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The Climate Technology Progress Report 2025

Advancing Biobased Technologies in the Bioeconomy

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Advancing Biobased Technologies in the Bioeconomy

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GLOSSARY

Biobased technologies Refer to processes, products, and systems derived from renewable biological resources such as biomass, agricultural residues, and algae that can be sustainably replenished over time (Benavides *et al.*, 2024, Chang *et al.*, 2025, Javed *et al.*, 2022, Stark and Matuana, 2021). By reducing reliance on fossil-based inputs, these technologies contribute to reducing greenhouse gas emissions (GHG) while supporting the protection, conservation, restoration, and sustainable use of nature and ecosystems, thereby advancing effective and enduring climate action (FAO, 2022, UNEP, 2024).
Bioeconomy The use of biological resources such as plants, animals, algae, fungi, and microorganisms to produce food, energy, materials, medicines, and other goods and services. It builds on traditional knowledge and modern life sciences, emphasizes renewable and sustainable processes, and links closely with biodiversity, climate goals, and community wellbeing. (UNEP, 2024).
Climate technology Climate technologies are those that help us reduce greenhouse gas emissions and adapt to the adverse effects of climate change. (See definition of technology below).
Deployment The act of bringing technology into effective application, involving a set of actors and activities to initiate, facilitate and/or support its implementation (IPCC 2022a).
Diffusion The spread of a technology across different groups, users or markets over time (IPCC 2022a).
Enabling environment The set of resources and conditions within which the technology and the target beneficiaries operate. The resources and conditions that are generated by structures and institutions that are beyond the immediate control of the beneficiaries should support and improve the quality and efficacy of the transfer and diffusion of technologies (Nygaard and Hansen 2015).
Feasibility The potential for a mitigation or adaptation technology to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, sociocultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened (IPCC 2022b).
Governance Process of managing public and private interactions through collaboration, negotiation, and coordination between different actors, including the state, civil society, national and international organisations and the private sector. Governance is broader than government and does not rely solely on top-down authority. Instead, it emphasises participation, decentralization, cooperation, and the use of wider collective strategies for implementation.
Innovation Both the processes of research and development and the commercialization of the technology, including its social acceptance and adoption (IPCC 2000).
Innovation System All important economic, social, political, organizational and other factors that influence the development, diffusion and use of innovations (IPCC 2000).
Institution Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance (IPCC 2022b).
Regulatory Factors Regulation can be defined as: A rule or order issued by governmental executive authorities or regulatory agencies and having the force of law. Regulations implement policies and are mostly specific for groups of people, legal entities, or targeted activities. Regulation is also the act of designing and imposing rules or orders. Informational, transactional, administrative and political constraints may limit the regulator's capability for implementing preferred policies (IPCC 2022a;b).
System transitions System transitions involve a wide portfolio of mitigation and adaptation options that enable deep emissions reductions and transformative adaptation in all sectors. The systems include: energy; industry; cities, settlements and infrastructure; land, ocean, food and water; health and nutrition; and society, livelihood and economies (IPCC 2022a;b).
Technology Technology is "a piece of equipment, technique, practical knowledge or skills for performing a particular activity" (IPCC 2000). It is common practice to distinguish between three different components of technology (Müller 2003): • Hardware: the tangible component, such as equipment and products • Software: the processes associated with the production and use of the hardware • Orgware: the institutional framework, or organization, involved in the adoption and diffusion process of a technology These three components are all part of a specific technology, but the relative importance of each component may vary from one technology to another.
Technology transfer The exchange of knowledge, hardware and associated software, money and goods among stakeholders, which leads to the spread of technology for adaptation or mitigation. The term encompasses both the diffusion of technologies and technological cooperation across and within countries (IPCC 2022a).
Transformative change A system-wide change that requires the consideration of social and economic factors which, together with technology, can bring about rapid change at scale (IPCC 2018).
Transition The process of changing from one state or condition to another in a given period of time. Transition can occur in individuals, firms, cities, regions and nations, and can be based on incremental or transformative change (IPCC 2022a; IPCC 2022b).

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FOREWORD

As the world prepares for COP 30 in Brazil, we stand at a critical juncture for global climate and nature action. The urgency to accelerate progress under the Paris Agreement has never been greater, and the convergence of climate, biodiversity, and land use priorities presents a unique opportunity to reshape our collective response to planetary challenges.

COP30, hosted by a country of immense ecological significance, offers a pivotal moment to elevate the role of nature in climate policy. It is an opportunity to drive renewed ambition through updated nationally determined contributions (NDCs), while fostering deeper integration across the three Rio Conventions on climate change, biodiversity, and desertification. This alignment is essential to ensure that efforts to reduce emissions are complemented by ecosystem restoration, climate adaptation, and sustainable land management.

The 2025 Climate Technology Progress Report (CTPR) helps to shape this moment by highlighting innovative strategies that bridge climate and nature goals. It underscores the potential of combining technologies with sustainable biobased solutions to deliver cost-effective, scalable, and inclusive outcomes. Drawing on insights from the Glasgow Climate Pact, the Sharm el-Sheikh Implementation Plan, and the UAE Consensus including the Global Stocktake, the report emphasizes the importance of protecting and restoring ecosystems, halting deforestation, and investing in joint mitigation and adaptation approaches. It highlights the key roles of both domestic policy, including clear and inclusive regulatory and legal frameworks, and international cooperation and financing.

Structured to provide both global and regional perspectives, the report's hybrid format reflects the diversity of challenges and opportunities across geographies.

We hope this report serves as a valuable resource for policymakers, practitioners, and stakeholders working to advance integrated, effective, and equitable climate and nature action in the lead-up to COP30 and beyond.

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EXECUTIVE SUMMARY

Accelerating technological innovation and policy momentum is driving growth in biomass utilization and biogenic carbon solutions, sustainable land use and advanced biobased materials. The global bioeconomy is valued at an estimated US$4–5 trillion, with the potential to grow to US$30 trillion by 2050, positioning it as a cornerstone of the transition to a low-carbon, climate-resilient, and sustainable future. Realizing this potential will require targeted action across technology, finance, governance, and policy.

Biobased technologies are at the heart of the bioeconomy, offering innovative ways to use biological resources, such as crops, forests, and organic waste, to produce energy, materials, and other products sustainably. These technologies improve resource efficiency, reduce waste, and support circular systems, while also delivering climate, environmental, and social benefits. They respond directly to global calls to recognize the broader value of nature-based solutions, including sustainable forest management.

What makes biobased technologies especially promising is their ability to operate locally, using regionally available resources and knowledge. This enables innovation and production to flourish in rural and peri-urban areas, beyond traditional industrial hubs. Spanning sectors like bioenergy, bioplastics, food systems, and natural fertilizers, biobased technologies draw on diverse actors and practices, from indigenous knowledge to small-scale circular innovations. When integrated with climate technologies, they offer a powerful pathway to reduce emissions, build resilience, and promote inclusive, sustainable development.

Adoption and Scaling Potential

Technological innovation is making big strides in how natural materials, like plants and waste, are used to produce energy and other useful products. Biobased technologies for biomass conversion, such as turning organic waste into biogas or using biochar to improve soil and store carbon, are already being used commercially. However, expanding the use of other promising technologies requires lowering costs, ensuring a steady supply of raw materials, and building the right infrastructure and policies to support them.

Biogenic carbon capture, utilization, and storage (Bio-CCUS) technologies are emerging as critical tools for decarbonization, yet they remain far from being deployed at scale. Scaling these technologies will require significant progress in biomass sourcing, infrastructure development, and investment, as adoption remains uneven across countries. Nature-based solutions such as afforestation and reforestation, agroforestry, and soil carbon enhancement offer valuable co-benefits for biodiversity and livelihoods but need stronger integration into climate strategies. A diversified portfolio of land-based and biologically driven carbon removal technologies is essential. While some are technically mature, broader deployment depends on sustainable land use, long-term planning, and robust policy support.

Sustainable agriculture and land-use technologies are expanding, with increased uptake of biobased technologies such as biofertilizers and improved forest management. Yet, regional disparities persist.

Biobased construction materials, such as wood, bamboo, straw, hemp, and cork, have long histories in building traditions and are increasingly recognized as central to low-carbon transitions in the sector. These materials are mature and increasingly scalable, offering climate benefits through carbon storage and substitution, while also supporting energy efficiency and rural livelihoods. New biobased materials are gaining momentum in construction and packaging, with innovations like hempcrete and biochar-infused concrete showing promise for carbon storage. However, most applications still follow linear models. Scaling both established and emerging materials will require circular design principles, improved recovery systems, alignment with regenerative land-use practices, strong governance to ensure sustainable sourcing, continued regulatory adaptation, and broader public acceptance of engineered wood and other biobased materials.

The feasibility, and therefore the potential to scale, of biobased technologies varies across contexts, but they offer significant climate mitigation and adaptation benefits. Among bioenergy technologies, waste-based biogas is considered a viable option, offering strong climate mitigation, adaptation, and socio-environmental benefits. In contrast, biofuels like algal fuels and biohydrogen show long-term promise but face high costs and low technical readiness. Biofuels such as ethanol and biodiesel may be or may not be challenged by land-use pressures and sustainability concerns. Although sustainable feedstock selection and strong safeguards can help address these concerns, the extent of land competition from biomass expansion is largely shaped by local conditions. Moreover, integrating bioenergy into broader energy systems enhances climate resilience and energy security. Solid, liquid, and gaseous bioenergy offer flexibility for storage, logistics, and blending with existing infrastructure, particularly in gas networks. Feasibility and deployment of bioenergy technologies vary significantly across regions.

Financing the Scale-Up

Financial instruments must be tailored to meet the diverse needs of biobased technologies. Waste-based biogas and sustainable agriculture benefit from results-based payments and ecosystem service markets, while advanced biofuels and Bio-CCUS technologies need access to carbon markets and blended finance or performance-linked finance to monetize emissions reductions. Biomass conversion technologies often rely on grants, venture capital, and green finance to produce renewable fuels and chemicals. Sustainable agriculture and biobased materials are increasingly supported by innovative financing models. Agriculture leverages results-based payments and ecosystem service markets, while biobased materials tap into corporate alliances and equity markets to scale production and commercialization.

Despite growing interest in biobased technologies, significant financial barriers persist. High upfront costs, long development timelines, and market uncertainty often deter private investment. Therefore, blended finance instruments, especially in the Global South, are critical to attract private capital by leveraging concessional public funding and risk-sharing mechanisms aligned with conservation and adaptation goals.

By adopting targeted financial mechanisms, governments can support emerging value chains to scale biobased technologies and medium-sized enterprises, linking climate finance with inclusive development strategies. Regulatory clarity is also critical: inconsistent policies across regions create uncertainty, particularly in biotechnology and Bio-CCUS sectors. Clear pricing for natural capital and transparent sustainability metrics can reduce risk and improve governance.

Access to carbon markets is vital for bioeconomy actors. Inclusive frameworks such as Article 6.4 of the UNFCCC and the Verified Carbon Standard can unlock carbon credit revenues from Bio-CCUS and nature-based solutions. Instruments like green bonds and sustainability-linked loans should be scaled through global collaboration, harmonized standards, and clear performance benchmarks.

Policy and regulatory clarity are needed to unlock investment and scale deployment. Clear pricing for natural capital, harmonized certification systems, and access to carbon markets can reduce risk and direct capital to high-impact solutions.

Unlocking Potential Through Effective Governance

Effective governance and policy coordination are vital to unlock the full potential of biobased technologies in the bioeconomy. Phasing out fossil fuel subsidies remains critical, and aligning this transition with national socio-economic priorities ensures equity and effectiveness. A systemic approach to biobased policies can enhance coherence across sectors, balance land-use demands, and strengthen synergies between mitigation and adaptation.

Transparent, context-specific strategies for advancing biobased technologies that reflect local priorities and institutional capacities especially in rural and non-OECD regions are vital for public understanding and stakeholder engagement. Promoting common technical standards, robust certification systems, and harmonized monitoring frameworks supported by digital tools can improve transparency, accountability, and outcomes across fragmented bioeconomy landscapes.

To reduce environmental pressures from growing biomass demand, sustainability should be embedded into the design and deployment of biobased technologies from the outset. This includes integrating sustainability frameworks into policies, using sound indicators and disaggregated data, and promoting nature-based solutions like soil health and ecosystem restoration. Aligning biobased technology deployment with social and environmental integrity is key to ensuring sustainable outcomes. In biodiversity-rich and ecologically sensitive areas, safeguards are needed to protect Indigenous Peoples and Local Communities. Equitable transitions depend on responsible innovation that thoughtfully incorporates these considerations.

International cooperation and multi-stakeholder networks, such as the G20 Initiative on Bioeconomy, share best practices, and mobilize investment. Secure land tenure, strong legal frameworks, and multilevel governance are foundational to enabling coherent, accountable, and inclusive bioeconomy development.

From Biodiversity to Biobased Innovation: Enabling Regional Transitions

Latin America and the Caribbean region hold immense potential to lead in sustainable bioeconomy innovation, drawing on the region's exceptional biodiversity, diverse ecosystems, strong agricultural systems, and rich indigenous Knowledge. Nevertheless, institutional, infrastructural, and governance capacities vary across countries. To scale biobased technologies effectively, they need to be adapted to local contexts, fostering more inclusive and resilient growth.

Key sectors where biobased technologies have a significant role, such as agriculture, energy, waste, and forestry, form a strategic nexus between economic growth, climate action, and sustainable development. These sectors represent a substantial part of national climate plans, yet their integration into formal climate policies remains fragmented. Strengthening the link between biobased technology deployment and national climate planning frameworks is crucial to unlocking synergies across mitigation, adaptation, and resilient production systems. To unlock the region's bioeconomic potential, targeted investments are instrumental to support innovation-led transitions. Strengthening research clusters, innovation platforms, and peer learning networks, especially in emerging economies, can accelerate adoption and scale.

Social inclusion is essential for advancing biobased technologies in Latin America and the Caribbean. Recognizing indigenous rights and supporting local livelihoods enhances legitimacy, reduces inequalities, and strengthens both socio-ecological resilience and sustainability. Ensuring that biobased innovation reflects diverse knowledge systems and community needs is key to equitable development.

A systematic, inclusive, and climate-aligned approach to biobased technologies will enable Latin America and the Caribbean to lead in shaping a sustainable global bioeconomy. Regional cooperation and policy coherence are vital. Aligning the region's ecological potential with inclusive socio-economic outcomes requires coordinated governance, harmonized strategies, and shared learning across borders.

Photo: Pexels

1. Introduction

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1.1 CONTEXT

In November 2025, COP30 will be held in Belém, Brazil and will mark a pivotal moment for global climate action. Countries are expected to submit new or updated Nationally Determined Contributions (NDCs) ahead of the COP. Hosted by Brazil, a country of vast ecological importance, COP30 offers a critical opportunity to emphasize the role of nature vis-à-vis climate action. As the world faces growing challenges from the loss of biodiversity and land degradation, COP30 is also expected to drive stronger alignment between climate and nature, reinforcing the link between reducing emissions, restoring ecosystems, climate adaptation and sustainable land management. In this context, COP30 can also serve as a platform to advance synergies between the three Rio Conventions on climate change, biodiversity and desertification supporting integrated and effective action for people and planet.

To advance the climate and nature agenda, innovative strategies that combine technology with sustainable biobased solutions offer a robust, comprehensive and cost-effective path to simultaneously achieving the climate and nature agendas (United Nations Framework Convention on Climate Change [UNFCCC] and International Union for Conservation of Nature [IUCN] 2022). Both the Glasgow Climate Pact[1] (UNFCCC 2021) and the Sharm el-Sheikh Implementation Plan[2] (UNFCCC 2022) underline the urgent need to address, in a comprehensive and synergetic manner, the vital importance of protecting, conserving, restoring and sustainably using nature and ecosystems for effective and sustainable climate action. Furthermore, the Global Stocktake (GST) stressed the importance of conserving, protecting and restoring nature and ecosystems to achieve the Paris Agreement climate targets (UNFCCC 2023). This includes enhanced efforts to halt and reverse deforestation and forest degradation, promote afforestation by 2030 and maintain terrestrial and marine ecosystems as greenhouse gas sinks and reservoirs, while conserving biodiversity. The GST further emphasized the need for increased support and investment, including financial resources, technology transfer and capacity-building. It also highlighted the importance of joint mitigation and adaptation approaches for sustainable forest management and incentivizing non-carbon benefits.

The 2025 Climate Technology Progress Report (CTPR) explores the role of the bioeconomy in addressing climate change, including both mitigation and adaptation, with a particular focus on the biobased technologies that are most relevant in this context. It examines the progress being made in scaling up the availability and use of these technologies, highlighting both global trends and region-specific developments. For consistency, in this report we use the term "biobased technologies" to refer to processes, products and systems derived from renewable biological resources such as biomass, agricultural residues and algae that can be sustainably replenished over time (Benavides *et al.* 2024; Chang *et al.* 2025; Javed *et al.* 2022; Stark and Matuana, 2021). By reducing our reliance on fossil-based inputs, these technologies help lower greenhouse gas (GHG) emissions while promoting the protection, conservation, restoration and sustainable use of ecosystems, thereby supporting effective and lasting climate action, UNEP, 2024a, FAO, 2022).

By assessing how innovations relating to the bioeconomy contribute to climate action, the report aims to inform policy, investment and implementation strategies that can accelerate transformation towards net zero and climate resilience. At the same time, it also endeavours to highlight the care that is needed to ensure that the incorporation of biobased technologies into climate strategies is consistent with broader biodiversity and sustainability goals.

The development of the bioeconomy impacts carbon flows and climate change mitigation in four main ways (UNEP 2024): by enhancing carbon sinks through biomass (e.g., afforestation and conservation farming), by substituting GHG-intensive products and fossil fuels with biobased alternatives (e.g., engineered wood, bioplastics), by storing carbon in biobased products for varying lengths of time, and by utilizing waste biomass for energy and materials. These practices not only reduce GHG emissions but also promote the sustainable use of resources and environmental conservation. Therefore, if managed sustainably, the bioeconomy holds significant potential for reducing the impact of climate change. In addition, the Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC 2023a) emphasized the importance of effective governance of land-based mitigation options, including those linked to the bioeconomy, and the requirements of integrated policy frameworks that balance climate goals with biodiversity, food security and social equity, ensuring that biobased solutions contribute positively to mitigation without exacerbating land-use conflicts (Babiker *et al.* 2022).

Additionally, the bioeconomy can play a crucial role in adapting to climate change, such as by reducing climate impacts on ecosystems and biodiversity and accelerating ecosystem-based adaptation and nature-based solutions. For example, by promoting sustainable agricultural and forestry practices, it can enhance ecosystem resilience and support biodiversity. Biobased technologies can improve soil health, water management and crop yields, making agricultural systems more resilient to climate variability. Furthermore, the sustainable management of forests and other natural resources helps protect communities from climate-related risks such as flooding and erosion, contributing to overall climate resilience.

1 Decision 1/CP.26, paragraph 21 and preamble.

2 Decision 1/CP.27, paragraph 18.

It is from this perspective that the G20 Initiative on Bioeconomy was created in 2024 and continued to be developed in 2025. This initiative focuses on leveraging science, technology and innovation, promoting the sustainable use of biodiversity and enhancing the role of the bioeconomy in sustainable development. The High-Level Principles on Bioeconomy (G20 2024), derived from the GIB, emphasize sustainable development, inclusivity, climate change mitigation and adaptation, biodiversity conservation, sustainable resource use and responsible innovation.

With countries set to submit new or updated NDCs in 2025, COP30 presents a critical opportunity to identify the most effective means of implementing the Paris Agreement. These NDCs must include clear and measurable steps towards achieving their conditional targets. Financial, technological and capacity-building support from the global community, including non-state actors, will be essential in helping many lower-middle-income and low-income countries meet these targets. The provision of guidance on where and how such support can have the greatest impact will be key.

Box 1.1: Bioeconomy

In simple terms, the "bioeconomy" involves using biological resources, such as animals, plants and trees, algae, fungi and bacteria, to provide food, feed, shelter, clothing, medicine and many other goods and services.

While there is no universally agreed definition of the term, most definitions of bioeconomy directly or indirectly share the following common characteristics. First, the bioeconomy draws on traditional and indigenous knowledge, as well as research and development in the life sciences and biotechnology, which drive its growth. Second, it involves the production of renewable and sustainable biobased materials, energy and products through biological processes, with renewable biomass or resources, the availability and quality of which depend on biodiversity and the broader nature-economy nexus, serving as a critical foundation for the development of the bioeconomy. Third, the bioeconomy is closely associated with energy efficiency, the reduction of emissions, sustainable and renewable practices, health and well-being, sustainable product transformation and economically sustainable transformation (UNEP 2024a).

Care must be taken when focusing narrowly on any one objective– such as reducing GHG emissions and not taking into account the impact of bioeconomy initiatives on biodiversity or on local communities. A life cycle assessment of bioeconomy investments, which includes social, economic and environmental impacts, is recommended. For example, biodiversity economy and wildlife economy initiatives have benefit-sharing and sustainable livelihoods at their core.

1.2 CLIMATE TECHNOLOGY AND THE BIOECONOMY

The bioeconomy leverages nature, indigenous knowledge, biological science, technology and innovation to conserve, produce and utilize biological resources sustainably. One positive effect of the bioeconomy is that it enhances resource-use efficiency and promotes circularity, while also delivering climate, environmental, economic and social benefits to society. In doing so, it directly addresses the call from the GST to incentivize the "non-carbon benefits" that are integral to sustainable forest management and other nature-based approaches. The bioeconomy is unique because it can be inherently decentralized, rooted as it is in locally available biological resources such as biomass, forests, waste and agricultural by-products (Vijay *et al*. 2022; Haarich and Kirchmayr-Novak 2022). This allows production and innovation to emerge across rural and peri-urban areas, rather than being concentrated in high-tech hubs. It is also diverse in both application and in terms of the actors it involves. The bioeconomy spans sectors such as food systems, bioplastics, bioenergy and natural fertilizers, drawing on a wide range of indigenous knowledge, circular practices and small-scale innovations. This broad base tends to make it more inclusive and adaptable to local contexts.

Importantly, the Global South is leading in many bioeconomy initiatives, particularly in Latin America, Africa and Southeast Asia (Stockholm Environment Institute [SEI] 2025; International Advisory Council on Global Bioeconomy [IACGB] 2024). These regions and countries are not just technology adopters but innovators in context-specific, low-carbon biobased solutions, challenging the dominant narratives of North-to-South technology transfer. This makes the bioeconomy an alternative development pathway, one that foregrounds place-based innovation, ecological knowledge and more equitable models of growth.

Several recent international reports focus on the bioeconomy. For instance, in a report published by the Food and Agriculture Organization, (Albinelli *et al*. 2024) highlight the way in which bioeconomy strategies are being implemented worldwide, with a focus on the role of sustainable forest management, sustainable food systems, resource efficiency and rural development. The Organisation for Economic Co-operation and Development (OECD) has developed key policy frameworks, particularly through its report entitled "The Bioeconomy to 2030" (OECD 2009), which emphasizes the role of biotechnology, circular economy principles and innovation in driving sustainable growth, and the need to ease land pressures from agriculture and forestry by expanding the bioeconomy with alternative, non-fossil sources of carbon (OECD 2023). In 2024, the NatureFinance and World Bioeconomy Forum examined the financial mechanisms and investment strategies necessary for scaling up biobased industries while ensuring environmental sustainability and social inclusion. Additionally, the World Economic Forum publication, "Accelerating the Global Transition to a Bio-based Economy: The Strategic Role of Policy", emphasizes the vital importance of policy frameworks in promoting the growth of the bioeconomy, particularly in areas such as bioenergy, bioproducts and sustainable resource management (World Economic Forum 2024). In 2024, UNEP examined global trends, challenges and opportunities for utilizing biological resources and technologies to promote sustainable economic growth while also addressing environmental and social issues (UNEP 2024).

The CTPR sets itself apart from these reports, while adding to the perspectives presented in them, by examining technological progress through the national systems of innovation framework and the conditions that enable the adoption and scaling of climate technologies. It is important to acknowledge that contemporary discourse on bioenergy has broadened beyond the initial framing of the "food versus fuel" dilemma. Today, the discourse encompasses broader and more complex concerns, including global equity, water scarcity, land degradation and land use change as well as potential impact on water resources and indigenous land rights (Dietz *et al.* 2018; Kennedy *et al.* 2023). Central to these discussions are possible trade-offs between different Sustainable Development Goals (SDGs), particularly between climate change mitigation efforts and the preservation of ecosystems (Warchold and Pradhan, 2025). For instance, expanding bioenergy production to reduce emissions may or may not come at the cost of protecting natural landscapes such as forests and water use, underscoring the complexity of the relationship between environmental protection and decarbonization strategies (Tobben *et al.* 2024).

In response to these possible and complex trade-offs, the emphasis has shifted towards systemic change, promoting resource efficiency, circularity, the reduction of demand and regenerative practices. Climate technologies in the bioeconomy exemplify this shift by integrating ecosystem restoration, circular design and cross-sectoral innovation. The opportunity lies in scaling these solutions while amplifying environmental benefits such as the conservation of biodiversity.

Box 1.2: The Climate Technology Progress Report (CTPR)

Understanding technology development and transfer significantly influences how we enhance and accelerate the implementation of climate technologies. The CTPR provides a systematic and annual assessment of the current state of technology adoption in selected areas and the feasibility and requisite enabling conditions for technological development and transfer at the sectoral, regional and global levels. The reports ask the following questions, all within the context of enhancing technology development and transfer:

1. **What progress is being made?**
2. **What has enabled it?**
3. **Where are the gaps?**
4. **Building on this understanding, how do we better enhance climate technology development and transfer?**

While these guiding questions shape the overall direction of the report, they are adapted each year to reflect emerging issues in the global climate landscape.

The report series falls within the 2023-2027 UNFCCC Technology Executive Committee (TEC) rolling workplan and forms part of the first joint work programme of the Technology Mechanism. The UNFCCC Technology Mechanism consists of two bodies: the TEC and the Climate Technology Centre and Network (CTCN). The TEC is the policy arm of the Technology Mechanism. It focuses on identifying policies that can accelerate the development and transfer of low-emission and climate-resilient technologies and its key outputs are its annual technology-related recommendations to the COP and the CMA.[3] The mission of the CTCN is to stimulate technology cooperation and enhance the development and transfer of technologies, as well as to assist developing country Parties at their request to support action on mitigation and adaptation and enhance low-emission and climate-resilient development. The purpose of the first joint work programme of the Technology Mechanism[4] is to accelerate efforts on transformative climate technology development and transfer to help countries to achieve the goals of the Paris Agreement and those of the UNFCCC, and to implement their national climate plans (including NDCs).

3 Conference of the Parties (COP) and Conference of the Parties serving as the meeting of the Parties to the Paris Agreement (CMA).

4 https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/TEC_Documents_doc/6e7cae499c2b418e93d2d2a1bcca1a20/e9a1b6ffadbe47bcb3f2634881df13f5.pdf

1.3 THE CTPR 2025

With a view to providing both a comprehensive overview and targeted insights, the 2025 report adopts a hybrid global and regional format. Chapters 1 to 5 take a global perspective, while Chapter 6 provides a regional assessment focused on the Latin America and Caribbean (LAC) region. As a region where ecological wealth and development challenges converge in a unique way, the LAC region is positioned to be a global leader in bioeconomy and climate technology innovation. Its vast biodiversity and rich agricultural base provide strategic advantages for advancing sustainable solutions, for both people and planet. The structure of the 2025 CTPR makes it possible to evaluate overall progress in technology development and transfer while also offering more in-depth insights specific to the LAC region. By combining global and regional analyses, the report generates information for tailored interventions that consider unique factors such as regulatory environments, governance and financial structures. While regional analysis offers valuable contextual depth, information at both the global and regional levels is also essential. Global perspectives can inform regional actions, while also accounting for interconnectedness, patterns and trends on a worldwide scale. The specific questions that the 2025 CTPR seeks to address are as follows:

How can the bioeconomy contribute to addressing climate change effectively and sustainably, what are the key technologies involved, what progress is being made in scaling up their availability and use, and how can their accessibility and implementation be accelerated?

These questions guide the exploration in the report of the intersection between the bioeconomy, innovation and climate action. The CTPR frames the analysis of current trends, identifies gaps and highlights opportunities for scaling up impactful technologies. The integration of climate technologies into bioeconomy initiatives offers a powerful pathway to drive climate mitigation, enhance resilience and promote inclusive, sustainable development.

