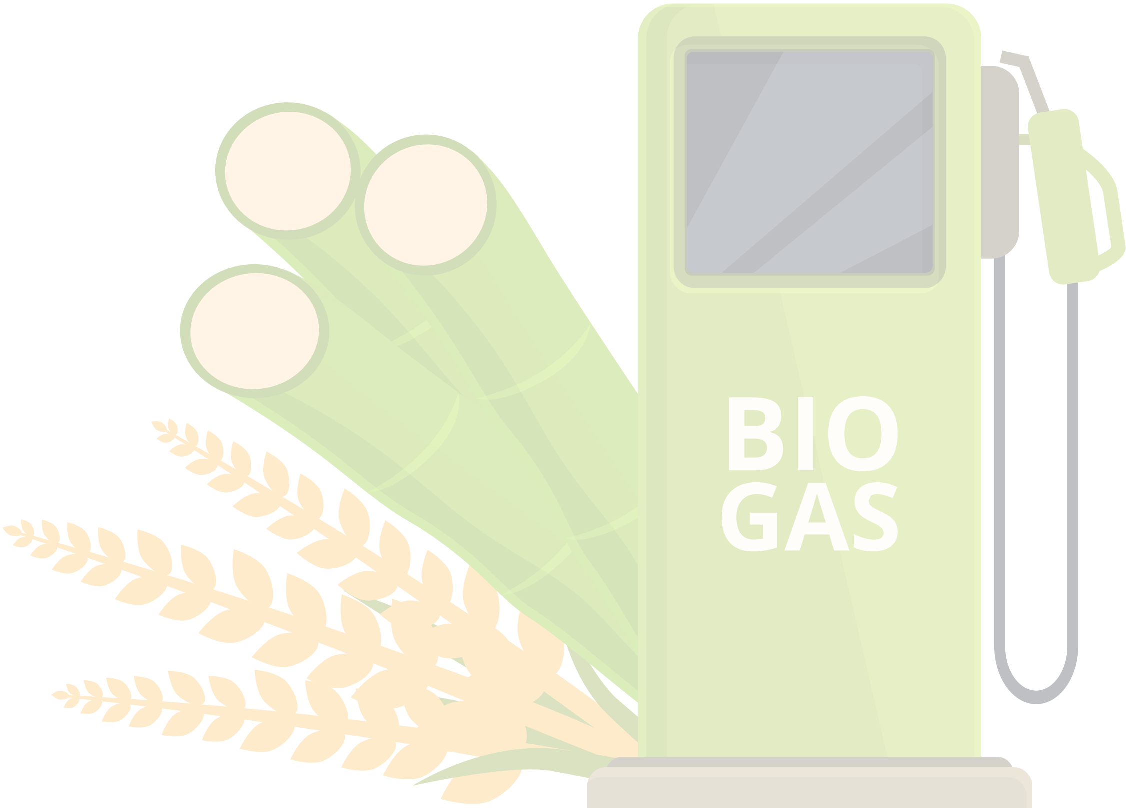
- All policy recommendations and the instruments used to implement them must always consider the key attributes of biorefining: product diversification, full utilisation of biomass, circularity, and regional/territorial integration.

- Both the systemic vision and the attributes of biorefining are concepts that are not widely recognised in academic, industrial, and government circles. Efforts should be made to publicise and discuss these concepts, as doing so could lead to a better understanding of the opportunities and challenges in biorefineries.

- Public policy proposals for the development of biorefining must consider the different stages of development in biomass supply chains, as well as the integration of sustainable production models that prioritise environmental and social aspects.

- Policies and strategies for the development of biorefining in Brazil should take into account international benchmarks in two key areas: governance and coordination, and the processes for drafting and monitoring programmes and calls for proposals.

- The creation of a coordination body, similar to the Biomass R&D Board in the USA, capable of guiding initiatives that involve government, research, and industry in integrated programmes, appears to be an essential first step towards establishing the conditions for the development of biorefining in Brazil. Given that the development of biorefining is closely linked to the advancement of the bioeconomy and the circular economy, it is urgent to establish a connection between these agendas and their respective coordination and governance bodies.



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