Four key biobased technology categories are identified as being central to this intersection and will form the scope of analysis for the CTPR 2025. Each category explores how technological, economic and policy drivers influence sustainable, low-carbon and climate-resilient system transitions, as well as their potential to address critical climate challenges. The categories are as follows:

Biomass conversion. Technological innovations that transform biological resources into alternatives to fossil fuel-based products. Biomass conversion processes transform biological resources into solid, liquid and gaseous biofuels, power and heat, reducing the use of fossil-based energy.

Biogenic carbon capture utilization and storage (Bio-CCUS). Technologies that rely on the uptake of atmospheric CO_2 by biological processes. In Bio-CCUS, the captured biogenic carbon is either stored in long-lived reservoirs or utilized in ways that extend carbon retention.

Sustainable agriculture and land use. These technologies aim to reduce greenhouse gas emissions, enhance carbon sequestration and improve adaptation and resilience to climate change through a broad range of practices, methods, tools and institutional frameworks.

Biobased materials. By converting agricultural and industrial waste, including wood and forest residues, into bioplastics, fibres, chemicals and engineered wood products, these technologies support both the reduction of emissions and resource efficiency.

Identification of these four categories of biobased technologies was motivated by key drivers observed across the bioeconomy landscape. First, the ongoing shift away from fossil fuels towards biomass-based alternatives, reinforced by subsidies and supportive environmental policies, has created strong incentives for investments in biobased sectors. This trend underpins biomass conversion technologies, which transform biological resources into low-carbon energy or material alternatives. Bio-CCUS technologies include innovations such as bioenergy carbon capture and storage (BECCS), which remove CO_2 from bioenergy processes and store it underground. The sustainable agriculture and land use category was selected due to its critical role in addressing both mitigation and adaptation challenges in climate change. And, lastly, downstream sectors focus on improving the efficiency of biomass utilization and waste stream recycling, often targeting low-bulk, high-value applications. The drive towards circularity and resource efficiency motivates the biobased materials category, which encompasses innovations that replace fossil-based inputs with sustainable, renewable alternatives. It is important to note that these four categories are not exhaustive. Other areas, such as biochemical manufacturing, biomining and bioelectronics, also have potential climate benefits but were considered to be beyond the scope of this report. The focus in this CTPR is on the technological pathways that are currently most policy-relevant, scalable and well-established in driving low-carbon and climate-resilient outcomes within the bioeconomy.

1.4 STRUCTURE

Part I (Global Focus)

Chapter 2 explores the application of biobased technologies across agriculture, forestry, energy, land use, industry, and the waste sector. **Chapter 3** evaluates the feasibility of biobased technologies, building on previous CTPRs and the IPCC AR6. It provides global and regional assessments, highlighting differences in feasibility due to resource availability, institutional capacity, and socioeconomic context. **Chapter 4** analyzes how the bioeconomy mobilizes finance and investment through instruments such as government grants, venture capital, blended finance, and carbon markets to drive innovation. **Chapter 5** examines how public-private coordination and international cooperation can accelerate the adoption of biobased technologies, with a focus on policies, governance, and regulatory frameworks.

Part II (Regional Focus)

Chapter 6 presents a regional assessment of Latin America and the Caribbean, recognizing the region's rich biodiversity and biomass resources. It explores the development and transfer of biobased technologies, highlighting opportunities to accelerate their deployment.

Photo: Unsplash

CHAPTER HIGHLIGHTS

- Biomass conversion technologies are progressing across gas, liquid and solid fuel applications, with several pathways such as anaerobic digestion and biochar already commercially mature. However, broader adoption depends on overcoming cost barriers, securing stable feedstocks and aligning with supportive policies and infrastructure, especially for emerging options such as gasification and biobased liquid fuels.

- Biogenic carbon technologies are emerging as viable decarbonization pathways, but current adoption levels fall far short of climate targets. Scaling technologies such as BECCS will require major advances in biomass sourcing, infrastructure and investment.

- Carbon removal technologies such as BECCS and nature-based solutions are progressing, but adoption remains uneven. Nature-based approaches, including afforestation, agroforestry and soil carbon enhancement, are gaining traction due to their co-benefits for biodiversity and people's livelihoods, yet require stronger integration into climate strategies.

- A diversified portfolio of land-based and biologically driven carbon removal technologies is essential for meeting global climate goals. While some technologies are technically mature, increasing adoption will depend on aligning innovation with sustainable land use, policy support and long-term planning.

- Technology adoption in sustainable agriculture and land use is advancing, with a growing uptake of climate-smart practices such as precision irrigation, biofertilizers and improved forest management. However, scaling remains uneven across regions and technologies, highlighting the need for stronger policy support, investment and inclusive governance to unlock full mitigation and resilience benefits.

- Nature-based and biologically driven carbon removal technologies, such as afforestation, agroforestry and biochar, are gaining traction, but adoption is still limited by land-use constraints and monitoring challenges. Progress is being made, but accelerating deployment will require integrated land-use strategies, stakeholder engagement and targeted support to ensure equitable and sustainable outcomes.

- Biobased materials are gaining traction in sectors such as construction and packaging, with innovations including biochar-infused concrete and hempcrete showing strong potential for long-term carbon storage and reduced petrochemical use. However, most applications remain linear and scaling adoption will require a shift towards circular design, better composting and recovery systems and stronger alignment with regenerative land-use practices.

Part I

2.

Adoption of Biobased Technologies

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2.1 INTRODUCTION

This chapter provides information on the adoption of biobased technologies. The development of the bioeconomy has multiple links to flows of atmospheric GHG emissions (CO_2, N_2O, and CH_4), as shown in Figure 2.1. The effect of the bioeconomy on climate change mitigation is mainly reflected in four ways:

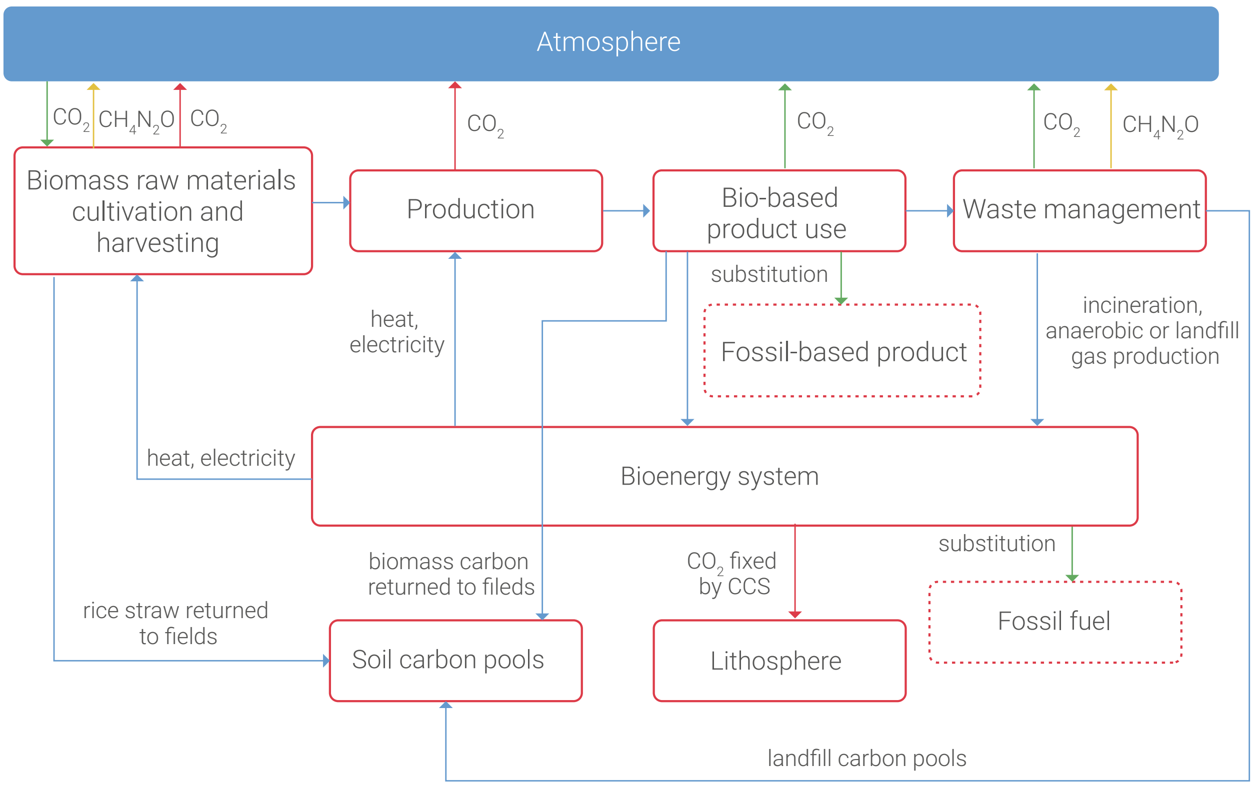
1. Carbon sequestration from biomass. Plants absorb CO_2 from the atmosphere during their growth and convert it into organic matter. Traditional sink enhancement technologies in agroforestry mainly include afforestation, reforestation and forest management, conservation farming in agriculture, management of grasslands and wetlands and coastal ecological projects (Li *et al.* 2022).

2. Substitution of GHG-intensive products and fossil fuels. Substitution effects exist in all industries. Engineered wood can replace steel and cement (Gustavsson *et al.* 2021), biobased and biodegradable plastics can replace petroleum-based plastics, bioethanol and biodiesel can replace fossil fuels such as oil and natural gas, biobased fibres can substitute synthetic ones and so forth (Guo *et al.* 2023).

3. Carbon storage in biobased products. The use of biobased products enables the transfer of carbon absorbed by biomass from the atmosphere to the carbon pool of these products. The length of time this carbon remains stored varies from a few years to several centuries, depending on the type of product, its lifespan and end use, as well as its eventual fate at the end of its service life (Zuiderveen *et al.* 2023).

4. Utilization of waste biomass resources. Biomass residues can be used to generate electricity and/or heat, manufacture biofertilizer or produce biomass materials. Biomass residues are traditionally disposed of in landfills, open piles and incinerators, which produce not only large amounts of CO_2 but also methane (CH_4) and other gases (N_2O) that have a higher greenhouse effect. Nonetheless, biomass is generally considered to be carbon neutral, as it absorbs CO_2 from the atmosphere during its growth, offsetting the emissions released when it is processed or burned. Converting it into bioenergy or valuable products therefore not only saves resources, but also effectively reduces GHG emissions (Rosa and Gabrielli 2024).

Figure 2.1 Carbon flow, removals and emissions in the atmosphere, biomass and biobased products systems (UNEP 2024a).[5]



5 Green arrow refers to biogenic CO_2 removals/emissions, red arrow refers to fossil CO2 emissions, blue arrow refers to carbon flow.

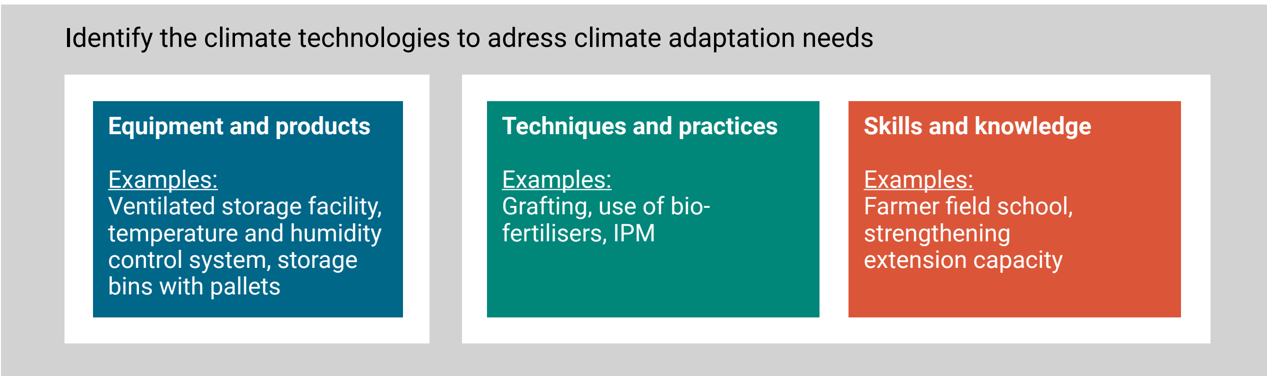
2.2. CLIMATE TECHNOLOGY INTERVENTIONS IN AGRIFOOD SYSTEMS

Within agriculture systems, biobased technologies play an important role in transforming agrifood systems, helping to reduce emissions, enhance resilience and address the challenges of climate change. Understanding their role and potential is key to designing effective, inclusive and sustainable responses to the climate crisis. These technologies can also contribute to the development of a sustainable bioeconomy, addressing climate change while contributing to sustainable consumption and production practices which are inclusive through circular economy approaches. A sustainable bioeconomy contributes to climate change adaptation and resilience by promoting restoration of the ecosystem and supporting indigenous and local livelihoods based on biological products and services. Furthermore, biobased technologies present opportunities to reduce GHG emissions across the agrifood system by replacing fossil-based resources and processes with biological alternatives (Gomez *et al.* 2022).

In the case of agrifood systems, adopting a value chain approach is essential in order to identify entry points for climate technologies. This approach allows for a comprehensive understanding of how climate technologies can be applied not only at the production level but also throughout processing, storage, distribution and consumption.

This approach also strengthens coordination among stakeholders, from input suppliers and farmers to processors and retailers, helping to improve the efficiency, scalability and resilience of agrifood systems. Furthermore, it allows for a better understanding of potential synergies and trade-offs between climate action and other objectives of the transformation of agrifood systems, such as improving livelihoods, nutrition and natural resource management (FAO and UNFCCC 2024). For complementary perspectives, refer to the discussions on agroforestry and forest-based adaptation in Chapter 3, which provides insights into strategies for resilient land-use. Cambodia provides a clear example of how a value chain approach can be applied in practice. Due to its high vulnerability to climate change, particularly in the agriculture sector which remains central to rural livelihoods and food security, enhancing the resilience of agrifood systems to climate shocks requires targeted climate technology interventions, including biobased technologies. In the specific case of the cashew nut, while this crop is considered to be relatively climate-resilient due to its drought tolerance, it is still affected by climate change risks. Potential adaptation interventions for this value chain are illustrated in Figure 2.2.

Figure 2.2 Examples of climate technology interventions in cashew nut value chains in Cambodia (Source: Forthcoming FAO 2025).



Disruptions to agricultural productivity in Cambodia have been occurring as a result of more frequent floods, prolonged droughts and outbreaks of pests. These impacts have contributed to lower yields, greater post-harvest losses and growing economic pressure on rural households (Cambodian Ministry of the Environment 2022). Agricultural technologies and practices, such as improved pest management, drying and storage, can help mitigate these challenges (Table 2.1). However, uptake remains low due to limited access to these technologies, high costs and the fact that technologies are often not appropriately targeted to the specific needs and local contexts. Some technologies address climate change impacts directly, while others contribute to adaptation indirectly, for example by reducing food loss. Ensuring that appropriate, locally relevant technologies are identified and promoted alongside adequate training and support is essential for enhancing the resilience of agrifood systems and long-term food and livelihood security.

Table 2.1 Selected technology interventions along the cashew nut value chain in Kampong Thom, Cambodia (Forthcoming FAO, 2025).

Stage	Climate technology intervention	Adaptation benefit
Pre-production and production		
Seedling production and grafting	Grafting houses with humidity control	Provides a temporary buffer against extreme heat events, creating favourable conditions for the graft union to develop successfully
	Grafting tools	Enhances the resilience of crops to drought, heat stress and other climate-related challenges
Input management	Bio-fertilizer production unit	Improves nutrient availability, enhances soil health and increases yields
Land preparation	Mini tractor with implements	Enhances efficiency in land preparation and reduces labour intensity and time, leading to increased capacities of smallholder farmers to adapt to variable climatic conditions
Orchard management	Power sprayer with personal protective equipment (PPE)	Motorized sprayers used with PPE designed to support efficient and safe pesticide application, leading to enhanced crop protection
	Integrated pest management (IPM) traps and monitoring tools	Enables early detection of pests, helping producers prevent crop damage and control infestations before they become widespread and harder to manage
	Weather monitoring station	Enhances climate resilience by providing real-time weather data for informed decision-making, which improves early warning systems and supports climate adaptation strategies
	Drones	Improves pest and disease control and enhances crop growth and yield potential
Harvest and post-harvest handling		
Harvesting equipment	Collection net system	Improves harvesting efficiency and reduces contamination
	Set of nut-picking tools	Improved harvesting efficiency
Drying	Drying yard	Prevents spoilage and reduces food loss
	Solar drier with humidity control	A solar-powered unit with humidity control that dries raw cashew nuts under optimal conditions, thereby minimizing mould and spoilage
Storage	Ventilated storage facility	Protects produce from extreme weather, helps manage pests and diseases, and reduces food loss
	Temperature and humidity control system	Proper storage conditions protect produce from extreme weather, help manage pests and diseases, and reduce food loss
Post-production		
Primary processing	Nut-cutting machine	Improves processing techniques and reduces food loss
	Steam boiler unit	
	Kernel extraction tools	
Quality enhancement	Grading tables with lights	Improves processing techniques and reduces food loss
	Moisture-testing equipment	Improves processing techniques and reduces food loss
	Packaging unit	Reduces physical damage, protects products from contamination and improves shelf life
Quality assurance	Kit to test for aflatoxin	Detects and mitigates contamination, safeguards food safety, preserves food quality and reduces food loss

The Cambodian case study, demonstrate how climate technologies can strengthen resilience across all stages of the agrifood system, from production to processing, distribution, and consumption. Targeted interventions including biobased technologies, capacity building, and skills and knowledge development for vulnerable smallholders demonstrate the importance of context-specific strategies to enhance adaptation, livelihoods, and sustainable agrifood system transformation.

While section 2.2 focuses on climate technology adaptation in agriculture and forestry sector, section 2.3 focuses on climate technology mitigation.

2.3. SELECTED BIOBASED TECHNOLOGIES FOR CLIMATE ACTION

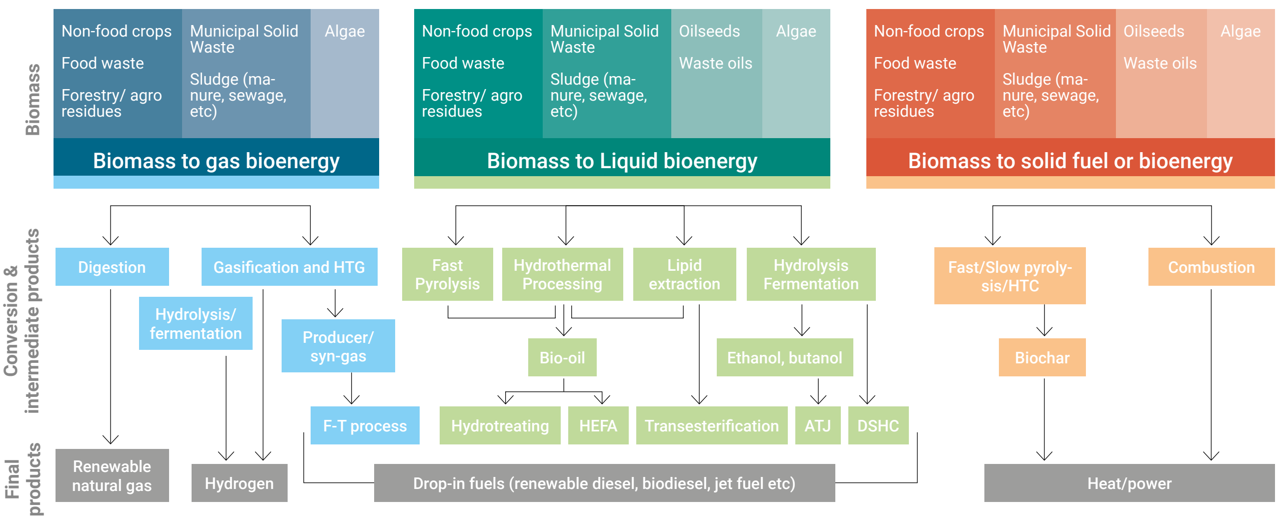
This section outlines selected biobased technologies in terms of the potential of biomass conversion technologies, Bio-CCUS, biobased materials.

2.3.1 Biomass Conversion Technologies

Biomass conversion processes transform biological resources into solid, liquid and gaseous biofuels, power and heat, reducing dependence on coal, oil and natural gas. as illustrated in Figure 2.3. Biofuels can be loosely divided into low-grade fuels for heating and power and "drop-in fuels" which can directly be substituted for petroleum-based transport fuels. Each biofuel pathway undergoes a detailed life cycle analysis to determine its GHG emissions. Generally, biofuels that involve more processing steps, such as those used for transport fuels, tend to have higher emissions during conversion, although the actual impact depends on factors such as the type of feedstock, production methods and local conditions. However, factors such as the type and availability of biomass, geographic location and existing infrastructure can significantly influence the overall GHG impacts. Moreover, the potential of any process is closely tied to regional conditions, for example, whether solid fuels are commonly used, the presence of gas or liquid pipeline systems and the distance to key markets. Importantly, assessing only the supply chain carbon footprint does not capture the full picture. In general, electrification and the use of biofuels can be complementary strategies for decarbonizing the transport sector.

Technologies should be evaluated neutrally, using life cycle analysis to assess their overall impact. It is important to consider factors such as biomass type and availability, as well as the specific energy services being replaced. For example, electrification may be well suited to heating and commuter transport, whereas biofuels may remain necessary for aviation and heavy-duty vehicles (See Chapter 4 on research, development and innovation investments related to complex processing and conversion challenges). For instance, oilseed crops may compete with food production, whereas lignocellulosic crops can often be integrated into farming systems in lower-productivity environments, thereby reducing direct competition for arable land. Additionally, scaling biomass demand can increase land competition, although the extent of this impact depends on the specific context. For example, in Brazil, biofuel growth has not harmed food production or land. The country became a leading exporter of agricultural commodities while producing biofuels. Pasture intensification freed up land without reducing meat output. In 2024, Brazilian food items supported around 900 million people, roughly 11 per cent of the global population. Biofuel production advanced alongside environmental protection measures (IEA, 2025). This demonstrates that, under suitable conditions, bioeconomic growth can align with food security and sustainable land use.

Figure 2.3 Conversion pathways for bioenergy (adapted from Guo *et al.* 2023)



Biomass to gas

Biomass can be converted to renewable natural gas, hydrogen or synthesis gas via anaerobic digestion, gasification or hydrothermal gasification. Anaerobic digestion, where bacteria break down organic matter in the absence of oxygen, produces a biogas (renewable natural gas), which can be used as a fuel or intermediate. The by-product "digestate", can be used as a fertilizer in agriculture or compost material. Biomass does require an additional drying step but the process is slow relative to thermal processes. In gasification, biomass must be dried and then combined with a gasifying agent (air, oxygen, steam or an air-steam combination) at temperatures greater than 700 degrees Celsius. The gas which is generated can be used directly in gas turbines (producer gas) or purified for hydrogen, or as feed for conversion to drop-in fuel (syngas) via the Fischer-Tropsch (FT) process. Processes can be operated at lower temperatures when a catalyst is used. Where the gasifying agent is air, the main product is a producer gas and when the main gasifying agent is steam, the product is a syngas and is richer in H2 (Alves *et al.* 2023). Hydrothermal gasification (HTG) is an emerging technology where water is combined with the biomass. It is best used for "wet" waste (e.g. municipal sludge) and produces a richer hydrogen gas stream. The HTG process uses a lower temperature (~400 degrees Celsius) in comparison with gasification but requires higher pressures (more than 200 bar), which impacts overall feasibility and operation.

While anaerobic digestion is commercially mature and scalable, particularly at municipal and industrial levels, gasification remains less widespread due to its complexity and high capital costs. However, the variety of potential applications (from a source of hydrogen to power via producer gas to transport fuels) makes gasification attractive, especially as new catalysts and reactor designs evolve.

Scalability considerations:

- The digestion (biological) process is slow, and biomass requires pre-treatment
- Gasification (thermal) is energy/capital-intensive and sensitive to feedstock quality

Table 2.2 A summary of biomass-to-gas options by technology maturity, scalability and the associated range of GHG per megajoule of fuel energy.

Technology	Maturity	Scalability	GHG range (gCO_{2e}/MJ_{fuel})	Note
Anaerobic digestion	Mature and commercially deployed	High	-50 to 8.4 (Li and Wright, 2020)	Widely used for municipal and agricultural waste. Slow process. By-product digestate.
Fermentation to bio-H2	Lab-scale	Unknown	5 to 17 (Luo *et al.* 2025)	Low yield of H2. High production costs relative to thermochemical processes. Process could be improved with optimization of biological activity and system conditions.
Thermal gasification	Mature	Medium-high	0.31-27 without carbon capture -102 to -153 with CC (H2 production) (Sher *et al.* 2025)	Suitable for dry biomass. Small scale (<200 kW) systems widely deployed globally. Larger scale systems (1-160 MW) operating across Europe. Feedstock pre-treatment required (drying).
Catalytic gasification	Emerging-demonstration stage	Medium		Catalyst allows for reduced energy/operating costs, enhancing long-term potential.
Hydrothermal gasification	Emerging	Low-Medium	Not enough data/ analysis	Suitable for wet biomass streams. High pressures (more than 200 bar) and water treatment limits feasibility and cost-effectiveness.

Biomass to liquid products

Liquid intermediates/fuels can be produced via fast pyrolysis, hydrothermal liquefaction, hydrolysis and fermentation and transesterification. Products include renewable diesel, biodiesel, jet fuel and sustainable aviation fuel (SAF). SAF has a similar function to petroleum-based jet fuel (kerosene) but has significantly lower GHG emissions (Wang, Ting and Zhao 2024). Fast pyrolysis can process (i) waste solid biomass (municipal solid waste, forestry residues, fish offal etc.) or (ii) lipid/oil-based waste (e.g. waste cooking oil, algae lipids, etc.). In solid biomass pyrolysis, three products are produced: liquid (bio-oil), solid (biochar) and gas. The yield products depend on the type of biomass, temperature and time. Fast pyrolysis occurs at moderate to high temperature (between 450 and 600 degrees Celsius) and processing times last minutes. The gases produced can be combusted to provide process heat. The bio-oil can be used as low-grade heating fuel or further refined to produce a drop-in fuel. The biochar can be used as solid fuel or in other applications (outlined in more detail in the following section). In waste bio-oil pyrolysis, the product is a liquid hydrocarbon that requires refining in order to produce drop-in fuel (i.e. renewable diesel or jet fuel).

Pyrolysis requires a dry feed, whereas hydrothermal liquefaction (HTL) is ideal for a "wet" biomass. HTL occurs at lower temperatures (between 280 and 400 degrees Celsius) and produces a liquid (bio-oil) with by-products of solid hydrochar and gases. The bio-oil requires further refining to produce drop-in fuels (Khandelwal *et al.* 2024). Oils extracted from algae, plant seeds, and animal processing by-products can be converted into drop-in fuels via transesterification or the hydrogenated esters and fatty acid process (HEFA). Transesterification is a common and widely deployed process for converting oil-based feeds to biodiesel. Unlike catalytic pyrolysis, the product is a fatty acid methyl ester-based biodiesel (FAME)-. FAME acts the same as a diesel in but is compositionally different (Nayab *et al.* 2022). The HEFA process uses processes which are common in petroleum refineries, where oil-based feeds are processed through a series of operations to convert the lipids into hydrocarbons. These reaction steps require hydrogen and, therefore, to be economically and environmentally sustainable there must be a "green" source of H2 (Wang, Ting and Zhao 2025).

In hydrolysis/fermentation processing, a series of processes (pre-treatment, enzymatic hydrolysis, fermentation, distillation and dehydration) break down the biomass to produce alcohol, hydrogen or hydrocarbons. Ethanol and n-butanol are the most common alcohol products. The solid residue digestate can be used in fertilizer and livestock feed. The alcohol can be used in fuel blends or converted via chemical processes such as Alcohol-to-Jet (ATJ), where the alcohol is transformed through a series of unit operations to a jet fuel-grade hydrocarbon. Through proper selection of microorganisms, fermentation can produce hydrogen or hydrocarbon instead of alcohol. The hydrocarbons can then be upgraded to drop-in fuels (referred to as the "direct sugar to hydrocarbons" process or DSHC) (Wang, Ting and Zhao 2025).

Key biomass-to-liquid fuel technologies include fast pyrolysis, HTL, fermentation processes such as ATJ and DSHC, and lipid-based methods such as HEFA and transesterification.

Scalability considerations:

- FAME-based biodiesel derived from oilseeds and waste oil and ethanol from sugar/starch-based crops are widely used as stand-alone fuels or blended with petroleum fuels. Renewable diesels and SAFs etc. are new to the market and are not as widely deployed (see Table 2.3).
- Refining bio-oils to produce drop-in fuels requires high capital and energy input.
- Feedstock variability and the need for hydrogen (especially for HEFA) constrain scalability.
- Commercial deployment, mostly of SAF and renewable diesel, is not yet widespread.

Table 2.3 A summary of Biomass to Liquid products by technology maturity, scalability and the range of associated GHG per megajoule

Technology	Maturity	Scalability	GHG range (gCO_{2e}/MJ_{fuel})	Note
Fast pyrolysis	Early commercial	High	11 to 30 (Kulikova *et al.* 2024; Sun *et al.* 2023; and Karimi, Simsek and Kheiralipour, 2025)	Suitable for dry biomass. Bio-oil requires upgrading for use as transport fuel.
Hydrothermal liquefaction (HTL)	Pilot to early commercial	Medium-high	26 to 300 (Luo *et al.* 2025; Brown and Tao 2023)	Ideal for wet biomass. High-pressure results in high energy/costs. Bio-oil/crude must be upgraded for transport fuels.
Transesterification (FAME biodiesel)	Commercially mature	High	-20 to 40 (van Dyk,S. and Saddler,J., 2024; Corsia 2022; Usman, M. 2025)	Well-established technology using waste or plant oils. Compatible with existing diesel engines. Infrastructure and global deployment (small and large scale) already in place.
HEFA (hydroprocessed esters and fatty acids)	Commercial, scaling up	Medium to High	5 to 70 (Karimi, Simsle and Kheiralipour 2025; Bascones, A., Hannula, I. 2024; Brown, C. and Tao, L. 2023)	Scalable with available lipid feedstock but limited by green hydrogen supply and high CAPEX.
Hydrolysis + fermentation	Mature for ethanol; emerging for higher order alcohols/hydrocarbon	Medium	-25 to 125 (Bascones, A, Hannula, I. 2024; Sun *et al.* 2023; van Dyk and Saddler, J. 2024)	Ethanol production is widespread.
Alcohol-to-Jet (ATJ)	Emerging	Low to Medium	10 to 90 (Brown, C. and Tao, L. 2023)	Pilot/pre-commercial stage. Dependent on alcohol feedstock cost and policy support.
Direct sugar to hydrocarbon (DSHC) also known as synthesized isoparaffin (SIP)	Emerging	Low	20 to 120 (Brown C. and Tao, L. 2023)	Biotechnologically promising but not yet commercially viable due to low yields and competition with pharmaceutical/cosmetic industry. Scaling depends on breakthroughs in microbial engineering and process economics.

Biomass to solid bioenergy/fuel

Biomass can be converted to a biochar/pellet or used directly "as is" in power generation. Electricity is generated from the combustion of biomass and the waste heat is recovered. This is referred to as combined heat and power (CHP). All types of biomasses can be used in direct combustion, but higher-moisture-content biomasses are less efficient due to the drying step required and high ash biomass can be problematic.[6] Torrefaction is a lower temperature pyrolysis (~ 300 degrees Celsius) over several hours, while slow pyrolysis is performed at the same temperatures with longer processing times (measured in hours). Torrefaction and slow pyrolysis favour a solid fuel (biochar). In hydrothermal carbonization (HTC) the primary product is a solid "hydrochar", achieved at lower temperatures than HTL or between 180 and 280 degrees Celsius (Khandelwal *et al.* 2024). As with HTL, HTC is ideal for "wet" biomass.

Biochar and hydrochar are the base material for palletization to a solid fuel (depending on the heating value and ash content), soil amendment, construction materials, energy and hydrogen storage, catalysts, microbial substrates and adsorbent in wastewater treatment and CO_2 capture. Biochar from agricultural, forestry, industrial and municipal waste sequesters carbon that would have otherwise been emitted via decomposition, reducing GHG emissions. (Guo *et al.* 2023)

Technologies such as direct combustion for CHP, torrefaction, slow pyrolysis, HTC and biochar production represent key thermal conversion routes for biomass (See Table 2.4).
Scalability Considerations:

- Moisture content reduces efficiency in combustion
- HTC still emerging and more common in niche or decentralized uses

Table 2.4 A summary of biomass to solid fuel options by technology maturity, scalability and the range of associated GHG per megajoule of fuel energy.

Technology	Maturity	Scalability	GHG range (gCO2e/MJfuel)	Note
Combined heat and power	Mature	High	23 to 80 (Zheng *et al.* 2022)	Widely used for all biomass types. Efficiency drops with high-moisture feedstocks.
Torrefaction	Emerging to mature	Medium	28 to 361 (Watson *et al.* 2024)	Produces biochar with improved fuel properties relative to feedstock. Best with dry biomass.
Slow pyrolysis	Emerging to mature	Medium		Produces biochar, improved fuel properties relative to torrefied biomass and feedstock.
Hydrothermal carbonization (HTC)	Pilot to emerging	Medium	83 to 181 (wet biomass) (Watson *et al.* 2024)	Ideal for wet biomass. High-pressure operation may be limiting due to energy costs.
Biochar applications	Mature (in niche uses)	High	Net decrease due to sequestration	Mature deployment to soil and fuel applications, less developed as adsorbent for gas/wastewater treatment, catalyst, etc.

2.3.2 Biogenic Carbon Capture Utilization and Storage (Bio-CCUS)

The Sixth Assessment Report from the IPCC (IPCC AR6) emphasized that the world must achieve net zero carbon dioxide emissions by 2050 and ensure the attainment of net-negative carbon emission to mitigate the catastrophic challenges posed by climate change. It has been projected that between five and ten billion tons (Gt) of CO_2 must be removed annually by 2050 to keep global warming below 2 degrees Celsius. Capturing biogenic CO_2 could play an important role in this process (IPCC 2023; and UNEP 2023a). Biogenic CO_2 is carbon dioxide originating from biogenic sources including solid biofuels, agricultural residues, forestry and farming waste. Unlike carbon emissions from fossil fuel, biogenic CO_2 is released from relatively recent carbon fixation and is considered to be part of the biogenic or natural short-term carbon cycle. When biogenic CO_2 is captured, utilized and stored it is referred to as Bio-CCUS (As outlined in the introduction to Chapter I). IPCC AR6 presented scenarios showing that the cumulative global CDR (Carbon Dioxide Remova) from BECCS and DACCS (Direct Air Carbon Capture and Storage) must reach between 30 and 780 Gt CO_2 and between 0 and 310 Gt CO_2, respectively, between 2020 to 2100 to keep global warming within 1.5 degrees Celsius with minimal or no overshoot (UNEP 2023a). According to the UNEP Emissions Gap Report 2024 (UNEP 2024b), which assessed sectoral

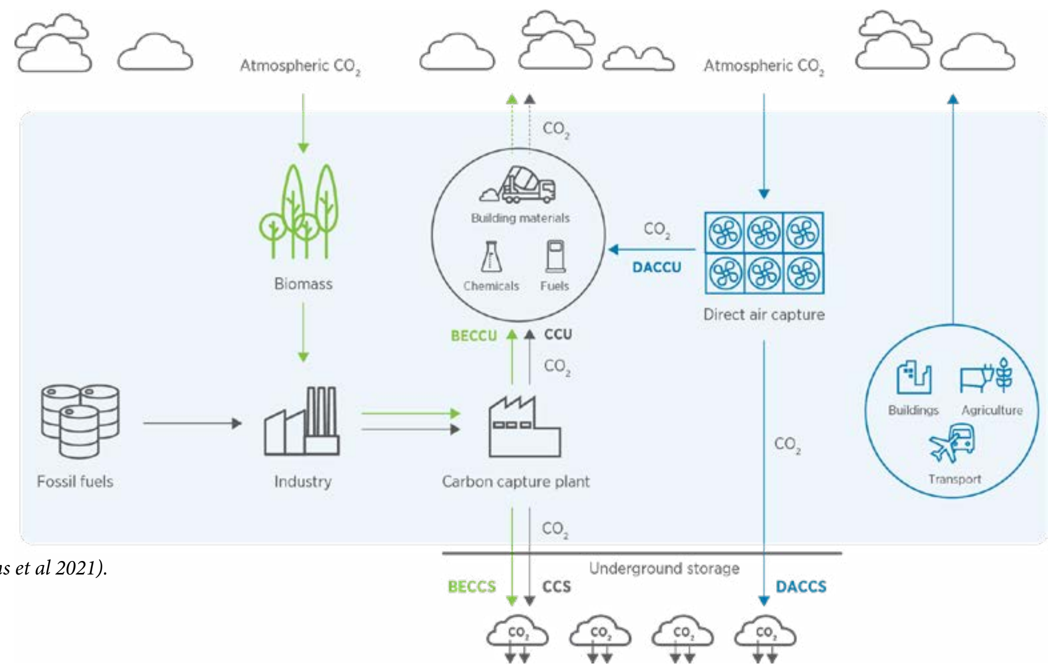
6 Biomass-fired power plants that use high ash feedstocks such as green plant matter, manures or animal carcasses often encounter significant challenges with material handling and slagging.

mitigation potentials from 2030 and 2035, BECCS is projected to achieve a 1.5 Gt CO_2 removal capacity by 2035, whereas the contribution from DACCS was cited as "small". Nonetheless, the report highlighted key investment areas, including carbon capture, electrification of industrial processes, energy efficiency and recycling, which are essential to meet climate mitigation goals.

The International Energy Agency (IEA) estimated that Bio-CCUS needs to remove approximately 185 Mt CO_2 per year by 2030 to reach net zero emissions (NZE) by 2050 (IEA 2025). However, despite the potential of CDR (including BECCS and DACCS), at present only 2 Mt of biogenic CO_2 per year is being captured, mainly in bioethanol applications. The heat and power sector could potentially remove 30 Mt of biogenic CO_2 per year by 2030. Although Bio-CCUS plans are encouraging, they are insufficient for the NZE scenario for 2050, which requires the removal of approximately 45 Mt biogenic CO_2 per year from the power sector, 120 Mt biogenic CO_2 per year in the fuel transformation sector and 25 Mt biogenic CO_2 per year from the hard-to-abate (mainly cement) industry by 2030, compared to the currently projected ~60 Mt biogenic CO_2 per year (projects in pipeline) (IEA 2025). Furthermore, the IEA also estimated that BECCS and DACCS techniques could globally remove 1.9 Gt CO_2 annually by 2050 (IEA 2021). A recent report on defossilizing the petrochemical industry provided detailed insights into the transition of the petrochemical industry from fossil-based to renewable feedstocks and the associated challenges (Quadrature Climate Foundation 2025). It highlighted that replacing fossil-based carbon with biogenic carbon will drastically increase the demand for biomass, which may not be sustainable on a global scale. Additionally, transitioning the petrochemical industry towards renewable feedstock requires significant investment in innovation, supported by strategic planning, governmental policy and business support mechanisms (See chapter 5 on the policies and regulatory frameworks needed for bio-based technologies to effectively compete with fossil fuel-based technologies). For instance, producing low-carbon chemicals is significantly more expensive, with bio-methanol costing in the range of US$320 to $770 per ton compared to fossil-fuel-based methanol which stands at between $100 to $250 per ton (IRENA and Methanol Institute 2021).

CDR pricing is based on the extraction technology, measurement, reporting and verification, and durability of storage methods. CDR pricing fluctuates significantly, with DACCS costing ~$1000/t$CO_2$e whereas BECCS is in the range of $100 – 300/ t$CO_2$e (CDR.fyi 2025). Additionally, DACCS requires large amounts of cheap carbon-free energy (between 2000 and 2400 kWh/t CO_2) to be economically and environmentally viable. While BECCS is regarded as one of the most promising CDR methods, the availability of biomass remains a limiting factor. Recent studies highlighted biomass gasification for hydrogen production with carbon capture and storage (BHCCS) as a key emerging negative emissions technology over biomass combustion with carbon capture and storage for electricity generation (BECCS) (Wu *et al.* 2023 and Bakkaloglu *et al.* 2024). The results showed that a solid DACCS system with integrated industrial waste heat emerged as the most cost-effective option, increasing total CO_2 removal by 14.4 per cent (Bakkaloglu *et al.* 2024). Figure 2.4. shows carbon capture and utilization, including biobased (IRENA 2021).

Figure 2.4 Conceptual diagram of carbon capture, including bioenergy carbon capture, utilization and storage (BECCUS)



(Source: (Lyons et al 2021).

2.3.3 Sustainable Agriculture and Land-Use Technologies

Climate technology in the land sector will improve land productivity, enhance carbon sinks, reduce emissions from agriculture and increase the resilience of agricultural production to climate change impacts. The agriculture, forestry and land-use (AFOLU) sectors are the source of significant emissions of GHGs but provide substantial potential for CDR technology implementation. These CDR technologies provide opportunities for both near and long-term carbon storage with flexibility and precision making them useful in all national and global mitigation strategies. There is a wide variety of technologies, but their effectiveness depends on tailoring them to local conditions and needs, as this sector requires substantial local co-development to ensure durable carbon storage.

The implementation of sustainable agriculture technologies that improve soil carbon in grasslands, pasture lands and croplands demonstrate the need for specific technology usage, as the differences in agroecosystems across regions, countries and continents require varying implementations of the related crop management, grazing management, soil tillage and fertilizer usage technologies (Bai and Cotrufo, 2022; Lessmann *et al.* 2022). Due to this, there is a significant range of mitigation potential related to soil carbon sequestration in grasslands, pasture lands and croplands. There is likewise a large range of mitigation potential related to afforestation, reforestation, agroforestry and improved forest management (see Table 2.5). However, rather than the range depending on technology adoption, this range is more substantially due to the variance in global estimates of the amount of land available for afforestation and reforestation along with the amount of carbon that can be sequestered in these areas (Buma *et al.* 2024). Peatland restoration as a CDR technology suggests that significantly slowing the destruction of forests and peatlands is crucial for any effective carbon storage strategy.

The use of biochar has a significant potential as a method for long-term storage of carbon within agricultural fields while improving productivity but has a relatively low rate of implementation when compared to other types of AFOLU CDR technologies (Weng and Cowie 2025). Future upscaling of this technology could be beneficial in carbon sequestration in combination with other sustainable agriculture land-use practices. "Blue" carbon CDR technologies, in the form of mangrove reforestation as well as seaweed and seagrass carbon sequestration, provide additional pathways to climate mitigation (Bertram *et al.* 2021; Buma *et al.* 2024; Pessarrodona *et al.* 2023; Song *et al.* 2023). While blue carbon shows relatively lower mitigation potential, it has other co-benefits by acting as a natural barrier and reducing wave energy. The relative permanence of sequestered blue carbon is highly variable, as coastal areas are prone to natural disturbances, such as storms, that can release the captured carbon. While the global scale of these pathways is significantly smaller than other types of AFOLU CDR, their use is necessary for short-and long-term carbon sequestration.

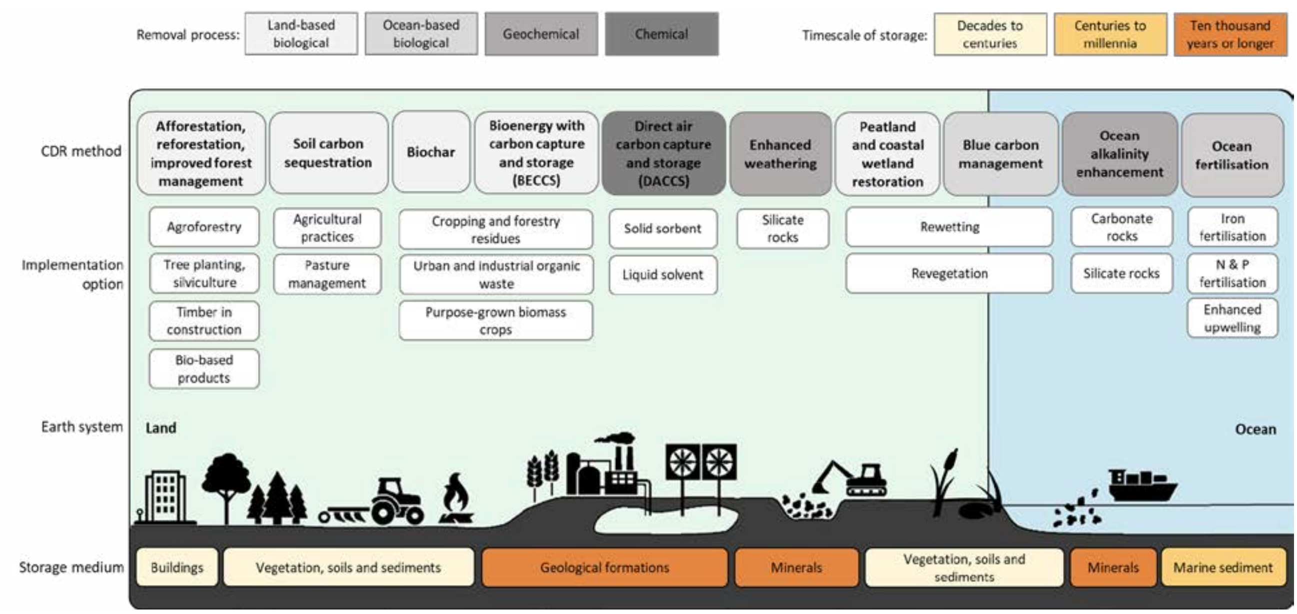
Table 2.5 Technology pathway for Biological based CDR.[7]

Technology options	Mitigation potential (Gt CO_2e/year)	Confidence in tracking mitigation from increased adoption[8]
Afforestation and Reforestation	1.47-5.95[8]	Medium-high
Improved forestry management	0.44-6.61[8]	High
Agroforestry	0.19-3.79[8]	High
Biochar	2.6-10.3[9]	Low-medium
Soil Carbon Sequestration in grasslands and pasture lands	2.38-7.47[10]	Low-medium
Soil Carbon Sequestration in croplands	1.03-1.61[11]	Medium
Peatland restoration	1.1- 2.6[12]	Medium
Mangrove Restoration	0.62-0.75[8]	Medium
Seaweed	0.00-0.62[8]	Low
Seagrass	0.03-0.5[13]	Low

7 Please note, CDR methods here are referring to definition derived from IPCC AR 6.
8 (Buma *et al.* 2024)
9 (Weng and Cowie 2025)
10 (Bai and Cotrufo 2022)
11 (Lessmann *et al.* 2022)
12 (Strack *et al.* 2022)
13 (Bestram *et al.* 2021)

The implementation of sustainable agriculture and land-use CDR technologies must be conducted from a systems perspective, as there could be significant secondary effects to global abiotic and biotic flows inadvertently caused by their use. For instance, large-scale afforestation could influence global water cycles, either mitigating or exacerbating previous effects of climate change. Iterative modelling work is needed to explore the impacts of the large-scale implementation of these technologies. These CDR technologies can also have substantial co-benefits in achieving the United Nations SDGs by improving food security, farmers' incomes and resilience to climate shocks. However, as many of these technologies rely on stakeholders' consistent long-term usage of specific practices, there is a risk that internal and external pressures to change practices will result in the release of the captured carbon. Emphasizing and exploring these co-benefits and risks through modelling and stakeholder involvement will deepen the understanding of the implementation capacity of these CDR technologies. Close attention must be paid to the scientific literature regarding the changing estimated potential of AFOLU CDR technologies, as estimation methodologies are regularly updated as increased data is generated and the scientific literature develops through increased focus on these key sectors. Figure 2.5 depicts the taxonomy of CDR technologies, including natural-based and technological-based options. It should be noted that there is potential overlap between land-based and biomass-based CDR, by considering the same biomass sources (for soil carbon sequestration or biochar allocation) or the same land (for biomass crops for biochar or reforestation allocation).

Figure 2.4 Taxonomy of carbon dioxide removals (Castellanos *et al*. 2022).[14]



2.3.4 Biobased Materials

The transition from fossil-based to bio-based materials represents a key pathway towards decarbonizing industrial systems within the broader bioeconomy. By reducing conventional, fossil-derived inputs with renewable and often biodegradable alternatives, biobased materials offer substantial GHG emission reductions, improved material circularity and the potential for carbon capture and storage within products. Sourced from renewable biological resources such as biomass, agricultural residues and algae that can be replenished over time, biobased materials provide a regenerative alternative to finite fossil-based resources. When managed sustainably, they form the foundation for more circular and resilient material systems.

Beyond simply substituting renewable resources for fossil-based ones, deploying biobased materials within circular practices such as reuse, recovery, regeneration and ecological restoration can help close material and carbon loops, further advancing sustainability. Biobased materials are increasingly

14 The biological and land-based CDRs are all CDR except: DACCS, which is enhanced weathering, ocean alkalinity enhancement and ocean fertilization.

integrated across diverse sectors, offering ways to reduce reliance on fossil-based resources and contribute towards bioeconomy objectives, as illustrated in the following case studies.

- Construction: hempcrete and biochar-infused concrete are emerging as sustainable alternatives to carbon-intensive cement, with the ability to sequester CO_2 within built environments for decades (Lehne and Preston 2022). Other emerging but less commonly discussed examples include cross-laminated timber (CLT), mycelium composites and bio-bitumen.

- Packaging: bioplastics made from starch, polylactic acid (PLA) and polyhydroxyalkanoates (PHA) reduce dependence on petrochemicals and support biodegradability, contributing to lower emissions and packaging waste (Sobeih *et al.* 2025). Other emerging but less commonly discussed examples include cellulose-based films, starch-based packaging and mushroom packaging (Pohan *et al.* 2023; Chen *et al.* 2023; Mohammadian *et al.* 2025).

- Textiles: natural fibres such as hemp, flax and lyocell are being used to replace synthetic fibres such as polyester, resulting in lower production emissions and improved end-of-life sustainability (You *et al.* 2023). Other emerging but less commonly discussed examples include Piñatex (leather alternative from pineapple leaf fibres) and bacterial cellulose.

- Agriculture: the application of biochar to soils improves fertility and supports long-term carbon sequestration, while agricultural residues are increasingly valorized for material production such as fuels, feeds and foods (Chiaramonti *et al.* 2025; Wang *et al.* 2025). Other emerging but less commonly discussed examples include biodegradable mulch films (from starch or PLA), biobased fertilizers (from algae, food waste, compost and other organic waste) and biopesticides (from plant extracts or microbes) (Wang *et al.* 2025).

Integrating biobased materials with circular practices can play a key role in reducing fossil-based inputs and lowering emissions across sectors. However, without systemic shifts such as a move towards closed-loop supply chains, regenerative practices and infrastructures that support material recovery and investing in the development of robust and widely agreed sustainability measurement frameworks, most biobased systems would risk replicating the linear models they are intended to replace. Several gaps needs to be addressed to implement biobased materials: (1) the continued reliance on virgin biomass instead of waste or residue streams; (2) linear life cycles, where biobased materials are often not designed for reuse, repair or high-value recycling; (3) lack of infrastructure for composting, separation or material recovery; and (4) limited integration of ecosystem regeneration and land-use efficiency in biomass production. Addressing these challenges is essential if the bioeconomy is to evolve towards circular and regenerative systems that deliver both climate mitigation and broader sustainability outcomes.

2.4 CONCLUSIONS

This chapter highlights the wide-ranging application of the bioeconomy across agriculture, forestry, energy, land use, industry and the waste sector. Several biobased technologies are already mature, such as climate adaptation measures and biomass conversion, while others, including BECCS and biobased materials, show strong potential for future deployment. CDR technologies are at varying stages of maturity and offer diverse levels of mitigation potential.

Biomass conversion technologies

- Biomass to gas: Anaerobic digestion is commercially mature at scale; gasification shows promise but remains limited by cost and complexity.
- Biomass to liquid products: Some technologies (e.g. transesterification, HEFA) are mature but scaling demands lower costs, stable feedstocks and green hydrogen.
- Biomass to solid fuels: Mature for power generation. Biochar use is growing, with scale-up reliance on regulatory support and co-benefit recognition.

Carbon sequestration and utilization technologies

- Reducing reliance on fossil-based carbon by using biogenic carbon is increasingly viewed as a promising pathway for decarbonization. However, scalability remains a significant challenge. Key factors that hinder progress include sustainable biomass sourcing, upgraded infrastructure and significant investment.
- The IPCC AR6 estimates that to limit warming to 1.5 degrees Celsius, cumulative CDR from BECCS and DACCS must reach 30–780 Gt CO_2 and 0–310 Gt CO_2, respectively, by 2100. Currently, only 2 Mt of biogenic CO_2 is captured annually, mostly from bioethanol, and existing Bio-CCUS efforts fall short of what is needed for the 2050 net zero emissions scenario.
- BECCS is often positioned as a leading CDR option due to its potential for large-scale, durable carbon storage. However, its promise is tempered by challenges around sustainable biomass availability, land competition and infrastructure requirements.
- BECCS should be seen as one part of a broader portfolio of land-based and biologically driven CDR approaches. Other nature-based solutions including afforestation and reforestation, agroforestry, improved forest management, biochar

application and soil carbon sequestration in grasslands and pasture lands, offer substantial mitigation potential.

- These approaches can provide more immediate co-benefits for biodiversity, livelihoods and resilience, while avoiding some of the scale-related constraints of BECCS. Current estimates suggest that, depending on the technology and context, land-based CDR could contribute between 0.5 and 10.7 $GtCO_2e$ per year.

Sustainable agriculture and land-use technologies

Sustainable agriculture and land-use technologies are critical for improving land productivity, enhancing carbon sinks, reducing emissions from agriculture and increasing the resilience of food systems to climate change.

- The AFOLU sectors are both a major source of greenhouse gas emissions and a key area for implementing CDR technologies.
- Afforestation and reforestation offers the highest mitigation potential among biological CDR approaches, yet their effectiveness is constrained by land availability, long-term permanence and variability in carbon sequestration estimates.
- Agroforestry and improved forest management also hold considerable promise but require supportive land-use governance and monitoring frameworks.
- Despite its potential, the deployment of biochar remains limited, highlighting the need for greater investment and policy support. Overall, expanding and protecting natural carbon sinks through integrated land-use strategies will be essential to meeting global climate goals.
- In the agriculture sector, climate intervention technologies such as biofertilizer production tools, pesticide management and water irrigation systems have been identified as tools to reduce the climate risk impact in the agriculture products. In the energy domain, technological advancements such as SAF show strong potential for reducing GHG emissions.

Biobased materials

- Most bioeconomy applications today remain linear, using renewable inputs without fully closing material or carbon loops
- Emerging uses include biochar-infused concrete and hempcrete in construction, which can store carbon over long periods, and bioplastics in packaging, which help reduce petrochemical use and plastic waste.
- Key barriers to scaling biobased materials include a continued dependence on virgin biomass rather than waste or residues, limited circularity in product lifecycles, inadequate systems for composting and material recovery, and poor alignment with regenerative land-use practices.


Photo: Pexels

CHAPTER HIGHLIGHTS

- The bioeconomy encompasses a broad spectrum of biobased technologies, each with distinct feasibility profiles depending on context, scale, and feedstock. This assessment focuses specifically on bioenergy technologies as a key segment within the broader bioeconomy.

- Biogas from waste streams offers strong synergies across mitigation, adaptation, and the SDGs. First-generation biofuels are mature but raise land-use, biodiversity, and food security concerns, requiring safeguards. Second-generation options offer improved environmental performance, though cost and logistics remain challenges.

- Waste-based biogas stands out as the most viable of the assessed bioenergy technologies, delivering strong mitigation and adaptation outcomes alongside significant socio-environmental co-benefits.

- Advanced biofuels like algal fuels and biohydrogen hold long-term promise but are currently constrained by high costs and low technical readiness. Meanwhile, conventional liquid biofuels (e.g., ethanol and biodiesel) often face feasibility challenges due to land-use pressures and sustainability concerns.

- Integrating bioenergy technologies into broader energy systems is essential for enhancing climate resilience and energy security. The dispatchability and system integration potential of solid, liquid, and gaseous bioenergy enable flexible storage, logistics, and blending with existing infrastructure, particularly gas systems.

- Bioenergy and biomass strategies should be pursued as part of an inclusive, just, and low-emission transition, aligned with the Paris Agreement and the Sustainable Development Goals, especially in support of Indigenous Peoples and marginalized communities.

- There is strong regional variation in the feasibility and deployment of bioenergy technologies. In developing economies, there is an urgent need to transition from traditional biomass to cleaner, modern bioenergy pathways aligned with climate-resilient development.

- In rural areas of developing countries, simple and decentralized bioenergy technologies, such as biogas, improved cookstoves, and biomass briquettes, demonstrate high feasibility and deliver strong co-benefits for health, livelihoods, and climate resilience.

- Achieving scale and equitable outcomes depends on institutional feasibility, which varies across contexts and technologies, and requires alignment with national policy frameworks, climate finance mechanisms, and clear governance arrangements.

3.

Feasibility of Deployment and Scaling of Biobased Technologies

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3.1 INTRODUCTION AND FRAMING

This chapter evaluates the feasibility of biobased technologies for climate adaptation and mitigation. Specifically, it assesses biobased technologies within the areas of biomass conversion, focusing on bioenergy in the area of sustainable agriculture and land use such as agroforestry and forest-based adaptation (FbA), and on biobased materials such as bioplastics and wood for building materials (See Appendix 1, Box 1, FA on biomaterial in buildings). The technologies are selected to reflect the competing demands on landbiodiversity, food production, nature-based solutions, and carbon dioxide removal as outlined in the rationale in Chapter 1. Building on previous CTPRs and the Sixth Assessment Report from the IPCC, this chapter provides a feasibility assessment of these biobased technologies at global and regional scales. The analysis highlights differences in feasibility profiles across regions, reflecting divergent resource endowments, institutional capacities and socioeconomic contexts.

The chapter is structured around a system transitions framework that links adaptation and mitigation responses to the sociotechnical transitions required to reduce emissions and generate the socio-ecological resilience needed to reduce vulnerability. Biobased technologies interact with broader transitions in energy, agriculture, water, land use and health systems, as well as with social transitions in equity and justice. This approach helps illuminate both synergies (e.g. biogas simultaneously mitigating methane, reducing indoor air pollution and improving gender equity) and trade-offs (e.g. biofuels competing with food production or biodiversity conservation). The system transitions framework is critical to understanding the role of technologies in achieving the more fundamental transformation needed to develop climate resilience.

3.2 FEASIBILITY ASSESSMENT FRAMEWORK

3.2.1. Technology portfolios

In order to conduct a regional and global level assessment, biobased technologies are assessed as follows:

1. Biomass conversion in rural contexts in developing countries to address energy poverty and regional assessments of biomass conversion for biofuel or electricity production, including distributed generation applications.
2. Sustainable agriculture and land use at the regional level, including biobased technologies within agroforestry and Forest-based adaptation (FbA).
3. Biobased materials at the global level, namely bioplastics and the use of biobased materials (e.g. biomaterials for the building sector).

3.2.2 Approach

This chapter employs the well-established "feasibility assessment" methodology which first appeared in IPCC Special Report on Global Warming at 1.5C published in 2018, which developed a multidimensional approach to assess "the degree to which climate goals and response options are considered possible" (IPCC 2018). See Appendix 3 (separate file, available online) for full details on how the feasibility assessment approach was applied in this chapter. In this methodology, the critical dimensions of feasibility are first identified and then the performance of the technologies on indicators that capture key elements of these dimensions are evaluated (Singh *et al.* 2020). This approach has been recognized as a useful tool for decision-making as it provides feedback about which technologies are immediately feasible, allowing technologies to be prioritized for funding and implementation as well as providing a clear indication of where the barriers or knowledge gaps are regarding technologies that may be less feasible, allowing for a specific consideration of what it would take to improve this feasibility. Feasibility will be assessed for a global warming level of 1.5 degrees Celsius.

The feasibility approach taken here follows those detailed in a number of previous studies (IPCC 2022b; UNEP CCC 2024; UNEP-CCC 2023; UNEP-CCC 2024). Feasibility is not static. Technologies may become more or less feasible over time as costs fall, climate change, climate and other policies, and institutional capacities evolve. The feasibility assessment framework is therefore both diagnostic and forward-looking. It identifies which technologies are feasible today, which face constraints that could be addressed through enabling conditions and which remain speculative without further research and development.

For each of the biobased technologies identified, reviews of the literature published after the release of the AR6 were conducted. The literature for this feasibility assessment is primarily scoped as building on the AR6 with updates between the literature cut-off dates for Working Group II (WGII) and Working Group III (WGIII,) and August 2025. The objective was to determine whether there were any significant changes in the feasibility scoring beyond the comprehensive assessment completed in AR6. Rather than undertaking a full systematic review, we carried out a targeted scan of the peer-reviewed literature to identify major updates and any systematic reviews that had already been published. Consequently, if a technology received the same score as in AR6, this indicates that no clear evidence of a shift in the literature was found. In cases where the assessment concluded that the score had not changed but stronger supporting evidence was available (for example, through a systematic review published post-AR6), this was reflected in the scoring of robustness and strength of evidence.

It is important to note that the WGII and WGIII reports adopted different approaches to scoring technologies. WGII followed the methodology introduced by the IPCC, which applied a single overall score for feasibility (IPCC 2018). In contrast, WGIII assessed increasing and decreasing aspects of feasibility separately, arguing that decision makers should be able to evaluate both supportive and unsupportive elements of a given technology. However, the WGII single-score approach is often more straightforward to interpret for screening and comparing across multiple technologies. For this reason, in this chapter we adopt the WGII approach, while retaining the details of scoring in the text (see Appendix 3 for more details on the scoring and the selected dimensions).

In the case of the selected biobased technologies, some were not explicitly scored in AR6. However, certain aspects of the bioeconomy were considered under related technology groupings, such as those within circular economy frameworks. Where possible, we draw on the same references used in AR6. In addition, we incorporate insights from more recent literature assessed in the IPBES Nexus Assessment (IPBES 2024). Taken together, these sources allow us to evaluate whether sufficient evidence exists to proceed with a feasibility assessment and scoring.

3.3 FEASIBILITY ASSESSMENT RESULTS

Box 3.1: Ecoregional dimension

A biobased economyincluding bioenergy, biomaterials for construction, and bioplastics primarily depends on biomass availability across the world's ecoregions. This reliance involves key geophysical factors such as solar radiation, rainfall, soil fertility, and average temperature, all of which are unevenly distributed. Moreover, climate change affects the feasibility of biobased technologies, as biomass production is closely tied to climate dynamics. Accurate feasibility assessments must consider the specific characteristics of each ecoregion. For example, wood biomass shows strong potential in tropical forests but may disrupt fragile soils and ecosystems. In arid and semi-arid regions, water scarcity and deforestation risks limit feasibility. Boreal areas offer moderate potential: although low temperatures slow tree growth, the extensive forested landscapes partly compensate. Similarly, biogas performs best under wet digestion conditions (solid content < 15%), making it difficult to operate in dry climates though higher temperatures in such regions can favour the process (Trimble and van Aarde 2012).

Photo: Pexels

Table 3.1 Feasibility results

FA results for Mitigation

Feasibility Dimensions	Technology	Biogas	Bioethanol First-generation	Bioethanol Second-generation	Biodiesel	Algal fuels	Wood and solid fuels	Bio-hydrogen	Municipal Solid Waste and biodigesters	Biomass conversion with and without Combined Heat and Power	Bioplastic	Agroforestry	Biomaterials for buildings
	Overall feasibility across dimensions	High	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium
Geophysical	Physical potential	High	Low	Medium	Medium	High	Medium	High	High	High	N/A	High	High
	Geophysical resources	High	Low	Medium	Medium	Low	Medium	Medium	N/A	Low	Medium	N/A	High
	Land use	High	Low	Medium	Low	High	Low	Low	High	LE	Medium	High	Medium
Environmental-ecological	Air pollution	High	Medium	High	Low	High	Low	High	LE	LE	High	High	Medium
	Toxic waste, ecotoxicity eutrophication	High	Low	Medium	Low	Low	High	Medium	N/A	N/A	Low	High	Low
	Water quantity and quality	High	Low	Medium	Low	Low	Medium	Medium	N/A	LE	Medium	High	Low
	Biodiversity	High	Low	Medium	Low	Medium	Low	Low	Low	Low	Medium	Medium	Low
Technological	Simplicity	High	Medium	Low	High	Low	High	Low	Medium	Medium	Medium	High	High
	Technological scalability	Medium	Medium	Low	Medium	Low	Medium	Medium	High	High	High	Medium	High
	Maturity and technology readiness	High	High	Medium	High	Low	High	Medium	Medium	Medium	High	High	High
Economic	Costs in 2030 and long term	Low	Medium	Medium	Medium	Low	Medium	Medium	Medium	LE	Low	Medium	LE
	Employment effects and economic growth	High	Medium	High	High	Medium	Medium	High	Medium	Medium	N/A	Medium	N/A
Socio-cultural	Public acceptance	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Medium	High	Medium	Medium
	Social co-benefits	High	Medium	High	Medium	High	Low	High	Medium	Medium	Medium	High	LE
	Social and regional inclusiveness	Medium	Low	Medium	Low	Medium	Low	Medium	N/A	N/A	Medium	N/A	N/A
Institutional	Political acceptance	High	High	High	High	Medium	Medium	High	Medium	Medium	Medium	Medium	Medium
	Institutional capacity, governance, cross-sectoral coordination	Medium	Medium	Medium	Medium	Low	Low	Medium	Low	Low	Medium	Medium	Medium
	Legal and administrative capacity	High	Medium	Medium	Medium	Medium	Low	Medium	Low	Low	Medium	Medium	Medium

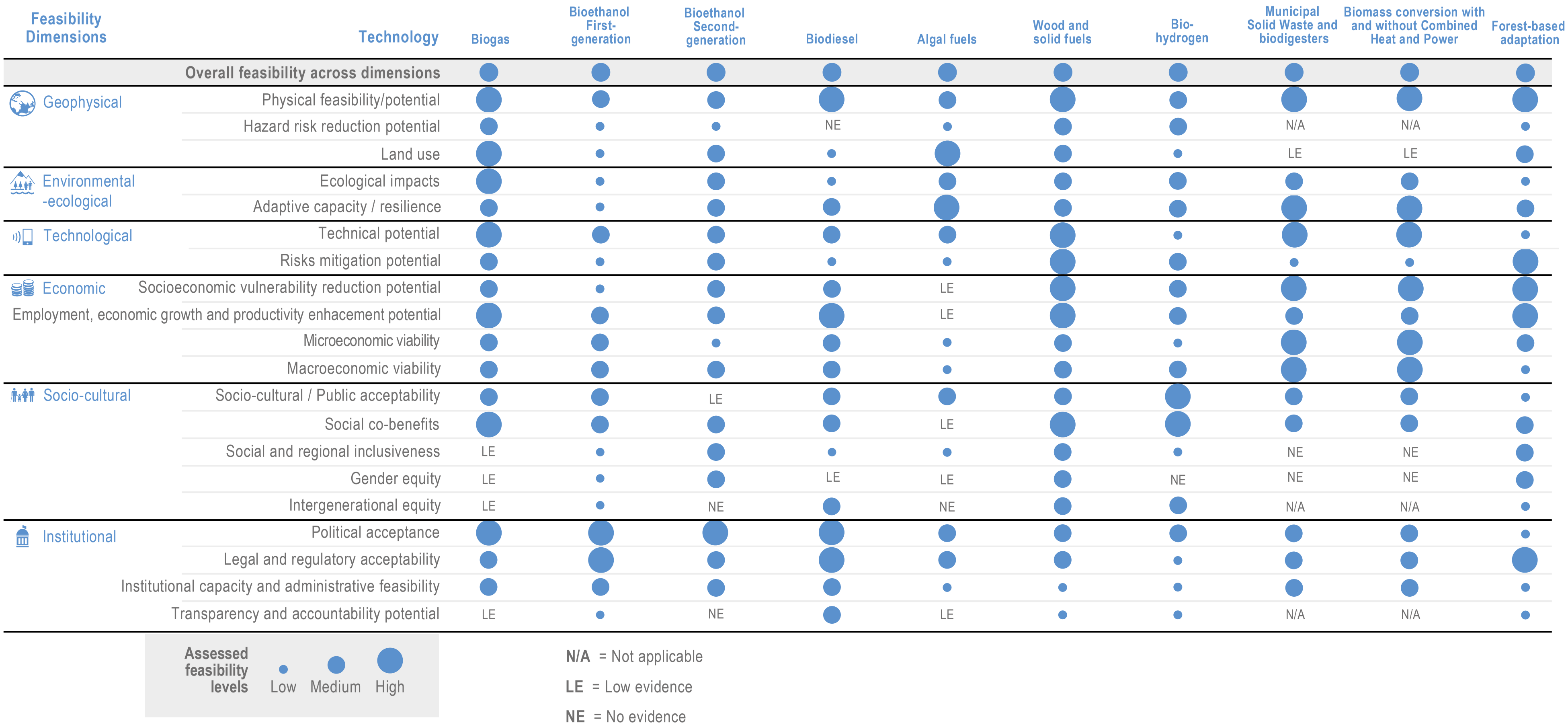
Assessed feasibility levels: Low, Medium, High

N/A = Not applicable

LE = Low evidence

NE = No evidence

FA results for Adaptation



FA results for Adaptation, Africa

Feasibility Dimensions	Technology	Biomass briquette / agroforestry technologies	Improved biomass cookstoves	Biogas digesters
	Overall feasibility across dimensions	Medium	Medium	Medium
Geophysical	Physical feasibility/potential	Medium	High	High
	Hazard risk reduction potential	Medium	Medium	Medium
	Land use	Medium	LE	Medium
Environmental -ecological	Ecological impacts	High	Medium	Medium
	Adaptive capacity / resilience	High	High	Medium
Technological	Technical potential	Low	Low	Low
	Risks mitigation potential	Medium	Medium	Medium
Economic	Socioeconomic vulnerability reduction potential	High	LE	Medium
	Employment, economic growth and productivity enhacement potential	High	LE	Medium
	Microeconomic viability	High	High	Medium
	Macroeconomic viability	Medium	High	Medium
Socio-cultural	Socio-cultural / Public acceptability	Low	Medium	Low
	Social co-benefits	Medium	LE	High
	Social and regional inclusiveness	Low	Medium	Low
	Gender equity	Medium	Medium	LE
	Intergenerational equity	Medium	Medium	LE
Institutional	Political acceptance	Medium	Medium	Low
	Legal and regulatory acceptability	Low	Low	Low
	Institutional capacity and administrative feasibility	Low	Low	Low
	Transparency and accountability potential	Low	LE	Low

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable
LE = Low evidence
NE = No evidence

FA results for Mitigation, Biomass

Feasibility Dimensions	Technology	Biomass Conversion with & without CHP (Global)	Biomass Conversion with & without CHP (Africa)	Biomass Conversion with & without CHP (Latin America)
	Overall feasibility across dimensions	Medium	Medium	Medium
Geophysical	Physical feasibility	High	High	N/A
	Hazard risk reduction potential	N/A	N/A	N/A
	Land use change enhancement potential	LE	Low	Medium
Environmental -ecological	Ecological capacity	Medium	High	Medium
	Adaptive capacity / resilience	High	High	Medium
Technological	Technical resource availability	High	High	Medium
	Risks mitigation potential	Low	LE	Low
Economic	Socioeconomic vulnerability reduction potential	High	High	LE
	Employment and productivity enhancement potential	Medium	High	Medium
	Microeconomic viability	High	Low	LE
	Macroeconomic viability	High	High	LE
Socio-cultural	Socio-cultural acceptability	Medium	Low	N/A
	Social co-benefits (health, education)	Medium	High	LE
	Social and regional inclusiveness	N/A	High	LE
	Gender equity	N/A	Low	N/A
	Intergenerational equity	N/A	N/A	N/A
Institutional	Political acceptability	Medium	Medium	N/A
	Legal and regulatory acceptability	Medium	Low	LE
	Institutional capacity and administrative feasibility	Medium	LE	LE
	Transparency and accountability potential	N/A	LE	LE

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable
LE = Low evidence
NE = No evidence

FA results for Mitigation, Municipal Solid Waste & Biodigesters

Feasibility Dimensions	Technology	Municipal Solid Waste (Global)	Municipal Solid Waste and biodigesters (Africa)	Municipal Solid Waste (Latin America)
	Overall feasibility across dimensions	Medium	Medium	Medium
Geophysical	Physical potential	High	High	High
	Geophysical resources	N/A	High	N/A
	Land use	High	N/A	High
Environmental-ecological	Air pollution	LE	High	High
	Toxic waste, ecotoxicity eutrophication	N/A	N/A	Medium
	Water quantity and quality	N/A	N/A	N/A
	Biodiversity	Low	High	N/A
Technological	Simplicity	Medium	LE	Low
	Technological scalability	High	High	High
	Maturity and technology readiness	Medium	High	High
Economic	Costs in 2030 and longterm	Medium	Medium	N/A
	Employment effects and economic growth	Medium	High	Low
Socio-cultural	Public acceptance	Medium	Medium	N/A
	Effects on health and well-being	Medium	High	High
	Distributional effects	N/A	High	N/A
Institutional	Political acceptance	Medium	Medium	LE
	Institutional capacity, governance, cross-sectoral coordination	Low	Low	N/A
	Legal and administrative capacity	Low	Low	LE

Assessed feasibility levels: Low, Medium, High

N/A = Not applicable
LE = Low evidence
NE = No evidence

3.3.1 Biomass conversion

The assessment of biobased technologies for biomass conversion, focuses on solutions that can offer promising solutions for sustainable development, particularly in addressing energy poverty in rural contexts of developing countries. In parallel, a regional assessment is carried out for the feasibility of biofuel and bioelectricity production. Such assessments help identify suitable feedstocks, optimize supply chains and support distributed generation applications, which decentralize energy production and enhance energy access and resilience. Together, these approaches contribute towards climate mitigation, rural empowerment and energy equity. Nevertheless, all biobased technologies rely on biomass production, which can be influenced by climate change, positively or negatively, thus raising critical sustainability challenges for long-term resource availability (See Box 3.1).

Biobased technologies for energy poverty

Biogas and digesters

Biogas production is consistently feasible in rural contexts, particularly when based on livestock manure, crop residues and municipal organic waste. It provides strong synergies between mitigation and adaptation by reducing methane emissions, improving energy access and supporting agricultural systems. Affordability, maintenance and coherent policy frameworks remain important constraints (Sibanda and Uzabakiriho 2024; Rasimphi *et al.* 2024). From a resource perspective, animal manure and agricultural residues can sustain small-scale digesters that supply household cooking fuel and strengthen local energy resilience. Adoption drivers include residue availability and farm characteristics. Digesters designs are available across climates and rural settings. Larger facilities can integrate with power systems but face reliability, operation and maintenance challenges that require skilled operation (Gbadeyan *et al.* 2024). Household digesters can achieve reasonable payback when subsidies and credit reflect avoided fuel and fertilizer costs, with studies reporting around three-to-seven-year ranges depending on context (Geddafa *et al.* 2023; Ketuama *et al.* 2024). Social acceptance is often shaped by peer effects and trust. For example, farmers are more likely to adopt when neighbours demonstrate successful use and when they receive information through trusted networks, while training and after-sales support are important for sustained operation (Zeng *et al.* 2022). Institutionally, political and legal acceptance is improving where clear biomethane frameworks and standards are emerging and capacity-building helps address administrative and coordination gaps (Guerra-Mota and Aquino 2024; Vidigal *et al.* 2025).

Environmental performance is strong when systems are well managed. Anaerobic digestion captures methane from waste streams, displaces fossil fuels and provides nutrient-rich digestate that improves soils, although nutrient losses can arise from poorly managed digestate and performance limits in arid conditions (Tolessa 2024; Ngetuny *et al.* 2025). There can also be positive land-use interactions when systems valorize wastes and manage cropping changes carefully. Biogas facilities can also contribute to reducing hazard risks in waste and sanitation contexts when paired with appropriate controls (De Laurentiis *et al.* 2024; Levavasseur *et al.* 2023; Ahmad *et al.* 2022).

Improved biomass cookstoves (ICS)

Improved biomass cookstoves enhance combustion efficiency, reducing the amount of fuel needed and lowering greenhouse gas emissions. These pollutants contribute significantly to climate change. By using cleaner and they are more efficient stoves, households also reduce deforestation and forest degradation caused by unsustainable wood harvesting, further supporting climate mitigation efforts. Simple, locally manufacturable designs work across diverse contexts, but durability, user training and after-sales support are critical to sustaining performance and avoiding the concurrent use of multiple stoves, a practice known as "stove stacking". Households typically save money and time, especially when upfront costs are eased through subsidies, microfinance or pay-as-you-go models and supply chains are reliable (Philip *et al.* 2023; Ankel-Peters *et al.* 2025).

From a technological standpoint, ICS are mature and scalable, with simple constructions using clay or metal that can be adapted to local cooking practices. However, sustained performance depends on durability, after-sales support and limiting stove stacking (Jagoe *et al.* 2020). Economic evidence indicates household savings from reduced fuel purchase and collection time. At programme level, analyses have found energy-efficient biomass stoves to be cost-effective in several African contexts and potentially "pro-poor" relative to alternatives when well targeted (Bensch *et al.* 2024; Ankel-Peters *et al.* 2025).

Institutionally, feasibility improves where governments and partners combine standards and quality assurance with long-term programme coordination and consumer protection. Weaker standards and fragmented delivery undermine trust and contribute to stove stacking (Mperejekumana *et al.* 2024; Jagoe *et al.* 2020). Sociocultural feasibility hinges on cultural fit (pot sizes, staple foods) and gendered time burdens. Adoption and sustained use rise when stoves meet local cooking needs and women's preferences. Documented co-benefits include improved indoor air quality and significant time savings for women and girls (Jagoe *et al.* 2020; Zulu *et al.* 2024.

Field syntheses and intervention studies across sub-Saharan Africa show that, when correctly used, ICS lower fuel consumption and reduce exposure to $PM_{2.5}$ and CO compared with three-stone fires, though real air-quality gains vary by design, setting and user behaviour (Phillip *et al.* 2023). Improved combustion reduces direct emissions and can ease pressure on nearby forests when ICS displace open fires at scale. The benefits are strongest where correct, consistent use is achieved and where programmes align designs with local fuels and dishes (Phillip *et al.* 2023; Matavel *et al.* 2022).

Biomass briquettes

Biomass briquettes are an increasingly relevant charcoal alternative in urban and peri-urban settings. They have medium to high feasibility both technically and economically, as briquettes can scale as a charcoal substitute where standards, distribution and working-capital access are in place. Environmental and health benefits are achievable but depend on consistent quality and user practices.

Briquettes are produced by densifying residues such as sawdust, rice husks and agri-processing wastes that might otherwise be burned in the open or left to decompose. Reviews and feasibility studies show strong technical viability and clear routes to product quality through binder choice, densification pressure and moisture control (Yunusa *et al.* 2024; Sweya and Saitoti 2024). Production pathways range from manual presses to semi-industrial extrusion systems. Compatibility with existing charcoal stoves typically eases adoption, but consistent density, moisture and heating value require attention to standards and process control (Kpalo *et al.* 2020).

In terms of economics, technical and economic assessments have found that briquettes can be cost-competitive against charcoal and other household fuels when supply chains are efficient and when feedstocks and binders are sourced reliably (Kpalo *et al.*, 2022; Bot *et al.* 2022). In conflict-affected and low-income contexts, briquettes can be introduced as a practical cooking fuel where charcoal is costly and wood harvesting is constrained (Waziri *et al.* 2024). However, high logistical costs for bulky feedstocks and finished products remain a constraint in dispersed markets.

From an environmental and health perspective, briquettes can reduce unmanaged residue burning and, when well-made and properly used, can reduce exposure to household pollutants relative to traditional fuels. However, emission performance varies with raw materials, binders and stove–fuel matching (Yu *et al*. 2022; Adeeyo *et al*. 2022). This underscores the need for product testing, ventilation guidance and user education alongside market development.

Biomass conversion for biofuels and electricity

Second generation ethanol

Second generation ethanol (2G) is viable where projects secure reliable feedstock logistics, high utilization rates and stable offtake agreements. Its feasibility is strengthened when residue hubs are dependable and when policy frameworks support integrated deployment (Zanivan *et al*. 2021).

Derived from lignocellulosic residues and organic wastes, 2G demonstrate moderate technological and economic feasibility, but tends to higher on environmental-ecological, geophysical and sociocultural feasibility, consistent with residue-based sourcing that can temper land-use pressure and align with agroprocessing value chains (Calvin *et al*. 2021; Løvenskiold *et al*. 2022).

Cost structures in 2G production, costs are dominated by feedstock logistics and plant utilization. Where sugar-rich residues are available nearby, effective feedstock costs decline, and operational stability improves. These advantages narrow with longer haul distances or intensive preprocessing (Scapini et al. 2023). Integration and optimization work indicates that process integration and advanced modelling can materially shift viability in lignocellulosic systems (Park *et al.* 2024; Pradhan *et al.* 2022; Wang *et al.* 2022). For environmental, geophysical and land use, 2G ethanol offer clear potential to ease land-use pressure compared to dedicated crops, provided residue supply chains are well managed and counterfactual land-use choices are addressed (Calvin *et al.* 2021; Løvenskiold *et al.* 2022). Life cycle emissions (LCA) further suggest significant emission benefits when supply chains and effluent management are robust (Patel *et al.* 2024). For 2G, sociocultural and inclusiveness benefits arise where projects integrate with local residue streams and agroprocessing employment, though these gains depend onexplicit social and safety criteria across the value chain (Messmann *et al.* 2023). Broader supply-chain studies underscore that scaling trajectories are shaped not only by sustainable resource availability but also by institutional governance conditions. (Nandi *et al.* 2023).

Biodiesel

Biodiesel is technologically mature and operationally scalable provided that consistent lipid feedstocks are available. The economics of its use depend on feedstock costs and logistics as well as utilization, while environmental performance is strongest for waste-oil routes with robust emissions and by-product management. Policy coherence (standards, collection, traceability and offtake) needs to be improved to sustain feasibility at scale.

Biodiesel via transesterification of vegetable oils, used cooking oils and animal fats is technologically mature and widely deployable. Economic feasibility is moderate and hinges on feedstock price and logistics, conversion scale and utilization. Waste-oil routes can reduce input costs where dense collection networks exist, whereas dispersed suppliers and long-haul collection erode margins. System-integration and optimization studies show that improved process coupling and network design can materially shift viability, reinforcing the role of conversion and supply-chain alignment and steady offtake in project economics (Park *et al.* 2024).

From a geophysical standpoint, production sites are suitable wherever lipid streams are steady, with feasibility being shaped by collection density, seasonality and with hazard controls (flammables, methanol) being embedded in plant design and approval (Xue and Zhao 2023; Saurabh and Majumdar 2023). Environmental and ecological feasibility depends on the technical pathway. Pathways based on used oils and residual lipid can avoid unmanaged waste flows and reduce lifecycle burdens, provided that production sites manage air and wastewater emissions and ensure methanol and catalyst handling. By-product valorisation indicates opportunities to improve overall system footprints by integrating side streams (Yang *et al.* 2023).

Institutional feasibility is moderate as there is a need for clear blending standards (e.g. B5–B20), fuel-quality specifications, traceability/collection rules and routine permitting underpin bankability. Where these are fragmented, project risks rise. Sociocultural feasibility trends are positive where waste-oil collection creates local jobs, reduces informal disposal and aligns with existing diesel uses in agriculture and transport. Distributional outcomes and inclusiveness depend upon who captures value along the collection-processing–retail chain and upon explicit attention being paid to social criteria during system design (Polat and Altınbaş 2023).

Biodigesters and municipal solid waste

Anaerobic digestion and valorization of municipal solid waste (MSW) into biogas and other by-products (e.g. compost, bioethanol, biomethane) offer significant mitigation and adaptation synergies. They address waste management challenges, reduce methane from landfills and contribute towards generating renewable energy. LCAs show strong environmental benefits when waste segregation and collection systems are effective (De Laurentiis *et al.* 2024; Dadario *et al.* 2023).

Technological feasibility is mature for anaerobic digestion, composting and waste-to-energy routes, although performance depends on consistent waste streams and effective pre-sorting (Islam *et al.* 2024). Economic feasibility improves in urban contexts with high waste density, economies of scale and supportive feed-in tariffs or renewable energy incentives. In contrast, dispersed or informal waste systems raise costs and erode viability. MSW facilities are best situated near urban waste sources to minimize transport emissions. Risks include odour, leachate and air pollution if facilities are poorly managed. When coupled with robust monitoring and environmental controls, MSW valorization contributes to circular economy strategies and aligns with climate-resilient urban development (Levavasseur *et al.* 2023; Islam *et al.* 2024).

Institutionally, feasibility hinges on waste governance. Clear standards for segregation, collection and renewable energy integration reduce risks and attract investment (Park 2025). In practice, weak enforcement of segregation and collection standards makes governance not only an enabler but also a limiting factor for project viability (Park and Grundmann 2025). Co-benefits include improved sanitation, reduced open burning and job creation in the collection and processing sectors. Social acceptance is positive where systems reduce urban waste burdens, although equity depends on including informal waste pickers in formalized systems (Tisi *et al.* 2023).

While globally feasibility is moderate with clear benefits in circular economy frameworks, scaling requires stronger waste governance and policy integration. Regional differences persist. In African contexts, MSW and biodigesters offer strong mitigation potential due to high methane reduction and waste valorization opportunities, although institutional and financial gaps constrain scaling (Tolessa, 2023; Robin and Ehimen, 2024). A further technical challenge in African is the low calorific value of the organic fraction due to high moisture content, which reduces digestion yields and increases operational costs. In Latin America, the feasibility is more moderate. Large urban centres provide advantages linked to density and strong geophysical potential, but fragmented governance and uneven waste segregation reduce institutional feasibility (Dadario *et al.* 2023).

3.3.2 Sustainable agriculture and land use

Agroforestry

Agroforestry is one of the most feasible bioeconomy options across multiple dimensions. Its environmental, social and economic benefits are well documented, with relatively few trade-offs where land tenure is secure and institutions support farmer participation and value-chain links (Tagwi *et al.* 2023). It is regionally salient across Africa and Asia and is gaining recognition through policy and restoration initiatives as part of broader resilience strategies. Agroforestry offers high environmental, economic and social feasibility, with the principal constraints arising in scaling logistics (seedlings, nurseries, aggregation) rather than core technical limits (Bogale and Bekele 2023).

Agroforestry is the deliberate integration of trees and shrubs into croplands and pastures. It is one of the most promising strategies for combining mitigation, adaptation and development. From a resource standpoint, it extends from semi-arid drylands to humid tropics, with species and practices selected to match local soils and climates (Kuyah *et al.* 2023). Native or naturalized species can be matched to conditions and management goals, often with lower external inputs than monocultures when systems are appropriately designed.

Agroforestry is relatively low-tech and frequently builds on Indigenous and local knowledge of tree management, pruning and intercropping. Barriers lie less in core technical feasibility than in scaling. Bottlenecks in seedling supply, nursery capacity, extension services and farmer linkages to energy and bioeconomy value chains constrain adoption and market formation (Bogale and Bekele 2023; Tagwi *et al.* 2023). Benefits accrue both directly (timber, fuelwood, fruits, nuts, poles) and indirectly through reduced input needs, improved crop microclimates and soil function, and more stable incomes via diversification. Although returns can be delayed by tree growth cycles, longer-term net gains and resilience benefits are consistently observed (Bogale and Bekele 2023).

Institutional and governance frameworks strongly shape outcomes. Evidence emphasizes that clear rules, supportive extension and value-chain participation for smallholders increase transparency and long-term sustainability. Conversely, insecure land rights and fragmented governance suppress adoption and limit inclusion (van Noordwijk 2023; Tagwi *et al.* 2023). Social outcomes include strengthened household food security and diversified livelihoods in circular, farm-centred systems, with inclusiveness shaped by how programmes engage smallholders in bioenergy and tree-product markets (Nkansah-Dwamena 2024; Tagwi *et al.* 2023).

Agroforestry systems sequester carbon above and below ground, improve soil organic matter and regulate microclimates via shade and lower evapotranspiration (Sambou *et al.* 2024). Co-benefits include erosion control, water retention and enhanced habitat connectivity, while pruning and residues can supply household energy or local bioenergy value chains (García-López *et al.* 2024). In African drylands, farmer-managed natural regeneration and related practices increase drought resilience and contribute towards mitigation, provided that this management aligns species, density and farmers' objectives (Kuyah *et al.* 2023; Bogale and Bekele 2023).

Forest-based adaptation

FbA is a highly feasible strategy that integrates adaptation and mitigation with ecosystem and livelihood co-benefits, provided that land and resource rights are secure, participation is genuine and finance is available for upfront establishment and management. Evidence from policy syntheses and programme reviews shows that FbA is already embedded in many national and subnational strategies and is gaining momentum through nature-based solutions and restoration initiatives (Libert-Amico *et al.* 2022; Hallberg-Sramek *et al.* 2022; Restrepo *et al.* 2024).

FbA encompasses measures that enhance forest resilience and leverage ecosystem services, including reforestation, assisted natural regeneration, adaptive silviculture and conservation. Advances in climate-smart forestry and adaptive management provide practical pathways for integrating mitigation and adaptation in operational forestry, particularly where agencies and landholders apply risk-aware silviculture, diversified species mixes and monitoring to guide treatment over time (Hallberg-Sramek *et al.*,2022). Recent work on optimizing restoration shows that spatially explicit planning can deliver multiple benefits with minimal trade-offs when objectives (e.g. carbon, water, biodiversity, livelihoods) are designed jointly (Gopalakrishna *et al.* 2024). In lower-income contexts, bottlenecks include seed/seedling supply, extension capacity and finance, but inclusive models, such as community forest management aligned with climate programmes, strengthen implementation and benefits (Libert-Amico *et al.* 2022; Hytten and Pearson, 2025).

FbA can be tailored across humid and dry regions using locally adapted species and silvicultural systems, with co-benefits for microclimate regulation, water retention, soil stability and biodiversity (Hallberg-Sramek *et al.* 2022; Restrepo *et al.* 2024). Where agroforestry mosaics and tree-based systems are part of the landscape, FbA measures further reduce production risks from climate extremes and can enhance farm-level adaptation when designed with farmers and local institutions (Dobhal *et al.* 2024; Libert-Amico *et al.* 2022).

Economic and institutional feasibility is strongest where policy coherence (e.g. climate-smart forestry frameworks, restoration strategies), clear governance arrangements and stable funding are in place. Analytical reviews indicate that FbA interventions often exhibit favourable favourable cost-benefit profiles once ecosystem services and risk reduction are valued. However, projects remain sensitive to upfront costs, long time horizons and fragmented markets, particularly in settings where adaptation finance is limited and mitigation-oriented instruments dominate (Libert-Amico *et al.* 2022; Hallberg-Sramek *et al.* 2022; Restrepo *et al.* 2024). Case-based syntheses highlight that community forest management can improve implementation effectiveness, equity and adaptation outcomes when tenure and benefit-sharing are clarified (Hytten and Pearson 2025).

3.3.3 Biobased materials

Bioplastics

Bioplastics demonstrate advancing technological readiness and strong policy momentum, but near-term feasibility is constrained by higher costs and weak end-of-life systems. The best sustainability outcomes occur when feedstocks are residue-based and when materials are embedded in well-governed circular economy frameworks that include certified composting and effective recycling. Overall feasibility is moderate, with the potential to improve as standards, infrastructure and policy support mature.

Bioplastics derived from renewable feedstocks (e.g. starch, cellulose, plant oils, agroforestry residues) are increasingly recognized as part of circular economy pathways. They offer mitigation potential through lower life cycle greenhouse gas emissions compared to fossil plastics, while also contributing to adaptation by reducing plastic pollution pressures on ecosystems. Their feasibility, however, depends heavily on feedstock sourcing, end-of-life systems and institutional support. Feedstocks are broadly available, with strongest sustainability outcomes when residues and waste streams are prioritized. Commercial-scale technologies exist for PLAs and PHAs, while enzymatic depolymerization and chemical recycling are advancing but not yet widespread. Technological readiness is therefore high, although scaling requires better integration with end-of-life infrastructure (Zhao *et al.* 2023; Rosenboom *et al.* 2022; Mattlar and Ekholm 2025). Current production costs are generally higher than fossil-based plastics. Feasibility improves where policy incentives (e.g. producer responsibility schemes, single-use restrictions) and corporate demand stimulate investment.

Process optimization and design-for-recycling approaches can narrow the cost gap, while economies of scale remain an important enabler (Atiwesh *et al.* 2021; Weinrich and Herbes 2023; Islam *et al.* 2024).

Life cycle outcomes vary widely. Residue-based systems can substantially reduce GHG footprints, but without effective composting or recycling, bioplastics risk accumulating in landfills or leaking into ecosystems. Biodegradable microplastic risks remain a concern. Clear certification standards and robust waste-management systems are critical to ensure ecological benefits (Tang *et al.* 2024; Rosenboom *et al.* 2022). Governance frameworks are fragmented, with uneven certification and labelling systems across jurisdictions. Stronger alignment of standards, collection and processing infrastructure are essential. Policy coherence around end-of-life responsibilities and recycling incentives have proven critical for market uptake (Silva *et al.* 2024; Weinrich and Herbes 2023). Public acceptance of bioplastics is generally positive, reflecting growing demand for alternatives to fossil plastics. However, confusion around compostability, sorting and contamination thresholds undermines outcomes. Awareness campaigns, clear labelling and user guidance are needed to sustain acceptance and reduce mismanagement risks (Dilkes-Hoffman *et al.* 2019; Cruz *et al.* 2022).

Biomaterials for buildings

Biobased construction materials, including wood, bamboo, straw, hemp and cork, have long histories in building traditions and are increasingly recognized as central to low-carbon transitions in the sector, if correctly implemented. Biomaterials for buildings are a mature and increasingly scalable option in the bioeconomy. They combine mitigation potential through carbon storage and substitution with adaptation and development co-benefits, particularly in energy efficiency and rural livelihoods. Scaling requires strong governance to ensure sustainable sourcing, continued regulatory adaptation and wider public acceptance of engineered wood and other biobased materials.

Resource availability is broad. Wood has been widely used in northern Europe and North America for low-rise housing, while bamboo is a well-established structural material in Asia, where it grows rapidly (Fahim *et al.* 2022; Bredenoord 2024). Straw and straw-reinforced composites remain common in rural contexts, offering affordable and locally available solutions (Franzini *et al.* 2018). From a technological perspective, feasibility is high. Engineered products such as CLT and laminated veneer lumber (LVL) enable prefabrication and the construction of multistorey timber buildings, with recent projects in Europe, North America and Asia demonstrating technical viability (Michalak and Michalak 2024; Wiegand and Ramage 2022; Victorero and Bustamante 2025). Prefabricated elements lower labour costs and accelerate construction timelines (Sutkowska *et al.* 2024; Hrdlicka *et al.* 2022), while straw-reinforced bricks continue to meet rural needs where affordability and cultural familiarity drive adoption (Franzini *et al.* 2018). Economic feasibility varies by context.

Costs for wood-based construction are often comparable to concrete and brick, but local supply, construction traditions and regulatory frameworks strongly shape competitiveness (Balasbaneh *et al.* 2022; Hu 2023). Prefabrication can enhance affordability by reducing labour requirements and policies that reward carbon storage or penalize embodied emissions may improve the relative cost position of biobased materials. Institutional feasibility is improving rapidly. Building codes, which were historically restrictive, have been updated in many jurisdictions to permit multistorey timber construction (Wiegand and Ramage 2022). Local policy networks and government programmes in Europe and beyond are fostering innovation and adoption (Rahman *et al.* 2024; Victorero and Bustamante 2025). Certification systems play an increasingly important role in ensuring sustainability, providing safeguards against risks of deforestation and unsustainable practices.

Sociocultural feasibility is generally positive, albeit context dependent. In regions with a long tradition of wood construction, public acceptance is strong (Nyrud *et al.* 2024; Lähtinen *et al.* 2021). Elsewhere, concerns around fire, durability and safety remain, but growing evidence from modern engineered timber is reducing these barriers (Harju 2022). The environmental and ecological benefits of biobased construction materials are significant. Timber structures sequester carbon during their use phase, while substituting wood for steel or concrete can substantially reduce life cycle emissions (D'Amico *et al.* 2021; Balasbaneh and Sher 2021; Kayo *et al.* 2019). When sourced from sustainably managed forests, wood can contribute to carbon-neutral construction, though debates remain about its long-term neutrality at scale (Vallejos *et al.* 2025). Straw, hemp and cork offer insulation with lower embodied emissions than fossil-based alternatives (Balasbaneh and Sher 2021), while biodiversity and water use impacts critically depend on sourcing and forest governance (Christiansson and Roos 2023).

3.4 SYNERGIES AND TRADE-OFFS

Biobased technologies sit at the intersections of land, water, energy and social systems and feasibility hinges on how portfolios are designed and governed. Synergies are strongest when deployments are residue-based, decentralized and participatory, aligning with existing practices and value chains. Trade-offs intensify when technologies compete for land and water, when end-of-life systems are missing or when institutions are too weak to enforce safeguards and sustain finance. In this assessment, the most consistent co-benefits emerge where technologies valorize wastes and residues, pair local livelihoods with risk reduction and operate within clear, inclusive rules (Tagwi *et al.* 2023; van Noordwijk 2023; Hallberg-Sramek *et al.* 2022; Libert-Amico *et al.* 2022).

Across technologies, the recurring trade-offs are: (i) land-use competition and biodiversity risks for crop-based fuels/materials relative to residue-based pathways; (ii) logistics and quality control gaps that undermine performance and equity at scale; and (iii) institutional fragmentation that dilutes safeguards and slows finance. The recurring synergies are: (i) residue valorization that avoids open burning and leakage, and cuts GHGs; (ii) co-benefits to health and livelihoods via cleaner cooking and diversified farm income; and (iii) risk reduction from tree-based systems and adaptive forestry. Feasibility rises when portfolios are residue-first, locally co-designed and supported by standards, inclusive governance and targeted finance.

Household and community energy technologies (biogas, improved cookstoves, briquettes) show immediate, multidimensional synergies when they use agricultural or municipal residues and are supported by training, after-sales service and appropriate finance. Documented benefits include lower methane and short-lived pollutant emissions, reduced indoor air pollution and time savings for women. Consistent use and programme quality control are the keys to turning technical potential into real health and environmental gains. Stove stacking and weak after-sales support erode benefits (Gbadeyan *et al*. 2024; Tolessa 2024; Ngetuny *et al*. 2025; Bensch *et al*. 2024; Jagoe *et al*. 2020; Mekonnen *et al*. 2022; Phillip *et al*. 2023; Zulu *et al*. 2024;; Kpalo *et al*. 2020; Bot *et al*.,2022; Bot *et al*. 2023; Yu *et al*. 2022).

In energy systems, residue-based bioenergy complements variable renewables when it is dispatchable, logistics-feasible and embedded in existing agro-industrial streams. Biogas fits well in such systems while capturing waste emissions and cycling fertilizers back to the food production system (Zielińska and Bułkowska. 2024). For ethanol, 2G pathways reduce land-use pressure by using residues and wastes, while 1G benefits from mature institutions (blending rules and quality standards). System-level viability depends on feedstock logistics and utilization, with process integration and optimization shifting costs and performance (Calvin *et al.* 2021; Løvenskiold *et al.* 2022; Messmann *et al.* 2023; Scapini *et al.* 2023; Park *et al.* 2024; Pradhan *et al.* 2022; Wang *et al.* 2022; Patel *et al.* 2024; Nandi *et al.* 2023). Biodiesel offers strong synergies where waste-oil collection is dense and traceable, cutting unmanaged waste and improving air and water outcomes when production sites manage methanol, catalysts and effluents and valorize glycerol. Trade-offs arise with crop-based routes where land-use pressure and logistics dominate costs. Feasibility improves with standards, blending policies and offtake that stabilize markets (Mahla *et al.* 2023; Park *et al.* 2024; Yang *et al.* 2023; Das *et al.* 2025; Xue and Zhao 2023; Saurabh and Majumdar 2023; Polat & Altınbaş 2023).

As nature-based approaches, agroforestry and FbA reliably stack synergies across carbon, water regulation, soils, biodiversity and livelihoods. They also reduce production and hazard risks when tenure and participation are secure. Scaling constraints centre on seed/seedling systems, extension capacity and long-horizon finance. Inclusive governance and community forest management improve equity and implementation (van Noordwijk 2023; Tagwi *et al.* 2023; Bogale and Bekele 2023; García-López *et al.* 2024; Sambou *et al.* 2024; Gupta *et al.* 2023; Kuyah *et al.* 2023; Bapfakurera *et al.* 2024; Nkansah-Dwamena 2024; Hallberg-Sramek *et al.* 2022; Libert-Amico *et al.* 2022; Gopalakrishna *et al.* 2024; Restrepo *et al.* 2024; Dobhal *et al.* 2024; Hytten and Pearson 2025).

Bioplastics and biobased polymers add circularity synergies when residues and wastes are used as feedstocks and products are integrated into effective end-of-life systems (collection, certified composting or mechanical/chemical recycling). Without that infrastructure, environmental gains shrink and biodegradable microplastic risks remain. The economics improve with policy signals and design-for-recycling (Brizga *et al.* 2020; Rosenboom *et al.* 2022; Zhao*et al.* 2023; Mattlar and Ekholm 2025; Atiwesh *et al.* 2021; Weinrich and Herbes 2023; Nik Nurhidayu Nik Mut *et al.* 2024; Tang *et al.* 2024; Cruz *et al.* 2022; Silva *et al.* 2024; Islam *et al.* 2024).

Biobased construction material is a viable alternative to traditional construction material and could reduce GHG emissions, if source for residues or sustainable forest practices. Residual material used for insulation or bricks are a viable solution with many co-benefits.

Table 3.2 Interlinkages between biobased technologies, mitigation, adaptation and SDGs

Technology	Mitigation	Adaptation	SDG Linkages
Biogas (waste-based)	High: 80–90% emission reductions versus fossil fuels; methane capture from manure/residues.	Soil fertility via digestate; reduced deforestation; flexible dispatch supports renewable integration.	7 Affordable and clean energy; 3 Good health and well-being; 5 Gender equality; 12 Responsible consumption and production
Improved Cookstoves (ICS)	Moderate: 30–50% less biomass use reduces deforestation and emissions.	Reduces pressure on local forests; improves household resilience to fuelwood scarcity.	3 Good health and well-being; 5 Gender equality; 7 Affordable and clean energy; 15 Life on land
Biomass Briquettes	Moderate: displaces charcoal; reduces methane from residue burning.	Protects forests and soils; reduces land degradation.	7 Affordable and clean energy; 8 Decent work and economic growth; 12 Responsible consumption and production
2G Ethanol (residues)	High: avoids food competition, reduces open burning; 60–80% lifecycle reductions.	Residue use reduces pollution and enhances soil-air quality linkages; risks of soil nutrient depletion.	3 Good health and well-being; 7 Affordable and clean energy; 15 Life on land
Biodiesel (waste-based)	High: 40–80% reductions if waste-oil based; low if palm/soy monocultures.	Diversifies rural income in some contexts; risk of land conflicts in monocultures.	7 Affordable and clean energy; 8 Decent work and economic growth; 12 Responsible consumption and production; 13 Climate action; 2 Zero hunger; 15 Life on land
Agroforestry	High: carbon sequestration above/below ground; substitution of fertilizers.	Enhances resilience to droughts/floods; improves soils and microclimates; biodiversity corridors.	2 Zero hunger; 5 Gender equality; 15 Life on land; 1 No poverty
Forest-based adaptation (FbA)	High: carbon storage; avoided deforestation.	Hazard risk reduction (floods, avalanches); water regulation; Indigenous knowledge systems.	15 Life on land; 6 Clean water and sanitation; 1 No poverty
BECCS	Very high (theoretical): net-negative emissions in IAMs; several $GtCO_2$ potential.	Limited: resilience via energy diversification; risks of maladaptation from land-use change.	2 Zero hunger; 15 Life on land; 10 Reduced inequalities
Bioplastics	Moderate: 30–70% lifecycle GHG reductions (if residue-based).	Limited: reduces dependence on fossil inputs; potential for circular systems.	12 Responsible consumption and production; 14 Life below water; 15 Life on land
Biomaterials (buildings)	High: carbon storage in timber/bamboo; substitution for steel/concrete.	Energy efficiency through insulation; resilience in housing systems.	11 Sustainable cities and communities; 15 Life on land; 12 Responsible consumption and production

3.5 ENABLING CONDITIONS

The feasibility of biobased technologies is shaped by technical or resource considerations as well as the institutional, policy and financial environments in which they are deployed. Evidence across regions shows that enabling conditions can transform feasibility profiles, allowing technologies that might otherwise remain marginal to scale rapidly and deliver multiple co-benefits. Climate change impact the feasibility profile of all biobased technologies.

Multilevel governance and cross-sectoral coordination are equally essential. Bioeconomy technologies cut across energy, agriculture, water, environment and health sectors, yet responsibilities are often fragmented. Without coordination, policies risk duplication, gaps and unintended consequences. Integrated planning that includes multiple ministries and stakeholders can align incentives and ensure coherent deployment. For the bioeconomy, governance around land rights is especially important.

Clear land tenure rights are critical for agroforestry and FbA, where long-term investments hinge on secure access to land and resources. In contexts with insecure tenure, adoption rates are low and risks of inequity are high. Participatory governance frameworks enhance transparency, accountability and equity, while building trust and legitimacy.

Finance remains one of the most persistent barriers. At the household and community level, upfront affordability constrains the adoption of biogas, cookstoves and agroforestry. Microfinance, pay-as-you-go models and targeted subsidies have proven effective in Kenya, Tanzania and Ethiopia. On larger scales, concessional and blended finance instruments are required to de-risk emerging technologies such as 2G ethanol, bioplastics and FbA. Voluntary carbon markets can provide additional revenue streams, but they remain underdeveloped and often focus narrowly on carbon rather than broader adaptation and equity benefits. Public-private partnerships have been instrumental in demonstration projects, including the rice straw ethanol initiatives in India and bioplastic facilities in Europe.

Long-term and consistent policy signals, such as the ethanol blending mandates in Brazil and European Union sustainability standards, provide confidence for investors and industry. Conversely, inconsistent subsidies or abrupt policy reversals have led to stalled investments and plant closures in several countries. Regulatory safeguards are also vital. For biofuels, sustainability criteria must address indirect land-use change, biodiversity and labour rights. For cookstoves and briquettes, quality standards and certification systems ensure performance and build consumer trust. For bioplastics, harmonized composability and recyclability standards are needed to avoid consumer confusion and unlock environmental benefits (UNEP 2021). Life cycle assessment policies and sustainability certification for wood use in construction, both part of a regulatory framework, could foster the use of wood in buildings, which brings carbon reduction and sustainable development.

3.6 CONCLUSIONS

The feasibility of biobased technologies can be high across a variety of dimensions and contexts as portfolios of technologies can be assembled that reflect local contexts, resource endowments and development priorities. The evidence reviewed here demonstrates that some technologies, particularly waste- and residue-based technologies such as biogas, briquettes and 2G ethanol, as well as technologies within nature-based solutions such as agroforestry and FbA, consistently deliver strong synergies across mitigation, adaptation and sustainable development. These technologies are technologically viable, socially acceptable and environmentally beneficial, provided that enabling conditions such as land tenure security, participatory governance and targeted finance are in place.

At the same time, other biobased technologies remain more contested. First-generation biofuels are mature and widely deployed, but their large-scale expansion continues to raise unresolved trade-offs with food security, biodiversity and water resources. Emerging technologies such as Bio-CCUS, bioplastics and biomaterials in construction hold long-term promise but face substantial near-term feasibility barriers, including cost, infrastructure requirements and institutional readiness. Their role will depend on innovation, strong sustainability safeguards and integration into coherent policy frameworks.

Regional variation is a defining feature of the feasibility of biobased technologies. In Africa, technologies that directly alleviate energy poverty, such as biogas, cookstoves, briquettes and agroforestry, rank highest in terms of near-term potential. In Asia, residue management has emerged as a priority, with 2G ethanol and biogas offering compelling synergies for air quality and rural incomes. In Europe and North America, institutional capacity and finance enable more advanced technologies, but social acceptance and sustainability standards will determine their scale.

Across all regions, success depends on moving towards integrated strategies. Synergies are strongest when biobased technologies are embedded in circular economy approaches, linked with nature-based solutions and aligned with national development and climate strategies. Trade-offs intensify when deployment is pursued without safeguards, when land and resource competition is ignored or when institutional capacity is insufficient. Secure land tenure, particularly for Indigenous peoples and smallholders, participatory governance to ensure equity and legitimacy, long-term and predictable policy signals and concessional finance to bridge affordability gaps and de-risk investment are all critical to enabling the bioeconomy. When well-governed, these transitions can simultaneously reduce emissions, strengthen resilience and expand opportunities for sustainable livelihoods, positioning biobased technologies and the bioeconomy to achieve just, climate-resilient development. Finally, the feasibility of biobased technologies is closely linked to climate dynamics, as shifts in temperature, precipitation, and extreme events directly affect biomass availability, reliability, and long-term sustainability.

CHAPTER HIGHLIGHTS

- Biobased technologies require tailored financial mechanisms to support their development and deployment. Financing needs vary by technology type and maturity. Biomass conversion technologies often rely on grants, venture capital, and green finance to produce renewable fuels and chemicals. Bio-CCUS technologies, such as BECCS, benefit from carbon markets and performance-linked finance to monetize emissions reductions.

- Sustainable agriculture and biobased materials are increasingly supported by innova-tive financing models. Agriculture leverages results-based payments and ecosystem service markets, while the biobased materials sector is tapping into corporate alli-ances and equity markets to scale production and commercialization.

- Significant financial challenges remain. High upfront costs, long development time-lines, and market uncertainty often deter private investment. To overcome these challenges, blended finance instruments must be expanded—particularly in the Global South — by leveraging concessional public funding and risk-sharing mechanisms that support conservation, resilience, and adaptation goals.

- Governments play a critical role in enabling scale-up. Targeted financial mechanisms should support emerging value chains and link climate finance with support for micro-, small-, and medium-sized enterprises (MSMEs), fostering inclusive bioeconomy development. Regulatory clarity is also essential. Inconsistent policies across regions create uncertainty, especially in biotechnology and Carbon Sequestration and Utilization (CSU) sectors, which depend on stable, supportive frameworks.

- Access to carbon markets is vital for bioeconomy actors. Clear and inclusive regulatory frameworks can incentivize participation in mechanisms such as Article 6.4 of the UNFCCC and the Verified Carbon Standard. These frameworks enable actors to benefit from carbon credits linked to BECCS and nature-based solutions, reinforcing the bioeconomy's role in delivering verified climate outcomes.

- Financial mechanisms must be adapted to geographic and technological contexts. Support structures differ across the Global North and South, not only in funding avail-ability but also in technology priorities. Blended finance and public-private partnerships should be paired with investments in human capital, institutional capacity, and knowledge networks to ensure long-term scalability.

- Market integration remains a challenge. As biobased companies scale, they face barriers entering global markets dominated by established industries. Governments must develop enabling trade policies, harmonize certification systems, and invest in infrastructure to facilitate market access.

- Emerging tools, such as green bonds, sustainability-linked loans, and carbon credits, should be scaled through clear performance benchmarks and global collaboration to align financial flows with climate and development goals.

4.

Financing and Investing in Biobased Technologies

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4.1 INTRODUCTION

The bioeconomy is emerging as a key pathway for addressing global challenges such as climate change, biodiversity loss and resource depletion. Valued at $US 4 to 5 trillion, it is projected to reach $US 30 trillion by 2050 (World Bioeconomy Forum (WBEF) and Nature Finance (NF) 2024), offering major opportunities for sustainable development, job creation and environmental resilience. Realizing this potential, however, hinges on the availability and effectiveness of financial mechanisms that support innovation and investment across biobased sectors, including agriculture, forestry, bioenergy and biotechnology.

This chapter explores the financial landscape enabling the bioeconomy, analysing mechanisms that mobilize capital, reduce investment risks and foster technological deployment. It examines how finance can catalyse transitions in both the Global North and South, often in synergy with climate and biodiversity finance. Targeted funding is especially critical for capital-intensive and high-risk technologies such as biomass conversion, carbon capture and sequestration (e.g. BECCS), sustainable agriculture and biobased materials. These require blended financial approaches, ranging from grants and venture capital to green bonds, public-private partnerships, carbon markets and results-based payments. This chapter highlights how financial mechanisms differ by technology. Biomass conversion often depends on grants and green finance, carbon capture benefits from carbon markets and performance-linked finance, sustainable agriculture is supported through ecosystem service payments and biobased materials increasingly draw on equity and corporate partnerships.

Financing mechanisms for the bioeconomy are evolving beyond traditional instruments, with greater emphasis on systemic approaches, risk-sharing and policy-finance alignment (BIC 2023; ShapingBio 2024; WBEF and NF 2024; WEF 2025), especially in the European Union. This includes: (i) transition finance tailored to help biobased industries move from the pilot stage to an industrial scale; (ii) platform-based mechanisms aggregating small projects into investable portfolios; and (iii) integration of circular economy and just transition criteria in financial instruments (UNEP 2020). Robust financial frameworks are therefore essential not only to attract investment but also to align capital flows with climate, biodiversity and Sustainable Development Goals. Through case studies and best practices, this chapter identifies the enabling conditions and investment pathways needed to accelerate a just and sustainable bioeconomy transition.

4.2 FINANCING SCHEMES AND MECHANISMS FOR TECHNOLOGIES WITHIN THE BIOECONOMY

Financing the bioeconomy requires a broad mix of instruments to support the range of technologies, resources and business models across the sector. Due to high capital requirements, long innovation cycles and elevated investment risks, particularly in the early stages, an integrated approach using public, private and hybrid mechanisms is necessary. This section presents key financial instruments in line with the maturity of bioeconomy enterprises and technologies, with a particular focus on their role in supporting climate-related solutions.

a) Public support instruments (grants, subsidies, fiscal incentives)

Public support is essential for stimulating innovation and reducing risk in early-stage technologies, particularly in biomass conversion. Grants and tax incentives promote research, development and the adoption of sustainable solutions.

Operation: In the United States of America, the Department of Energy (DOE), the National Institute of Standards and Technology (NIST) and the Small Business Innovation Research (SBIR) fund research and development and scaling biomass conversion technologies. In Europe, Horizon Europe funds bioenergy and offers tax incentives (European Commission 2023). The Bio-Circular-Green Economy (BCG) initiative in Thailand has mobilized $US 310 million through public-private collaboration to advance bioeconomy, circular economy and green growth (BCG 2020).

b) Crowdfunding and impact investment

These alternative mechanisms are suited to early-stage companies, particularly in biobased materials and sustainable agriculture, focusing on environmental and social impact.

Operation: Crowdfunding addresses seed-stage gaps by democratizing access to capital (Hoque 2024). Sustainability-oriented campaigns, particularly those backed by professional investors, outperform others (Gai *et al.* 2025).

c) Equity financing (venture capital and private equity)

Equity finance is crucial for scaling early-stage and high-growth businesses, particularly in biomass conversion and biobased materials.

Operation: Venture capital and private equity firms offer funding in exchange for equity or convertible instruments, while also providing strategic support and networks for commercialization (OECD 2020). A lack of growth-stage capital limits the scale-up of biobased SMEs (WEF 2025; EIF 2025). The European Circular Bioeconomy Fund (ECBF) is a notable example of a targeted fund addressing this gap (BIC 2023).

d) Blended finance (concessional and commercial capital)
Blended finance mechanisms combine concessional capital from public or philanthropic sources with commercial investment, helping to reduce risk and attract private capital to underfunded sectors. It is particularly important for CSU technologies and sustainable agriculture.
Operation: Development finance institutions (DFIs) and multilateral organizations such as the Global Environment Facility (GEF) and World Bank provide guarantees, grants and subsidized loans to de-risk.[15] Successful models in Latin America and sub-Saharan Africa demonstrate that bundling smallholder or local initiatives into regional platforms, for example, in agriculture or the forest bioeconomy, can increase their investment readiness (World Bank 2021).

e) Debt-based instruments (green bonds and sustainability-linked finance)
These tools finance biomass conversion and biobased materials by linking returns to environmental performance and rewarding progress towards sustainability goals.
Operation: Green bonds fund projects such as bioenergy or bioplastics, with terms tied to emission reductions (Climate Bonds Initiative 2023). Sustainability-linked loans adjust interest rates based on achieving climate benchmarks (ICMA 2023).

f) Market-based instruments (carbon markets and credits)
Carbon sequestration (and utilization) and related biobased solutions, including CCUS, can generate revenue through monetized emission reductions in carbon markets, providing pathways for scale-up. benefit from monetized emission reductions through carbon markets, creating revenue streams for scale-up.
Operation: Platforms such as the European Union Emissions Trading System (EU ETS) and voluntary markets enable biomass and carbon sequestration projects to earn and sell CO_2 credits (ICAP 2023). Countries are transitioning towards article 6 of the Paris Agreement with bilateral Internationally Transferred Mitigation Outcomes (ITMO) agreements (e.g. Ghana-Chile-Switzerland under article 6.2) and centralized mechanisms under article 6.4 (BAFU n.d.).

g) Hybrid investment structures (public-private partnerships)
Public-private partnerships (PPPs) combine public sector resources with private sector innovation to scale sustainable agriculture and biomass conversion.
Operation: PPPs range from public ownership with private operation and maintenance to co-investment models. They support sustainable farming and bioenergy (World Bank 2021). The World Economic Forum (WEF) has called for systemic partnerships, as seen in the shift in Europe towards bioclusters integrating research and development and logistics (WEF 2025).

h) Institutional public finance mechanisms (DFIs and multilateral funds)
DFIs and multilateral institutions play a crucial role in financing biobased technologies in developing and emerging markets, where capital is scarce and risk perceptions are high.
Operation: Institutions such as the Development Finance Corporation (DFC) and the European Investment Bank (EIB) provide concessional loans, guarantees and equity for projects in bioenergy, bioplastics and Inter-American Development Bank (IDB (2024). They work alongside governments and private sector actors to mobilize investment.

Agriculture is vital to both climate resilience and bioeconomy development yet remains underfunded in global climate finance. Using the methodology proposed by Galbiati et al. (Galbiati et al. 2023) and data from the FAO and UNFCCC (FAO and UNFCCC 2024), based on climate-related finance tracking provided by the Organisation for Economic Co-operation and Development (OECD), only a small share of funding from bilateral, multilateral and private actors supports agriculture. This highlights a clear gap between global climate goals and actual financial allocations to sustainable agriculture technologies (see Figure 4.1).

15 De-risking: To lower the capital charge, a first-loss tranche is provided to absorb early losses and reduce the risk of the senior tranche funded by private investors (OECD, 2018a).

Figure 4.1. Horizontal analysis of the ratio of agricultural climate technologies and climate financing. (Data Source: OECD 2025).

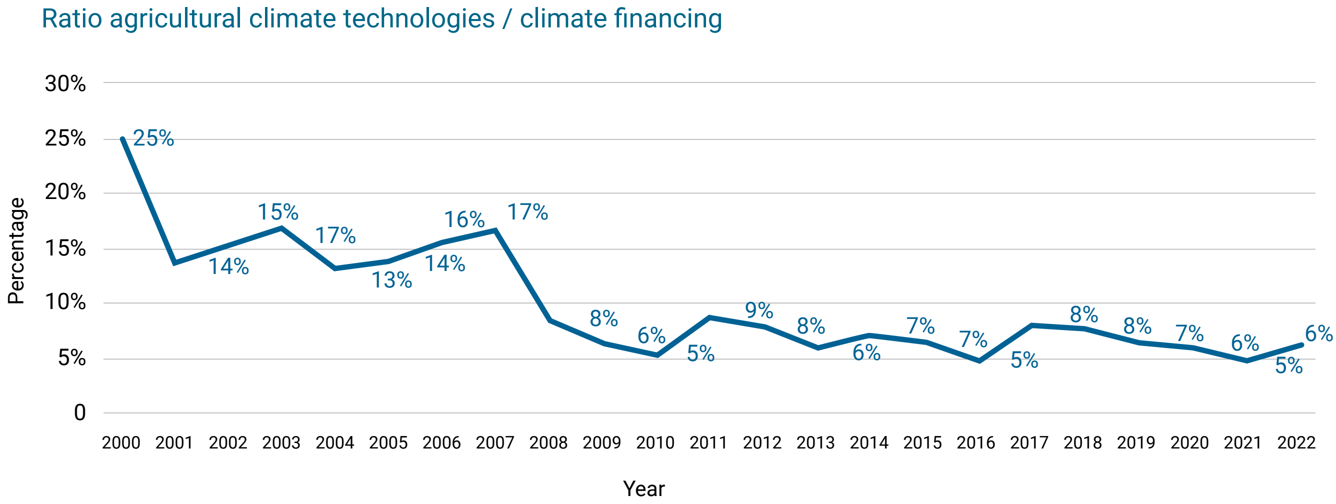
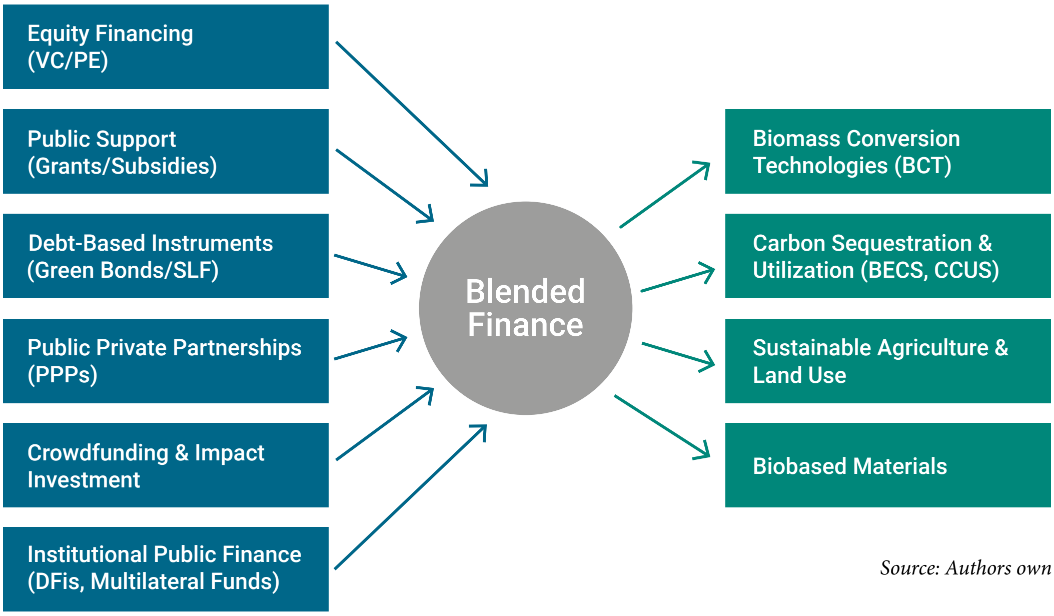


Table 4.1. Summary of financial mechanisms and sources for key climate technologies within the bioeconomy in the Global North.

Source of financing	Description	Key technologies supported	Examples/trends
Venture capital (VC)	Equity financing for proof of concept or scaling up business.	Biomass conversion, biobased materials	High investment in biofuels, bioplastics and carbon utilization (OECD 2018a; Berger *et al*. 2024)
Blended finance	Combines concessional funding with private investment to de-risk projects.	Carbon sequestration, sustainable agriculture, biomass conversion	DFIs and multilateral banks supporting biomass projects in developing economies
Government grants and subsidies or tax incentives	Public funding for R&D, pilot projects and commercialization. Not payable back.	Biomass conversion, carbon sequestration, sustainable agriculture	United States of America DOE, EU Horizon Europe funding for bioenergy and carbon sequestration (European Commission 2023)
Green bonds and sustainability-linked finance	Debt instruments linked to environmental outcomes, reducing the cost of capital.	Biomass conversion, biobased materials	Green bonds funding biofuel projects, sustainability-linked loans (Climate Bonds Initiative 2023)
Carbon markets and credits	Monetizes emissions reductions through carbon trading schemes.	Carbon sequestration, biomass conversion	Carbon credit sales generating revenue for biomass projects (Philips *et al*. 2024; Goess 2024)
Public-private partnershipsw	Joint ventures between public and private sectors to share risks and resources.	Biomass conversion, sustainable agriculture	Government subsidies and private sector innovation for bioenergy projects (World Bank 2021)
Crowdfunding and impact Investment	Community-driven and environment-social-governance (ESG)-focused investment for early-stage companies.	Biobased materials, sustainable agriculture	For early-stage biobased ventures, impact investors funding sustainable projects (Hoque 2024; sustainable agriculture)
DFIs and multilateral funding	Concessional loans and equity investments from international financial institutions.	Biomass conversion, carbon sequestration, biobased materials	DFIs providing funding to bioeconomy projects in emerging markets (Philips *et al*. 2024; DFC 2024)

The financial landscape of the bioeconomy is increasingly diverse, integrating instruments that de-risk investments, promote sustainability and align capital with environmental goals (WBEF and NF 2024). Blended finance combines public, private and philanthropic funding to attract private investment into bioeconomy projects (The Lab 2024) (Figure 4.2). This approach has been effective in biodiversity-rich areas such as the Amazon, where the Amazon Food and Forest Bioeconomy Financing Initiative aggregates small projects into investable portfolios (The Lab 2024; Käfer and de Aragão Fernandes, 2024). Sustainability-linked instruments such as sustainability-linked bonds (SLBs) and sustainability-linked loans (SLLs), link financing to environmental or social outcomes. Natura's SLB[16] supports Amazonian bio-ingredients, tying capital cost reductions to sustainability results (IDB, 2024). Natura Cosméticos S.A., for example, received investments from IDB Invest of R$ 200 million. The operation follows the announcement of Natura's 13th debenture issuance in the format of SLBs for R$ 1.32 billion (IDB Invest 2024).

Figure 4.2. Sources of finance for key biobased technologies in the bioeconomy.



Source: Authors own

Nature-based financial mechanisms, such as payments for ecosystem services (PES) and biodiversity credits, offer emerging revenue streams for bioeconomy projects aligned with sustainability goals. Carbon-biodiversity stacking, which combines credits, increases investment appeal by valuing biodiversity and ecosystem services alongside carbon, integrating land restoration into wider climate and bioeconomy finance strategies.

Advancing the bioeconomy requires financial models aligned with circularity, climate goals and the SDGs. UNEP has highlighted gaps in instruments, equity and taxonomies across Latin America (UNEP 2023b). Strengthening institutional capacity, training financial actors and supporting MSMEs, alongside scaling blended finance, impact investment and knowledge-sharing, can unlock investment in climate-resilient, inclusive and economically viable bioeconomy pathways.

4.2.1 Biomass conversion

Biobased technologies are vital for creating products that either replace fossil-based ones ("drop-in" fuels, such as ethanol-derived ethylene) or offer new functionalities ("non-drop-in" fuels, such as polylactic acid). Converting biomass into bioproducts requires high research, development and innovation (RD&I) investment due to complex processing and conversion challenges, posing significant risks for private investors. Public funding plays a crucial role, as has been seen with Horizon Europe, the EMBRAPII initiative in Brazil (which supports innovation through PPPs), and grant and subsidy programmes in the United States of America and Canada.[17]

16 Natura's SLB may not represent a direct investment in climate mitigation, but it remains closely connected, as it strengthens the supply chain for bioeconomy products while also advancing the conservation of forest biodiversity.

17 https://www.naturefinance.net/wp-content/uploads/2024/08/FinancingASustainableGlobalBioeconomy-.pdf

While local innovation financing strategies exist, mechanisms for fostering international cooperation remain limited, aside from initiatives led by the European Union. Given that the Global South possesses a wide range of biomass resources and, in many cases, the expertise to process them, international grants and subsidies could play a pivotal role in unlocking the potential of novel bioproducts. Although defining shared agendas poses a challenge, there are promising opportunities for collaboration, particularly in areas such as the forestry sector and the emerging blue bioeconomy.

4.2.2 Carbon sequestration and utilization

Bio-CCUS technologies and practices, which enhance the removal of CO_2 from the atmosphere using biological systems, are essential in mitigating climate change. These technologies, including BECCS, afforestation and soil carbon sequestration, play a vital role in the bioeconomy by utilizing biological resources for carbon removal (See Box 4.1). However, these technologies face significant financial barriers due to high costs, long timelines and technological challenges. The key financial mechanisms that support carbon capture, utilization and storage (CCUS)[18] technologies are as follows:

a) Public funding and grants: Public funding is crucial in early-stage research and scaling of CCUS technologies. Programmes such as Horizon Europe support carbon removal solutions through grants and funding for projects such as soil carbon sequestration and forest-based carbon capture. Similarly, in the United States of America, the DOE Carbon Capture Program funds BECCS and other carbon capture technologies to help make these solutions commercially viable (European Commission 2023). Similarly, in the United States of America, the DOE Carbon Capture Program funds BECCS and other carbon capture technologies to help make these solutions commercially viable (US DOE 2022; US DOE 2024).

b) Blended finance: Blended finance, combining public concessional capital with private investments, de-risks CSU projects, encouraging private sector involvement. The Green Climate Fund (GCF) uses blended finance to support carbon sequestration projects in developing countries. Other organisations also provide blended finance for decarbonisation projects such as the International Climate Initiative (GCF 2023; IKI 2024).

c) Carbon markets and credits: Voluntary carbon markets are vital for financing CCUS technologies. Projects that capture and store CO_2, such as BECCS, can generate carbon credits, which are sold in carbon markets to offset emissions. The EU ETS and voluntary carbon markets create a market for these credits, providing a revenue stream for projects focused on carbon sequestration (ICAP 2023). Although the EU ETS no longer allows for the use of carbon offsets (e.g. swapping offsets for assigned amount units (AAUs). However, sustainable biofuels (wood and straw) can be used in EU ETS installations, which frees up the allocated carbon credits to be traded See Box 4.3 on forest, wood and wood bioproducts finance). Examples of CDR are presented in Box 4.1 and 4.2.

d) Venture capital and private equity: Venture capital and private equity play critical roles in funding deep-tech startups developing breakthrough carbon sequestration technologies and other biobased technologies. Companies developing BECCS and direct air capture technologies often rely on VC to scale their operations. This financing mechanism is well-established in the United States of America and Europe but is still growing in the Global South, where carbon sequestration projects have significant potential (Breakthrough Energy Ventures, 2023).

e) Public-private partnerships: PPPs combine public sector funding with private sector expertise to accelerate the deployment of CCUS technologies, although some are all private sector funded. Drax is an energy generation company with capital investment and government subsidies in different areas from pellet production to power generation. The European Investment Bank granted a loan of €260 million to Stockholm Exergi for the construction of first large-scale bioenergy plant with BECCS in Sweden (EIB 2025).

18 BECCS is a negative-emissions pathway that forms part of the broader category of Carbon Capture, Utilization and Storage (CCUS) technologies.

Box 4.1: Examples of international support for carbon capture projects

Kyrgyz Republic, carbon sequestration through climate investment in forests and rangelands.This project enhances carbon storage through sustainable land management practices. It received a $US 29.99 million grant from the GCF, an operating entity of the UNFCCC financial mechanism (GCF 2023).
Ethiopia, nature, people and climate programme: This is a national plan to restore degraded lands, protect forests and improve food security through carbon sequestration. It was backed with a $US 37 million investment from the CIF, a multilateral partnership supporting low-carbon transitions (CIF 2024). BECCS initiatives are receiving more support, such as a sugarcane bagasse CO^2 capture project in Brazil (Carbon Pulse 2025).

Box 4.2: Scaling up biobased durable carbon removal

A growing market for durable CDR credits has emerged, with over 564 projects globally and 28 million tons contracted since 2020, more than half of which were in early 2025. Engineered biomass pathways dominate, especially BECCS (75 per cent of future contracts), with major projects such as CO280 (USA), AtmosClear (USA), Ørsted (Denmark) and Stockholm Exergi (Sweden), all supported by subsidies of $US 130–180 per ton. Biochar leads in actual deliveries (81 per cent) thanks to its low-cost, decentralized approach, using crop or forestry waste. The market is highly concentrated, with Microsoft alone responsible for over 75 per cent of contracted CDR. Forest-based credits are also rising, with 127 million ton having been contracted or announced since 2021, including 6.8 million tons from afforestation and reforestation credits issued in 2024 (CDR 2024). [19]

Durable CDR method	Projects contracted	Projects delivered
Biochar carbon removal (BCR)	2.748	558
Bioenergy with carbon capture and storage (BECCS)	20.562	0
Biomass direct storage	106	11
Biomass geologic sequestration	495	26
TOTAL	23.911	595

Box 4.3: Forest, wood and wood bioproducts finance

Sustainable forestry and wood bioproducts are attracting rising financial flows for climate mitigation, bioeconomy expansion and materials innovation. The Global Forest Finance Pledge (GFFP) has reported that since COP26, public donors have committed $US 10–13 billion towards sustainable forest protection, restoration and management globally (Forest Climate Leaders' Partnership 2025). The FAO Global Forest Sector Outlook 2050 suggests an investment need of approximately $US 25 billion annually by 2050 to modernize wood industries and value chains (FAO 2022).

Forest-timber assets are emerging as viable investment classes. An analysis by Ernst & Young shows over 100 closed forestry and timber funds globally in 2022, delivering median internal rates of return (IRRs) of around 15–16 per cent, making them attractive to institutional investors (Capolaghi 2022). Despite the global forest-based climate mitigation targets requiring $US 20–72 billion per year by 2030 (Austin *et al.* 2025), current flows remain below this threshold. To scale wood-based bioeconomies, blended finance, ESG-aligned certification (FSC, PEFC) and risk-sharing tools are increasingly being employed. The most promising wood-based products for large-scale substitution of fossil- and mineral-based materials include mass timber and engineered wood in construction, man-made cellulose fibres (MMCF) in the textile industry, and wood for renewable energy applications (Verkert *et al.* 2022). These uses not only offer high carbon abatement potential but also open investment opportunities in sustainable materials infrastructure. Investor sentiment in the bio-materials sector echoes this focus, prioritizing sustainable feedstocks, performance-based materials and scalable innovation. Investors such as Zero Carbon Capital, Sustainable Ventures and Rockstart are particularly drawn to technologies with strong intellectual property, large-scale GHG reduction potential and viable co-financing structures (Science-Entrepreneur 2024). In addition to venture capital, alternative financing such as grants, advance market commitments and corporate co-manufacturing agreements are increasingly seen as essential for scale-up.

19 Forest based initiatives were not included in the table because the reference reported only financial fig-ures in millions of USD, without providing the number of projects. More broadly, the forest carbon mar-ket has remained largely opaque, while companies often announce major deals, the overall market scale, emerging trends, and critical details such as pricing, contract structures, and delivery risks have not been systematically tracked.

4.2.3 Sustainable agriculture and land use

In recent years, bioinput products used in agriculture to improve soil fertility, stimulate plant growth and control pests have expanded significantly across the Global South, driven by public policies, regulatory frameworks and private sector engagement. In Brazil, the government launched the National Bioinputs Programme in 2020, aiming to expand and strengthen the use of bioinputs for sustainable development (Brazil, Ministerio da Agricultura e Peuaria [MAPA] n.d.). This initiative supports investments in science, technology and innovation, promotes the implementation of biofactories, and encourages the development of state-level bioinput programmes. In 2024, Brazil also enacted the Bio-inputs Law (Federal Law No. 15.070/2024, 2024), which regulates various aspects of the production, distribution and use of bioinputs across different cultivation systems. In Argentina, the National Advisory Commission on Agricultural Biotechnology (CONABIA), under the National Directorate of Bioeconomy, plays a key role in policymaking, regulation and promotion of these technologies (Ministry of Economy, n.d.).

The Argentine Chamber of Biotechnology (CAB) promotes innovation and sustainable agriculture. The 2025 National Bioinputs Plan in Uruguay supports bio-input development and aligns with the country's Sustainable Bioeconomy Strategy (MGAP 2025). In India, the National Mission on Natural Farming has established Bio-Input Resource Centres to provide locally adapted solutions (Government of India 2024). In Africa, the BioSSA project run by the International Institute of Tropical Agriculture (IITA) delivers bio-inputs to boost smallholder farming in countries such as Nigeria and Tanzania (IITA n.d.). These initiatives reflect a global shift towards biological alternatives to reduce synthetic inputs and promote more sustainable, resilient agriculture.

4.2.4 Biobased materials

Financing often prioritizes biofuels and bioenergy, neglecting bioplastics and biochemicals, even though petrochemicals remain a major blind spot. Supporting integrated biorefineries can enable the production of both bulk commodities and high value bioproducts.[20] However, commercialization phases receive less funding. For example, after developing bioplastic resins, further work is needed on additives and adapting equipment to produce the final products. End-of-life solutions, such as advanced sorting and recycling, are also essential (Teixeira *et al.* 2023). Financing schemes should address the full product life cycle and support market creation (B2C and B2B) to ensure these technologies become financially viable at scale.

4.3 FINANCING CHALLENGES

The bioeconomy offers a powerful pathway for sustainable growth through biobased products and services. However, it faces significant financial barriers, including high costs, market risks and regulatory uncertainty. These challenges are more acute in developing regions due to limited funding and strong competition from fossil fuel-based industries. Addressing these barriers requires coordinated action from governments, the private sector and international partners to strengthen financial mechanisms and drive market adoption.

a) High initial costs and risk: Biobased technologies such as carbon sequestration and advanced bioproducts demand substantial upfront investment in research, development and scaling. These long timelines and high risks deter private investment, especially in early-stage ventures (WBEF and NF 2023). Their technological complexity further increases risk, limiting access to conventional venture capital (OECD 2020).

b) Lack of commercial viability: Markets for biofuels, bioplastics and biobased chemicals are still emerging. These products often compete with fossil fuel alternatives that benefit from subsidies, making it difficult to achieve price competitiveness and steady demand (See policies and regulatory frameworks needed to compete against fossil fuel-based technologies in Chapter 5). This market uncertainty undermines investor confidence and stalls the commercial viability of biobased innovations (WBEF and NF 2024).

c) Limited public funding in the Global South: Although PPPs and blended finance models have been successful in the European Union, such mechanisms remain limited in the Global South. Many governments lack the fiscal space to provide sufficient support and capital markets in these regions are often underdeveloped (OECD 2020). Without international capital (including grants, guarantees and concessional investments), PPPs tend to underperform, even when the bioeconomy potential is high.

d) Regulatory and policy uncertainty: Investors are hesitant to commit to markets lacking clear and consistent regulations. This is especially relevant for biotechnology and carbon sequestration sectors, which depend on enabling policy frameworks (WBEF and NF 2024). Progress in setting a pricing mechanism for nature could also drive regulatory improvements and promote stronger enforcement of financial integrity rules, including those against nature-related crimes.

20 See https://www.iea.org/news/petrochemicals-set-to-be-the-largest-driver-of-world-oil-demand-latest-iea-analysis-finds

e) Challenges in market integration: Integrating biobased goods and services into established global markets remains difficult, particularly in B2B and B2C segments. Traditional industries dominate trade and distribution networks and bioeconomy firms face structural disadvantages. Supportive trade policies and upgraded infrastructure are essential to help biobased industries scale (NF 2024). The UNCTAD Trade and Biodiversity database helps track such trends and frameworks from the G20 and UNCTAD aim to ensure that bioeconomy trade supports biodiversity, local communities and equitable benefit-sharing (United Nations Trade and Development 2025).

Overcoming these interlinked barriers requires a coordinated, multi-stakeholder effort, combining targeted government policy, private sector leadership and international cooperation, to expand financial flows and scale a resilient, inclusive bioeconomy.

4.4 FINANCIAL ACTORS IN THE GLOBAL NORTH AND THE GLOBAL SOUTH

Financial actors in both the Global North and Global South play crucial roles in this process, with investments from international donors, government programmes and private sector initiatives focused on fostering sustainable development.

In Europe, funds such as the Forbion BioEconomy Fund I (€ 164 million) and the European Union-backed ECBF support biobased and circular innovations. The ECBF, initiated by the European Union and supported by the EIB, is the first venture fund dedicated to growth-stage companies in the bioeconomy and circular bioeconomy, focusing on accelerating biobased innovations across European Union countries. The EIB finances global bioeconomy and ecosystem restoration projects through loans, grants and blended finance to promote sustainable value chains and green infrastructure (EIB 2024). Table 4.2 presents some examples of financial actors in the Global North.

Table 4.2. Examples of financial actors in the Global North

Organization	Region	Key focus areas	Type of investment	Examples	References
North American Development Bank (NADB)	North America	Clean energy, sustainable agriculture, waste treatment	Low-interest loans, grants, technical assistance	Bioenergy projects in Mexico and the United States of America. reducing waste and improving energy access	NADB
The Rockefeller Foundation	Global	Sustainable agriculture, climate -resilient farming, food security	Grants, strategic partnerships	YieldWise Initiative to reduce food waste in sub-Saharan Africa, sustainable farming	Rockefeller Foundation
The Bill & Melinda Gates Foundation	Global	Biotechnology, crop resilience, sustainable farming techniques	Grants, investments in agricultural innovations	Invested in biofortified crops and innovations in sustainable agriculture (e.g., drought-resistant seeds)	Gates Foundation
UK Green Investment Bank (GIB) / Green Investment Group	United Kingdom	Bioenergy, waste-to-energy, sustainable land management	Equity investment; green infrastructure financing	Invested in waste-to-energy plants and renewable bioenergy projects	Green Investment Group
KfW Bankengruppe	Germany	Bioenergy, forest management, sustainable agriculture, bio-based material development	Loans, grants, technical assistance	Bioenergy plant in Brandenburg converting waste into renewable energy	KfW Bank
Swedish International Development Cooperation Agency (Sida)	Sweden	Sustainable agriculture, resource-efficient production, clean technologies	Grants, project financing	Supported the East African Bioeconomy Strategy; project in Tanzania promoting climate-smart agriculture and sustainable food production	Sida
Blue Horizon	Switzerland	Sustainable food systems, plant-based foods, alternative proteins, sustainable farming	Venture capital	Invested in Oatly and Beyond Meat to promote sustainable food systems	Blue Horizon
Impact Investment Funds (Triodos, Aavishkaar, Aurelia Ventures)	Global	Sustainable agriculture, clean energy, circular economy	Impact investing; venture capital	Triodos invested in Bio-bean (waste coffee grounds into biofuels)	Triodos IM, Aavishkaar, Aurelia Ventures
Venture Capital & Private Equity (Seventure Partners; Breakthrough Energy Ventures)	Europe/ Global	Alternative proteins, biofuels, bioplastics	Venture capital; private equity	BEV invested in Heirloom (direct air capture with bioenergy solutions)	Seventure Partners, Breakthrough Energy Ventures
EIB & European Bank for Reconstruction and Development (EBRD)	Europe/ Global	Clean energy, sustainable agriculture, circular biobased technologies, ecosystem restoration	Loans; green bonds; blended finance	Financed GreenBio projects on biobased materials and sustainable energy (EBRD also includes biofuels and energy)	EIB
European Circular Bioeconomy Fund (ECBF)	Europe	AgTech/ blue economy; FoodTech/ nutrition; Industrial Biotech & biochemical; Biobased materials for Packaging, Construction and textiles	Growth-stage equity investment	Invests exclusively in late-stage bioeconomy ventures (25) across EU countries (13)	ECBF
Forbion BioEconomy Fund I	Europe	Food, agriculture, materials, environmental technologies; biotech, medtech	Venture capital	Growth capital for bioeconomy-related technologies and companies	Forbion Fund https://forbion.com/en/

In the Global South, bioeconomy innovation is backed by public tools such as concessional credit, green bonds and results-based financing to promote sustainability and reduce fossil fuel dependence, supporting national development and climate goals. Globally, organizations are increasingly investing in bioeconomy projects to advance sustainable development, climate action and biodiversity (Table 4.3).

Table 4.3. Examples of financial actors in the Global South

Organization	Region/ Country	Key Focus Areas	Type of Investment	Comments	References
North American Development Bank (NADB)	North America	Clean energy, sustainable agriculture, waste treatment	Low-interest loans, grants, technical assistance	Financed bioenergy projects in Mexico and the United States of America to reduce waste and improve energy access	NADB
Petrobras & Régia Capital	Brazil	Impact climate action; biodiversity preservation; carbon/biodiversity credits	Petrobras Bioeconomy Fund	R$ 100 million (~$US 20 million) fund for socio-environmental bioeconomy projects; linked compensation model aligning returns with sustainability outcomes	Petrobras Agency, 2025
Inter-American Development Bank (IDB) & The Nature Conservancy (TNC)	Amazon region	Sustainable supply chains; reforestation; regenerative agriculture	Capital investment	Partnership to boost the regional bioeconomy through nature-based solutions	IDB Invest
FAO & Amazon Cooperation Treaty Organization (OTCA)	Amazon region	Amazonian Bioeconomy Investment Program	Programme finance	$US 89.9 million to promote inclusive rural transformation across eight Amazon countries	FAO and OTCA
RenovAgro; Inovagro; ABC+	Brazil	Climate technologies in agriculture (rehabilitation of degraded lands; organic transitions; residues; biological inputs)	Concessional credit facilities	Supports domestic bio-inputs manufacturing to substitute fossil-based agrochemicals and reduce emissions	UNFCC Agroicone
Agriculture Infrastructure Fund (AIF) & Green Credit Programme (GCP)	India	Climate-resilient infrastructure; adoption of biobased technologies	Financial and market-based incentives	Supports biological inputs, waste management and regenerative agriculture practices	(Bhattacharjya, 2024; Government of India, 2023; MAPA, 2024).
BioInnovate Africa	East Africa	Smallholder-focused biotech and agronomy; commercialization of biobased ideas	Grants for research and training; venture finance for private businesses	~80% donor-funded; needs public financing and regional mechanisms to de-risk innovation and attract larger investors	(Ecuru, Savadogo and Araba, 2024) Bioinnovate AfricaBCG (2025)
Bio-Circular-Green Economic Model (BCG)	Thailand	Agriculture; food; bioenergy; biomaterials and biochemicals; health; tourism; circular & creative economies	$US 310 million public-private partnership	Cooperative agreement among 18 organizations including government, industry and financial institutions	NTSDA
Ministry of Environment	Colombia	Decarbonization; restoration; climate change projects; bioeconomy	Public-private funds (COP 49 trillion ≈ $US 12.2 billion)	Socio-ecological transition and climate action in Colombia	Gov Colombia

4.5 OPPORTUNITIES IN THE FINANCIAL WORLD FOR KEY CLIMATE TECHNOLOGIES WITHIN THE BIOECONOMY

The bioeconomy offers significant investment opportunities aligned with climate and sustainability goals. Governments, investors and firms are scaling technologies to address environmental and social challenges. Key instruments include public funding, venture capital, blended finance and carbon markets. Horizon Europe and the GCF support technology deployment and risk reduction. Early-stage firms depend on venture capital and government-backed VC (GovVC). Blended finance is crucial in low- and middle-income countries. Growing consumer demand and supportive policies drive biofuels, bioplastics and biobased chemicals. As the sector matures, carbon credits (e.g. BECCS) and sustainability-linked tools such as green bonds become increasingly important.

Key financial opportunities:

- **Growing market demand for biobased products:** The rising global demand for sustainable alternatives creates a robust market for biofuels, bioplastics and other biobased chemicals, which is expected to reach a market value of $US 30 trillion by 2050 (WBEF and NF 2023).
- **Government funding and PPPs**: Public funding programmes such as Horizon Europe and the GCF, alongside PPPs, provide substantial financial backing for bioeconomy projects. These mechanisms reduce risks for investors and accelerate the commercialization of new technologies (GCF 2023).
- **VC and GovVC**: Government-backed venture capital and private investments are key to supporting early-stage bioeconomy startups, particularly in high-tech sectors such as biotechnology and renewable energy (OECD 2019; Berger *et al.* 2024).
- **Blended finance and nature markets**: Blended finance models that combine concessional public funding with private capital help scale bioeconomy projects, particularly in developing countries. Nature-based solutions, such as carbon and biodiversity credits, also offer financial incentives for bioeconomy initiatives (GCF 2023).
- **Carbon markets and sustainability-linked finance**: The growth of carbon pricing systems such as the EU ETS provides opportunities for bioeconomy projects that generate carbon credits. Sustainability-linked bonds and loans also provide bioeconomy companies with favourable financing terms based on their environmental performance (OECD 2019; Berger et al. 2024). Worldwide, UNFCCC CDM/article 6.4 and Verified Carbon Standard trading are an example of generating carbon credits for international trading and finance (UNFCCC 2024).
- **International cooperation and collaborative frameworks**: Global initiatives such as the G20 Bioeconomy Initiative promote international collaboration and funding for bioeconomy projects, unlocking growth potential in biobased industries worldwide (WBEF and NF 2023).

These mechanisms combine to offer a favourable environment for investing in the bioeconomy, paving the way for scalable, sustainable biobased solutions that address global challenges. Furthermore, these mechanisms make it possible to consider the transfer of technologies from North-South, South-North and South-South.

4.6 CONCLUSIONS

A sustainable, resilient bioeconomy needs substantial financial mobilization using diverse tools such as government grants, venture capital, blended finance and carbon markets, to drive innovation in sectors such as agriculture, bioenergy and carbon sequestration. These instruments help de-risk investments and support climate, biodiversity and social goals. While current funds have specific objectives (e.g. climate or bioenergy), together they shape the bioeconomy financing framework. As the sector evolves, new targeted funding approaches may also emerge, expanding opportunities further.

Despite its potential, the bioeconomy faces major barriers, high costs, market uncertainty, regulatory hurdles and limited capital access, especially in developing regions. However, successful examples from the Global North and South show that targeted mechanisms such as blended finance and PPPs can bridge financing gaps, particularly in emerging economies rich in biological resources. Moving forward, collaboration among governments, investors and international organizations is crucial to create clear regulations, incentivize investments and build capacity. International cooperation is also key for harmonizing standards and expanding markets. Overcoming these barriers offers opportunities for innovation, economic diversification and climate action through strategic bioeconomy investments.

CHAPTER HIGHLIGHTS

- Phasing out fossil fuel subsidies remains critical to advancing the bioeconomy. Aligning this transition with national socio-economic priorities ensures equity and effectiveness. A systemic approach to biobased policies can enhance coherence across sectors, balance land-use demands, and strengthen synergies between mitigation and adaptation. Supporting biobased research clusters, innovation platforms, and peer learning, especially in emerging economies, can accelerate adoption and scaling.

- Inclusive and participatory governance is essential. Policymakers are encouraged to address the diverse perspectives across bioeconomy sectors by fostering transparent, context-specific strategies that reflect local priorities and institutional capacities. Awareness-raising is particularly important in rural and non-OECD regions to build public understanding and stakeholder engagement.

- Standardization and innovation are key to ensuring sustainability. Promoting common technical standards, robust certification systems, harmonized monitoring frameworks, and digital tools will improve transparency, accountability, and environmental and social outcomes across fragmented bioeconomy landscapes.

- It is recommended that the deployment of biobased technologies be guided by social justice and environmental integrity. In biodiversityrich and ecologically sensitive areas, safeguards are essential to protect the rights and livelihoods of Indigenous Peoples and Local Communities (IPLCs). Responsible innovation must integrate these considerations to ensure equitable transitions

- Embedding sustainability in bioeconomy strategies is essential to address the environmental pressures from increasing biomass demand. This includes integrating sustainability frameworks into national and regional policies, adopting robust monitoring systems with sound indicators and disaggregated data, and promoting nature-based solutions such as soil health and ecosystem restoration.

- International cooperation and multi-stakeholder networks are vital to scaling biobased technologies. Platforms such as the G20 Bioeconomy Initiative, the International Advisory Council on Global Bioeconomy (IACGB), and the FAO-led Global Bioeconomy Partnership can align efforts, share best practices, and mobilize investment and political support.

- Effective policy coordination is essential. The cross-sectoral nature of the bioeconomy requires alignment across national and subnational levels. Gaps and inconsistencies in existing policies can hinder deployment. Multilevel governance, international collaboration, and digital tools are needed to harmonize standards and safeguards for sustainable biomass use.

- Secure land tenure and strong legal frameworks are foundational. Strengthening land and resource governance, especially through multilateral initiatives, can unlock solutions like agroforestry on small farms, supporting multiple SDGs. Regulatory frameworks with clear, verifiable targets are essential to ensure accountability, drive innovation, and enable coherent action across sectors.

5.

The Role of Institutions, Governance and Global Cooperation

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5. 1 INTRODUCTION

The implementation and upscaling of biobased technologies comprising biomass conversion, Bio-CCUS, sustainable agriculture and land use and biobased materials, as defined in Chapters 1 and 2 of this report is shaped by a variety of policies, institutions and governance mechanisms at different levels. At the subnational level, provision of raw inputs may be affected by policies such as local land and water use regulations, informal institutions for resource use or sharing (especially in low-income countries) and governance systems for public and private actors. At the national level, a wide array of enablers and barriers may be relevant, such as land use legislation, engagement in certification and voluntary carbon markets, licensing of technologies, national planning priorities and the relevant national plans and mechanisms under the Paris Agreement. At the international level, multilateral cooperation, trade and investment institutions and a variety of international and regional cooperation mechanisms determine the operating context.

As with all developments of markets and resources, there are "enabling" and "constraining" functions in policies, institutions and governance. Technological innovation platforms and policy support mechanisms are crucial for scaling up (enabling) biobased technologies and facilitating new markets for value-adding bio-resources. Regulations and governance are important in ensuring sustainability (constraining) in biomass production and use and in the appropriate application of biobased technologies. Regulations can play a key role in shaping biomass markets such as by either incentivizing or discouraging the export of raw biomass versus processing biomass for value-added products within the country. Well-designed policies can encourage value addition and keep more economic benefits domestically, rather than simply exporting unprocessed biomass. Conversely, a lack of such regulations may incentivize raw biomass exports, often resulting in limited local value creation and potentially unsustainable harvesting practices driven by demand from countries with greater technological and processing capacity (Albinelli *et al.* 2024). Considering the broad jurisdictional scope that ranges from local to global, biobased technologies clearly require effective multilevel governance to thrive and remain sustainable (Hurlbert *et al.* 2019).

The capacity to deploy biobased technologies varies widely around the world and the operating context is highly heterogenous. Due to the close connections to agriculture, forestry and land use, the market-technology organization and policy context of the bioeconomy varies and tends to be site-specific, not only across countries but also across different biomes and climates. The range of supply chain and value chain issues that significantly impact the success or failure of biobased technologies can be somewhat complex (Diakosavvasand Frezal 2019). In addition to market and physical aspects discussed elsewhere in this report, complexities also arise due to highly diverse stakeholder groups, some of whom may lack awareness of biobased technologies (Bößner *et al.* 2023). The cross-sectoral nature of biobased technologies further affects the ability to reach a common understanding among these stakeholders (Pender *et al.* 2024).

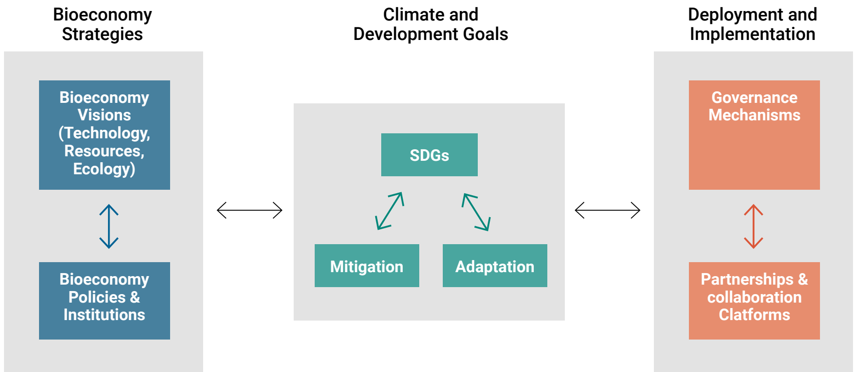
Stakeholders often have quite different visions of the bioeconomy that can lead to contentious issues such as the classic food versus fuel issue (Rosillo-Calle and Johnson 2013), which impact perceptions of credibility and the resulting challenges for governance. One useful characterization of stakeholders in analysing governance is derived from three visions of bioeconomy based on bio-resources, bio-ecology and biotechnology (Bugge *et al.* 2016). The biotechnology vision emphasizes research, application and the commercialization of bio-technologies in different sectors and the potential for economic growth. The bio-resource vision focuses on the potential in upgrading and conversion of biological raw materials and associated job creation. Finally, the bio-ecology vision highlights the importance of preserving biodiversity, conserving ecosystems, and managing wastes for a bio-circular economy (Bugge *et al.* 2016).

These contrasting visions are part of the institutional dynamics in designing and implementing policies, regulations and governance mechanisms, which are then negotiated, interpreted and adjusted alongside their climate and development context (see Figure 5.1).

Advancing bioeconomy pathways and transitioning to a more sustainable use of biobased resources has been of growing interest for policymakers around the world, especially since 2015, due to linkages with the SDGs and the role of the bioeconomy in achieving the goals of the Paris Agreement. Bioeconomy strategies and the supporting policies and technology platforms have been moving from niche to mainstream during the past two decades or so (OECD 2018b). More than 60 countries have adopted strategies regarding the bioeconomy, bio-science or biotechnology (Gomez San Juan 2024). Countries such as Brazil, Thailand and Germany have created dedicated units (commissions, working groups etc.) to further biobased innovation (Khatri-Chhetri *et al.* 2022; Bößner and Mal 2024).

Recognizing the inherent heterogeneity, dynamism and complexity of the entire multilevel landscape of biobased technologies, this chapter takes a deeper look at enabling and constraining policies and institutions, as well as the associated governance mechanisms and collaboration platforms that have developed. Although the marine and/or ocean bioeconomy can be significant for climate technology solutions, this

Figure 5.1. Biobased technologies: visions, goals and governance



Source: Authors own

chapter (as with the report as a whole) focuses on the land-based deployment of biobased technologies. The authors offer examples of progress in policies and governance, including, where applicable, the opportunities for bioeconomy to leverage synergies with the SDGs. Indeed, in some respects the bioeconomy-climate nexus can be seen as an alternative development model (McCarthy *et al.* 2025).

This chapter is divided into three main sections. The next section provides an overview of key policies and regulatory frameworks aimed at reducing emissions, with an emphasis on substitution for fossil fuel-based technologies and systems. This is followed by a complementary perspective that emphasizes risk management, adaptation co-benefits and synergies with SDGs. The third section considers governance at different levels and international cooperation from a broader perspective, with respect to key modes of collaboration and cooperation platforms aimed at advancing biobased technologies. In each of the three sections, selected policy-relevant developments and cases are referenced, in some instances as separate boxes or tables, covering a range of local, national, regional and global perspectives as well as different resources and thematic issues.

5.2 BIOECONOMY POLICIES FOR REDUCING EMISSIONS AND CLIMATE RESILIENCE

The potential for reducing emissions and promoting climate resilience is especially significant in the AFOLU sectors and associated biobased industries. In particular, sustainable agriculture and forestry, technology innovation in biobased production and global trade in biobased products can advance both mitigation and adaptation goals (Babiker *et al.* 2022). However, these sectors are characterized by greater diversity and uncertainties compared to other sectors such as energy and transport (Rinn *et al.* 2024; Johnson *et al.* 2025). Whereas we have seen rapid uptake of low-emissions technologies and practices in electricity generation, the AFOLU sector faces unique structural and economic challenges which complicate technology adoption and behaviour change (Bößner and Mal 2024; Khatri-Chhetri *et al.* 2022). Although there have been significant advances in technology and resource innovation within the bioeconomy, upscaling and commercialization are lagging, suggesting a need for improved enabling policies. Barriers and challenges are briefly reviewed below, followed by an overview on progress in policy design and implementation.

In the AFOLU sectors, climate mitigation goals intersect in complex ways with issues such as land degradation, deforestation and food security, due to future climate impacts on the productivity of land use systems, as well as socioeconomic factors (IPCC 2022c). Navigating these interactions requires policy support and regulatory structures that can provide more certainty for investment such as secure land rights, a level playing field between fossil fuel based and biobased technologies and practices and innovation support policies.

Emerging innovations and markets for biobased technologies must also contend with or compete with entrenched systems of norms and infrastructure, often referred to as the "dominant regime" (Geels 2002; Geels 2014; Geels and Schot 2007). In the context of competing with innovative biobased technologies, the fossil fuel-based regime benefits not only from decades of regulatory and monetary support but also from a widely developed infrastructure and entrenched political backing (Bößner 2019). Pressure from powerful private vested interests maintains the stability of the fossil fuel regime, whereas biobased technologies are heterogeneous, decentralized and fragmented, a critical factor impacting technology adoption and the effectiveness of governance frameworks for the bioeconomy.

Policies and regulatory frameworks for the emerging bioeconomy can only be effective if there is a more level playing field between fossil fuel-based technologies and biobased ones. The International Monetary Fund (IMF) estimates that around $US 7 trillion of subsidies is spent globally each year on oil, gas and other fossil fuels (IMF 2022). Rather than declining, this figure has been increasing over recent years. In regions such as the Middle East and South-East and Central Asia, allocating between 10 and 23 per cent of GDP on subsidizing fossil fuel production and consumption, a disproportionate share of public budgets (IMF 2022). And although equity concerns complicate fossil fuel subsidy reform (e.g. lower income households might depend on fuels with lower upfront cost) (Couharde and Mouhoud 2020), each advantage conferred upon non-biobased technologies and practices makes it harder for biobased ones to compete. Challenges in setting a realistic carbon pricing and taxation system further compound the challenges of effective fossil fuel subside reform (OECD 2023).

Even if policy support is forthcoming, bioeconomy and land-based climate action are also subject to the same policy dilemmas that pit the need for regulatory support (Dietz *et al.* 2018; Maxon 2023) against overregulation concerns (Wesseler and von Braun 2017). Policy coordination is another issue, particularly due to the inherently cross-sectoral nature of bioeconomy planning (Pender *et al.* 2024) as well as the need to plan across subnational, national and, where applicable, international levels (Schlaile *et al.* 2025). Moreover, policies and regulatory frameworks (or the absence thereof) that might not be directly related to biobased technologies may present a barrier to those innovations. For instance, in many low-income countries, robust land tenure systems may be lacking, which often disincentivizes producers from investing in new technologies due to lack of ownership. This in turn might lead to short-term planning, resulting in deforestation, excessive fertilizer use and other unsustainable land-use practices (Betts *et al.* 2022; Murken and Gornott 2022; Tseng *et al.* 2021) with negative consequences to aquatic ecosystems and the people they support. This study creates a framework for how deforestation from cattle ranching causes shifts in stream community structure, mediated by changes in stream habitat over time. It integrates temporally explicit land use information with stream habitat, macroinvertebrate, freshwater shrimp, and fish community data to assess impacts of cattle ranching on 15 headwater streams. The deforestation history measure (DHM. To make matters even more complex, between 70 and 80 per cent of all farmlands globally is operated by small-scale farms with under two hectares of land (FAO 2024b). This fragmentation poses challenges for pooling biomass effectively (Lautala *et al.* 2015) and can limit the potential of biobased technologies. On the other hand, improvements in land tenure and land governance, including through multilateral initiatives, could be part of reforms that facilitate upscaling of biobased technologies such as carbon sequestration and utilization within agroforestry, even for small-scale farms, with possible SDGs synergies (Calvin *et al.* 2021).

Furthermore, biobased technologies require sustainability and feasibility analysis across all three dimensions (see Chapter 3 on feasibility). The potential negative impact of crops grown for energy, for instance, on land-use, food availability and biodiversity has been studied (Immerzeel *et al.* 2014; Muscat *et al.* 2020) and ecological trade-offs with the global sustainability agenda from deploying biobased technologies have garnered the attention of scholars and policymakers (Vera *et al.* 2022). Moreover, while IPCC scenarios suggest that nearly a billion hectares of land could be required for carbon removal (IPCC, 2022c) these estimates are heavily shaped by the assumptions embedded in integrated assessment models (IAMs). Such models have historically emphasised BECCS and afforestation/reforestation, while underrepresenting the broader range of available CDR approaches. This narrow framing may not incorporate productivity improvements from other biobased technologies and risks overstating land needs (see Chapter 2). Expanding the portfolio to include other CDR options alongside revised assumptions on renewable energy integration and discount rates could reduce the modelled reliance on BECCS and, in turn, can lower expected land requirements (Chiquier *et al.* 2025).

5.2.1 Overcoming challenges and seizing the potential

Regardless of which options are chosen in different contexts. A reliable supply of sustainable biomass is key for most biobased technologies and especially for scaling up Bio-CCUS , since it will impose additional demands on land and biomass. Institutional mechanisms such as the European Biochar Certificate can support minimum standards and facilitate increased reliability through trade (EBC and WBC Guidelines & Documents n.d.). Voluntary markets for carbon removal can operate through corporate-level mechanisms such as the Science-Based Targets initiative (SBTi) commitments, which can be important in kickstarting the markets and establishing credibility. Even within the European Union, which has a highly mature level of economic cooperation and policy coherence, the proliferation of sometimes competing regulations alongside the lack of a level playing field with fossil fuels creates challenges to ensuring a sustainable biomass supply in the case of BECCS (See Appendix 2, Box 2). Fossil fuels do not face any certification requirements, while biobased resources in an effort to ensure their sustainability normally do.

Looking beyond barriers and challenges, the advancement of biobased technologies can be seen in the worldwide growth of dedicated bioeconomy and bio-science strategies and plans (Funduk 2022; FAO 2023). A dashboard developed by FAO maps these various strategies to IPCC-identified climate change mitigation and adaptation options and the Kunming-Montreal Global Biodiversity Framework (GBF) targets (FAO 2023). Of the 1 009 actions extracted from bioeconomy strategies, 503 have been mapped as relevant to IPCC mitigation options, 335 to IPCC adaptation options and 454 to GBF targets (FAO 2023). Table 5.1 highlights some examples of actions and mappings, demonstrating key linkages between bioeconomy strategies, and climate and biodiversity goals and targets.

Table 5.1 Mapping mitigation, adaptation and biodiversity in selected bioeconomy strategies

Country	Action from bioeconomy strategy	Mapped as relevant to:		
		IPCC mitigation option	IPCC adaptation option	Global Biodiversity Framework target
Austria	Systemic assessment of the interactions between climate change and increased biomass production and biodiversity	Biomass crops for bioenergy, biochar and other biobased products	Biodiversity management and ecosystem connectivity	Target 8: Minimize impacts of climate change and ocean acidification including through nature-based solutions and/or ecosystem-based approaches
Colombia	Biotechnology for a more productive, sustainable and resilient to climate change agrifood system	Sequester carbon in agriculture (Soil carbon management in croplands, soil carbon management in grasslands, agroforestry, biochar application)	Land and ocean ecosystems / Other	Target 10: Sustainably manage areas under agriculture, aquaculture, fisheries and forestry
Malaysia	Creating value from agricultural and industrial waste	Circular economy and industrial waste	Not mapped	Target 7: Reduce pollution, halving nutrient loss and pesticide risk
South Africa	Develop integrated biorefineries from biobased feedstocks. In a low-carbon future, biorefineries (comparable to petroleum refineries) will use renewable biomass to produce bioenergy, biomaterials and biobased chemicals	Industry / Other	Not mapped	Not mapped
Thailand	Conserve forested watersheds and develop a platform to support water use reduction, water recycling and water quality improvement	Protect forests and other ecosystems (reduce deforestation and degradation, reduce conversion of coastal wetlands, reduce degradation and conversion of peatlands, reduce degradation and conversion of grasslands and savanna)	Water use efficiency and water resource management	Target 3: Conserve 30 per cent of land, water and seas
East African Regional Bioeconomy Strategy	Biobased construction materials. Transforming the local construction industry into one that is low-carbon and climate-smart, and based on locally produced renewable building materials	Change in construction materials	Green infrastructures and ecosystem services	Not mapped

(Source: Adapted from FAO 2023)

A similar mapping exercise was performed for NDCs, National Adaptation Plans (NAPs), Long-Term Low Emissions Development Strategies (LT-LEDS) and National Biodiversity Strategies and Action Plans (NBSAPs), revealing several explicit references to the bioeconomy. Notably, 22 LT-LEDS look to the bioeconomy, suggesting its relevance for long-term planning. Table 5.2 provides some examples.

Table 5.2 Selected examples to represent bioeconomy principles or strategies in LT-LEDS

Country	Integration of bioeconomy in Long-term Low Emission Development Strategies (LT-LEDS)
Colombia	The bioeconomy is a pivotal element of the Colombia LT-LEDS, serving to internalize externalities and promote sustainable production. Implementation is supported by an investment fund for bioeconomy initiatives, with two main objectives: supporting goods and services based on biodiversity and securing additional funding. Enabling actions focus on building institutional capacities at both national and regional levels, fostering a better understanding of the bioeconomy and facilitating the development of related projects.
Costa Rica	To advance the development of highly efficient agrifood systems with low-carbon export and local consumption goods, Costa Rica aims to transition its agricultural sector to a bioeconomy model. In the short term (2023-2030), Costa Rica will focus on the direct use and sustainable transformation of biological resources, including biomass waste, within a circular economy framework. Looking ahead (2031-2050), the goal is to scale and transform the agricultural system to become a key contributor to the Costa Rican bioeconomy, becoming more productive and resilient while reducing its carbon footprint.
Lithuania	In the non-ETS sector, promoting the adoption of advanced, energy-efficient technologies is a key mitigation option for Lithuania. To this end, a competitive circular economy and a bioeconomy built on biomass resources is being fostered. Additionally, Lithuania aims to nurture a bioeconomy that emphasizes higher value creation, embraces circular principles and enhances its economic contribution at the national level.
New Zealand	In its long-term strategy, New Zealand emphasizes the significance of the bioeconomy. The country's economy is distinguished by its high value and its foundation in circular practices, innovation, skill development and the efficient utilization of renewable bioresources. Economic activities are intentionally designed to operate within the natural environment, with the dual objectives of regeneration and job creation, all aimed at enhancing the well-being of its citizens.
Nigeria	In Nigeria, the long-term vision for 2050 prioritizes sustainable development and aims to ensure resilient economic growth that can withstand the impacts of climate change. This vision emphasizes active collaboration among diverse stakeholders across various sectors including the bioeconomy, marine and environmental sustainability and the food industry.
Republic of Korea	The country's LT-LEDS emphasizes the importance of harnessing by-products as valuable resources for bio-industry. Specifically, it highlights the significance of oyster shells, which are a highly prized, recyclable by-product of oyster production. Opportunities for their use include their substitution for conventional limestones, leading to a reduction in GHG emissions and their use in the production of food, pharmaceuticals and cosmetics, reducing waste.
Sweden	The country's National Forest Programme, guided by its vision of forests as "green gold", aims to harness the potential of forests to stimulate job creation, sustainable economic growth and the advancement of a thriving bioeconomy, by efficiently utilizing forest resources while adhering to sustainability criteria aligned with environmental and societal objectives. Furthermore, it prioritizes the preservation or enhancement of the forest's long-term capacity to sequester carbon. Additionally, Sweden plans to collaborate with green industries to formulate a comprehensive, national bioeconomy strategy, focusing on expanding biomass availability, generating employment opportunities and delivering environmental and climate benefits.
Thailand	In the context of decarbonizing the transport sector, the LT-LEDS developed by Thailand includes the promotion of investments in renewable energy technology, fostering research and development in the field of hydrogen and advancing bio-jet technology. Thailand emphasizes its commitment to supporting the growth of the bioeconomy.

(Source: Adapted from FAO 2023)

Several countries have emerged as regional leaders aiming to catalyse cooperation to facilitate trade and technology transfer for biobased innovation. Thailand is a notable example in Asia. The Thai BCG model promotes policy synergies across the bioeconomy, the circular economy the green economy and sustainable development planning (see Appendix 2, Box 3). For instance, circularity principles support biorefinery systems based on bio-waste, while solar PV or wind power can be integrated into bioeconomy strategies (D'Amato and Korhonen 2021). A plurality of approaches for biobased economies offers needed flexibility, particularly considering the multilevel and polycentric nature of biobased systems and their governance (Lubell and Morrison 2021). Integrating innovation and research policies across the bioeconomy, the circular economy and the green economy could boost the uptake of biobased technologies. Kenya has incorporated biobased climate actions and bioeconomy perspectives across a wide variety of legislation and policies (see Table 5.3) and is part of the comprehensive East African Community Regional Bioeconomy Strategy (see Appendix 2, Box 4).

Table 5.3 Policies/strategies in support of biobased technologies in Kenya

Policy/strategy reference	Biomass conversion technologies	Carbon sequestration and utilization technologies	Sustainable agriculture and land use technologies	Biobased materials
(Energy Act 2019)	Promotes development and use of renewable energy technologies, including biomass, biodiesel, bioethanol, charcoal, wood and biogas. The Act encourages cogeneration of electric power by sugar millers and use of municipal waste for energy production (section 75(1)	Supports harnessing opportunities under clean development mechanisms and carbon credit trading to promote renewable energy sources (section 75(2)(g)	Advocates for the use of fast-maturing trees for energy production and establishment of commercial woodlots (section 75(2)(c)	Encourages the production and use of gasohol and biodiesel, promoting biobased alternatives to fossil fuels (section 75(2)(j)
(National Climate Change Action Plan 2018)	Aims to increase the uptake of clean cooking solutions, including biomass briquettes and improved cookstoves (page 130)	Targets increasing forest cover to 10% and rehabilitate degraded lands, enhancing carbon sinks (page 123)	Implement Climate Smart Agriculture to improve productivity and resilience, promoting agroforestry and sustainable land management (page 123)	Encourages climate-resilient buildings and settlements, integrating biobased materials (page 129)
(Climate Change Act 2016)	Mandates the development of a National Climate Change Action Plan to guide low-carbon development (section 13(3)(a)	Establishes a framework for carbon trading, including participation in carbon markets and establishment of a National Carbon Registry (Sections 23B–23G)	Requires integration of climate change responses into sector functions, promoting sustainable land use (Section 13(3)(b))	Supports energy conservation and efficiency, potentially including the use of biobased materials (section 13(3)(j)
(National Energy Policy 2018)	Promotes research, development and dissemination of biomass energy technologies	Collaborates with stakeholders to grow and sustain tree cover, contributing to carbon sequestration	Encourages efficient use of land resources to minimize competition between biomass energy and forestry	Promotes the use of biogas as alternatives to fuel oil (page 33)
(Forest Conservation and Management Act 2016)	Supports sustainable management and use of forest resources, including biomass energy production (section 5)	Manages indigenous forests and woodlands on a sustainable basis for carbon sequestration (section 5)	Encourages community participation in forest conservation, promoting sustainable land use (section 49)	Facilitates the development of forest-based industries, potentially including biobased materials (section 49)
(Climate Smart Agriculture Strategy 2017)	Encourages the use of agricultural waste for biogas and biofertilizer production (page 82)	Promotes agroforestry and conservation agriculture to enhance carbon sinks (page 85)	Implement practices like conservation tillage and crop diversification to improve land productivity (page 80)	Supports the development of value chains for biobased products from agricultural residues (page 93)
(National Solid Waste Management Policy 2021)	Promotes conversion of organic waste into energy, such as biogas and refuse-derived fuel (page 14)	Encourages waste segregation and valorization, contributing to carbon emission reductions (page 16)	Supports sustainable waste management practices that enhance soil fertility (page 15)	Advocates for circular economic approaches, utilizing waste for biobased material production (page 24)
(Kenya Vision 2030 2007)	Identifies renewable energy and green growth as economic pillars, promoting biomass energy (page 8)	Aims to increase forest cover and rehabilitate degraded lands, enhancing carbon sequestration (page 19)	Encourages sustainable land management practices to improve agricultural productivity (page 19)	Supports the development of green/Agro-processing industries, including biobased materials (page 14)

Both broad and targeted policy measures are needed to strengthen the bioeconomy and biobased innovation pathways. Broader measures include levelling the playing field with fossil fuels by abolishing fossil fuel subsidies and implementing policies that support nascent, innovative technologies and practices. Feed-in tariffs for bioenergy, tax incentives to support biobased technologies and practices and specific innovation policies are examples of such targeted measures. In Germany, an interesting example of targeted innovation policies with a concrete outcome is the Bioökonomierevier initiative in the German Rhineland, which makes use of former coal mining sites as hubs for biobased innovation (Biooekonomierevier 2025).

Policies and development plans should aim at raising awareness of innovative biobased technologies among key stakeholders, which is still lacking in regions such as sub-Saharan Africa and South-East Asia (Bößner *et al.* 2023). Besides information campaigns, policies to implement pilot projects that facilitate peer-to-peer learning at the community level could strengthen the adoption of biobased technologies.

In regions such as Asia and sub-Saharan Africa, tackling land rights and tenure issues would help the scaling of biobased mitigation and adaptation options. In the same vein, policies that facilitate the founding of cooperatives and other mechanisms to pool the supply of sustainable biomass might help to scale innovative biobased mitigation and adaptation options (Gomez San Juan *et al.* 2022a). Since the level playing field between biobased and fossil fuel-based technologies and materials remains unfavourably biased towards the latter, dedicated support policies for biobased products, technologies and practices are needed. As an example, Brazil offers a minimum floor price for a certain number of sustainably sourced bio-products, should the market price fall below a certain threshold, to guarantee income for local communities even when prices fall (Silva *et al.* 2022; Mascarenhas *et al.* 2025). Similarly, tax breaks for new technologies or insurance policies that provide a safety net when users switch from one technology or practice to another could help scale bioeconomy technologies and practices.

Lastly, integrating comprehensive sustainability assessments into bioeconomy policies and regulatory frameworks is essential to ensure that environmental, social and economic impacts are considered. These assessments can help identify potential challenges, such as land degradation or food insecurity, and therefore guide more informed and equitable decision-making. Monitoring, Evaluation and Learning (MEL) protocols, including life cycle assessment and other methods, can support improved policy design for moving towards best practice (Lago-Olveira *et al.* 2024). These approaches also strengthen transparency and accountability, which are critical for gaining public trust and fostering long-term policy effectiveness.

While policy and regulatory reforms can unlock biobased mitigation potential, their lasting success depends on the ability of these systems to withstand increasingly volatile climate conditions. This calls for an integrated vision that embeds risk management, resilience and biodiversity into bioeconomy strategies, ensuring mitigation gains are protected and biobased innovations also deliver strong adaptation and socioeconomic benefits.

5.3 THE CO-BENEFITS OF RISK MANAGEMENT, ADAPTATION AND SUSTAINABLE DEVELOPMENT

Building on these policy and regulatory foundations, it is equally important to address the risks and vulnerabilities facing the bioeconomy, ensuring that mitigation efforts are reinforced by adaptation measures and co-benefits that enhance ecosystem and community resilience. The basic policy and regulatory frameworks outlined above have tended to emphasize mitigation and connections to selected key SDGs. However, the climate sensitivity and site-specific nature of biobased technologies suggest the need to view them within the context of the growing frequency and intensity of climate impacts, both observed and projected. Effective adaptation also depends on governance mechanisms that align policies across sectors and levels of government, ensure adequate financing and integrate scientific and local knowledge into decision-making. Innovative adaptation technologies and practices are needed in tandem with ongoing mitigation efforts (European Environment Agency 2024; IPCC 2022c). Climate adaptation requirements in the context of the bioeconomy are particularly great considering the growing pressures facing ecosystems due to rapidly increasing risks from wildfires, droughts, floods, invasive species and pest outbreaks. Climate adaptation innovation will therefore play a critical role in ensuring that the bioeconomy can withstand both shocks from extreme climate events and dangerous slow-onset changes. Improving soil health is a key example of how integrated climate action can deliver both adaptation and mitigation benefits. Healthier soils enhance water retention, reduce erosion and increase resilience to drought, floods and wildfires, while also supporting land-based carbon removal. This makes soil restoration a high-impact strategy for building a climate-resilient and sustainable bioeconomy (Gomez San Juan *et al.* 2022a; Lal 2011). Adaptation technologies include remote sensing systems for wildfire risk monitoring, artificial intelligence-based early-warning tools to detect crop stress, climate-resilient crop varieties resistant to drought and pests, precision irrigation systems and digital surveillance platforms for integrated pest and disease management (WEF 2024a; Zhu *et al.* 2011). At the same time, the development of a sustainable bioeconomy for the purpose of climate mitigation and land-based carbon removal can deliver adaptation co-benefits, such as through ecosystem restoration, sustainable forest management and improved soil health and enhanced water catchment (Gomez San Juan *et al.* 2022b). Such measures have been shown to reduce climate-related losses, safeguard livelihoods and maintain critical ecosystem services, thereby delivering tangible social and economic returns (Hurlbert *et al.* 2019 ; World Economic Forum 2020).

The need for an integrated approach to harmonize climate mitigation, biodiversity and adaptation objectives is, however, particularly warranted at the level of policy. Integrating climate adaptation and mitigation objectives into bioeconomy policies remains a governance challenge, partly because adaptation has historically received far less attention and investment than mitigation (Richmond *et al.* 2020). This challenge is compounded by the fact that adaptation and mitigation policies are often developed in sectoral silos, leading to fragmented planning, limited coordination and missed opportunities for leveraging synergies across land use, agriculture, forestry and biodiversity policy domains (Kappe *et al.* 2025).

To put this in numbers, of the national planning instruments communicated by countries by 2023, the nearly two hundred national parties to the UNFCCC and UNCBD, only two NAPs, eight NBSAPs and nine Biodiversity National Reports explicitly referenced bioeconomy solutions, while 23 National UNFCCC Reports and Communications did so (FAO 2023).

The failure to design and implement effective policies to enhance the resilience of our ecosystems can result in irrevocable changes caused by climate change. These changes can undermine the critical role of the bioeconomy in overcoming sustainability challenges by compromising the wide range of ecosystem services upon which we rely on for biomass production, carbon sink, food security and biodiversity conservation (IPCC 2023; Pilling and Bélanger 2019). Indeed, the escalating economic and societal costs from climate-related disasters, a growing expression of climate-induced loss and damage, have underscored the urgency for governments and companies to address this persistent gap in climate policy. As noted in the examples given in Table 1 of selected commitments from six national bioeconomy strategies, there is potential for deeper integration and sustainable development synergies across adaptation, mitigation and biodiversity (FAO 2023).

In Asia, the high vulnerability to climate change makes it essential that bioeconomy developments address adaptation and risk management alongside mitigation and Sustainable Development Goals (World Meteorological Organization 2024). This is increasingly reflected in national governance frameworks such as adaptation and sectoral strategies. The cases of China and India have disproportionate importance due to their significance in global markets and in technological development. In terms of land and biomass management, agricultural and forest sector policies and strategies reflect consideration for both longer-term resilience as well as promoting near-term shifts to best practices. In the NAS towards 2035 produced by China, the government promotes climate-resilient agriculture, enhanced early-warning systems for forests and grasslands, pest and disease control and ecosystem-based adaptation in terrestrial and marine environments, supported by targeted investments and institutional coordination (Ministry of Ecology and Environment of the People's Republic of China 2022). In fact, there has been a long record of policies and regulations supporting afforestation and reforestation in China, in recognition of its multiple benefits for carbon sequestration and ecological resilience (Mal *et al.* 2024).

India has integrated adaptation into national and state-level bioeconomy policies, including its BioE3 policy and the NICRA programme (Government of India 2021; IndiaBioscience 2025; Manju Prem *et al.* 2024), which focus on climate-resilient crops, climate-smart farming and technology demonstration projects, while subnational plans such as that produced by the city of Chandigarh link bioeconomy measures to water conservation and forest management (Chandigarh Union Territory Administration and ENVIS Centre Chandigarh 2022). However, implementation faces persistent hurdles. In China, local growth priorities and fragmented governance can dilute adaptation measures and nature-based solutions remain underdeveloped (Zhang *et al.* 2020; Yu and Mu 2023). In India, limited funding, skill gaps and weak coordination hamper progress (Ather and Madan Gopal 2024) biomanufacturing, bio-based solutions, and biopharma. The government's Bio-E3 (Biotechnology for Economy, Environment and Employment. Closing these gaps through stronger policy coherence, measurable indicators and scaled investment in nature-based solutions will be critical for bioeconomy strategies to both advance climate goals and increase socioeconomic resilience.

The European Union has advanced bioeconomy development through policies linking climate mitigation, adaptation and biodiversity objectives. Its 2018 Bioeconomy Strategy calls for leveraging co-benefits between mitigation and adaptation while managing trade-offs (European Commission 2018). Climate adaptation in the bioeconomy is supported by instruments such as the Common Agricultural Policy (CAP) 2023–2025, which promotes climate-resilient farming practices through eco-schemes and funds rural infrastructure to improve resilience (European Union 2021; European Commission 2025a). A major milestone is the Nature Restoration Law, which transforms biodiversity and forestry targets into legally binding commitments that also enhance carbon sink capacity. Targets include restoring 30 per cent of degraded habitats by 2030 (90 per cent by 2050), re-establishing 25 000 km of free-flowing rivers, rewetting 30 per cent of drained peatlands, and planting three billion trees. These measures strengthen ecosystem resilience, protect biodiversity and boost natural carbon sequestration, delivering adaptation gains while advancing mitigation goals. The law requires member states to produce National Restoration Plans by 2026, standardized monitoring and regular reporting, and aligns with the CAP, the European Union Biodiversity Strategy, Green Deal, Climate Law and Water Framework Directive for policy coherence. However, progress has been uneven across Member States, and implementation of adaptation measures in the bioeconomy has often been constrained by fragmented governance and a historical emphasis on mitigation; the Nature Restoration Law seeks to address these gaps by creating binding obligations and a unified framework for ecosystem resilience. Together with the revised European Bioeconomy Strategy and the 2025 European Union Vision on Agriculture and Food, the European Union has placed the bioeconomy at the heart of building sustainable, climate-resilient systems that restore nature and maintain vital carbon sinks.

In Africa, the continent's bioeconomy potential is closely tied to its rich natural capital, yet it faces some of the highest climate vulnerabilities globally (IPCC 2023). Many African countries integrate adaptation into bioeconomy measures through NAPs and NDCs, supporting agroforestry, rangeland restoration and sustainable forest management. These approaches protect biodiversity, enhance carbon sinks and improve food and water security. Regional frameworks, such as the African Union Climate Change Strategy and the Great Green Wall Initiative, link large-scale land restoration with livelihoods and resilience (African Union 2024). In the East African Community (EAC), the EAC Regional Bioeconomy Strategy (See Appendix 2, Box 4) envisions a climate-resilient bioeconomy but faces a variety of barriers including fragmented policy integration, insufficient climate finance, institutional weaknesses, poor coordination, data and monitoring gaps, and limited infrastructure and technical capacity (Campbell and Hope 2025; EASTECO 2022). These constraints slow the implementation of biobased technologies and limit the scaling of technologies such as drought-tolerant crops, resilient biorefineries and circular bioresource systems. Strengthening governance coherence, bridging finance gaps, improving climate data systems and investing in capacity-building will be essential to realize the adaptation, mitigation and socioeconomic benefits of the bioeconomy in Africa while building resilience to intensifying climate extremes (UNEP 2023; Virgin *et al.* 2024).

Collaborations that transcend both national and sectoral borders are vital to harness the synergies between mitigation, adaptation and biodiversity objectives (United Nations Environment Management Group 2025). However, such collaborations must embed justice and equity dimensions, as outlined in Chapter 3, at the heart of efforts to ensure that the measures address the unequal burden from climate impact on the bioeconomy across countries and communities. The Pan-Amazonian Network for Bioeconomy, launched at the COP16 on Biodiversity in Colombia, is a good case in point (AMZBio, n.d.). This multi-sectoral alliance brings together local producers and associations, indigenous communities, impact investors, financial institutions, research institutes and civil society, with the aim of supporting economic development in alignment with environmental stewardship and social equity. In particular, the network works on developing an integrated knowledge base, creating a collaborative platform and strengthening access to finance, in concert, to support sustainable forest-related business models to replace activities that lead to deforestation, thereby contributing to both ecosystem and community resilience in the face of climate change (WEF 2023).

5.4 MULTILEVEL GOVERNANCE AND INTERNATIONAL COOPERATION

Governance of the use of bio-resources and of biobased technologies requires an inclusive approach that considers the range of bioeconomy visions held by stakeholders (Bugge 2016). International cooperation has emerged in a variety of forms to support the implementation of these strategies and to establish common platforms for sharing lessons on policy and governance. Good governance draws on consultations with a wide variety of stakeholders and helps ensure that opportunities and trade-offs, especially those that have not been foreseen, are adequately assessed and accounted for (Gomez San Juan 2024). The need to facilitate bio-resource availability across different sectors, applications and technologies means that bioeconomy policies and regulations often have to contend with multilevel coordination and governance, ranging from local to global, in order for markets to expand and develop (Johnson *et al.* 2025).

Broadly speaking, four types of governance for international cooperation can be identified:

- market and economic (Jordan *et al.* 2003)
- knowledge-based (van Buuren and Eshuis 2010)
- informational (Jordan *et al.* 2003)
- commitment and agenda-setting (Widerberg *et al.* 2016)

Market and economic governance mechanisms involve steering society by shifting markets towards more sustainable technologies. A prominent example is the EU ETS which, by being technology neutral, allows the market to identify and adopt the most effective solutions for reducing emissions. It is possible to differentiate between knowledge governance and informational governance in that while the former focuses on research, innovation and development, the latter focuses on standard setting, monitoring and verification (Bößner *et al.* 2021). The commitment and agenda-setting governance category particularly characterizes international regimes such as the United Nations conventions.

As shown in Table 5.4, different international institutions and governance approaches have different strengths and weaknesses in advancing biobased technologies. International trade can support related technology transfer across some of these platforms and institutions, to accelerate technology adoption in line with UNFCCC principles and Paris implementation mechanisms (Souza 2025). At the same time, safeguards, sustainability monitoring and bilateral cooperation mechanisms are needed to ensure that biomass exporting countries do not face negative social and environmental impacts from unsustainable practices. Biobased technologies require integration between adaptation and mitigation aims and calls for transparent governance across a wide range of stakeholders for successful technology deployment to maximize benefits and manage trade-offs (Babiker *et al.* 2022).

Table 5.4 Bioeconomy governance characteristics of selected international institutions and/or organizations (Adapted from: Bößner *et al.* 2021)

Institution/Organization	Existing structures in place relevant to the bioeconomy	Key potential role in international governance	Shortcomings and challenges
Economic and market governance			
World Trade Organization (WTO)	No specific strategies, but have mandate and authority to play important role in economic and market governance	Harmonization of trade rules for biomass and bioproducts; address un-enforced environmental regulations	Impacts of free trade on food security; decreasing appetite for multilateralism
Organisation for Economic Cooperation and Development (OECD)	Among first transnational bioeconomy/biotechnology strategies; IEA evaluations of bioeconomy policies/technologies	Policy recommendations that can serve as international standards	Limited membership; limited accountability
United Nations Conference on Trade and Development (UNCTAD)	Biofuel initiatives, promotion of circular/bio-economy	Credibility and neutrality in supporting diverse perspectives; memorandum of understanding linking UNCTAD with WTO could support global trade in biobased products	Bureaucracy and difficulty with financial support can hinder progress
G20	Increasing focus and priority on bioeconomy and circular economy. The G20 Initiative on Bioeconomy is an intergovernmental body created in December 2023	Potential to act as a critical mass in driving and scaling biobased technologies, convening and coalition-building capacity	No binding mandate or authority for operational decisions
Knowledge governance			
Biofuture Platform	Intergovernmental body promoting international collaboration and dialogue on bioeconomy issues	Includes important bioeconomy actors and/or biofuel producers (Brazil, Indonesia)	Tends to focus on biofuels rather than broader bioeconomy; dependence on each country's capacity to engage
Food and Agriculture Organization (FAO)	Bioeconomy established as a strategic priority for FAO for the 2022-2031 period. Work dedicated to bioeconomy since 2015. Received a mandate from Members in 2024 to develop Global Partnership on Bioeconomy for Sustainable Food and Agriculture	Provision of key metrics, guidelines and elements for strategy and implementation. Neutral convening capacity, e.g. as potential future facilitator of Global Partnership on Bioeconomy for Sustainable Food and Agriculture. Unique role in capacity for sustainable intensification for biomass production and use	Work programme is extremely ambitious and needs more capacity and financial support. Institutional mandated focuses on agrifood systems, requiring collaboration also with non-agrifood system actors to cover the full breadth of bioeconomy
United Nations Environment Programme (UNEP)	UNEP "green economy" programme; green growth knowledge platform; Environment and Trade Hub	Unique role in capacity for linking biodiversity/ecosystems to climate and bioeconomy	Broad and complex mandate of UNEP can complicate progress
World Intellectual Property Organization (WIPO)	WIPO Green marketplace as a database and means of stakeholder engagement on biobased technologies	Agreements on patents and intellectual property rights (IPRs); WIPO Treaty adopted 2024 on interface between IP and genetic resources	Intellectual property rights may have a negative impact on technology transfers to less industrialized (or low-income) countries
International Bioeconomy Forum (IBF)	Guides international cooperation for sustainable bioeconomy, with a focus on research and innovation	Strong basis for knowledge governance role, especially within the European Union	somewhat limited in membership, towards OECD countries
World Bioeconomy Forum (WBF)	Private sector platform for exchange on bioeconomy/technology	Could help to mobilize finance and public-private cooperation	Relationships with other bioeconomy platforms not always clear
International Advisory Council for the Global Bioeconomy (IACGB)	Convening advisory platform of about forty high-level bioeconomy leaders and experts from around the world from policy, science, civil society and business sectors.	Produces key reports and dialogues; Initiates, designs and organizes the Global Bioeconomy Summit, a key global conference and platform for exchange.	Broad mandate alongside dual role of many members in advising their own national governments as well as serving on IACGB can impact effectiveness.
Information governance			
Roundtable on Sustainable Biomaterials (RSB)	Organizes working groups, issues sustainability certificates and provides tools	Fills the gap in providing standardization for sustainable bioeconomy and bio-resource use	Overlaps with other standards used by the international community
Global Bioenergy Partnership (GBEP)	Convenes a wide range of members including national governments and international organizations, focusing on sustainable bioenergy. Relevant stakeholders, including major bioenergy producers are involved in GBEP dialogues. Published sustainability indicators for bioenergy already in 2011. Currently discussing the use of these indicators to assess the sustainability of bioenergy in the context of the wider bioeconomy	Established to reflect a 2005 G8 mandate. FAO has led the GBEP Secretariat since its establishment in 2006. Strong linkages to G7 and G20 could be useful for international governance	Limited membership could be barrier to universal acceptance; focus on bioenergy and biofuels does not easily cover key non-energy elements of bioeconomy
International Organization for Standardization (ISO)	Standards for environmental management systems, GHG accounting systems, etc.	Potential for standards to promote best practice bioeconomy/technology; generally compatible with WTO	May favour higher-income nations; standards need to be "translated" into detailed, enforceable legislation by national legislators
Commitment and agenda-setting			
Convention on Biological Diversity (CBD)	Cartagena Protocol (CP); Nagoya Protocol (NP); Kunming-Montreal Agreement	Voluntary guidelines for design and effective implementation of ecosystem-based approaches to climate adaptation and disaster risk reduction can support sustainable bioeconomy strategies	Bureaucracy that might delay new biobased product development; potential conflicts with technology development (e.g. genetically modified organisms)
United Nations Convention to Combat Desertification (UNCCD)	Touches on variety of land issues relevant to bioeconomy, especially land degradation; G20-UNCCD collaboration	Potential to provide governance frameworks for key land use issues linked with bioeconomy/technology and bio-resources	Difficulties in achieving objectives due to diffuse and diverse land use governance issues, which can impede or advance the bioeconomy
United Nations Framework Convention on Climate Change (UNFCCC)	Climate-related mitigation measures e.g. renewable energy, afforestation etc have strong linkages with bioeconomy concepts; REDD+ initiative connects to the bioeconomy	Potential to utilize UNFCCC as a more direct forum to advance biobased technologies and find synergies with climate goals and targets	Scope of the Convention's mandate can complicate cross-sectoral approach of the bioeconomy

Governance of the bioeconomy is not easily analysed on the basis of climate goals but is more likely to be broken down either on the basis of the aforementioned bioeconomy visions (biotechnology, bio-resources, bio-ecology; see introduction to this chapter) or in relation to sectoral management (agriculture, forestry, energy, livestock, etc.). However, it is useful to consider the case of biobased CDR, considering its linkages to adaptation and bioeconomy development more generally as well as mitigation. The emerging market for biobased carbon removal includes both nature-based solutions and so-called "durable CDR," which refers to more technology-based solutions that cannot easily be reversed by changes in policy or natural events such as wildfires (Streck *et al.* 2025). The growth of the durable CDR market in recent years and its dominance by a few key corporate actors underscores the distinction and its effects on market governance (see Chapter 4). At the same time, nature-based solutions may have significant contributions to make towards biodiversity and other SDGs.

Turning from international or regional levels to more local levels, the sustainable scaling of biomass-based CDR calls for feedstock sourcing that protects land rights and biodiversity, and does not contribute to deforestation, which can involve landscape governance across jurisdictions (Diaz-Chavez and van Dam 2020). Inclusive governance models that recognize the differing visions of stakeholders (see introduction to this Chapter) and promote direct engagement have a greater chance of succeeding in advancing biobased technologies (Johnson *et al.* 2022). Inclusive governance models are particularly important in protecting the rights of IPLCs but can go much further in recognizing their role as stewards of bio-resources and biotechnology, with respect to carbon, biodiversity and resilience (Astolfi *et al.* 2025). Harnessing biodiversity sustainably calls for certain key principles: (1) empowerment of IPLCs; (2) diversifying and differentiating local bioeconomies for greater added value; (3) combining local-empirical and techno-scientific knowledge; (4) ensuring digital access and standardization to leverage natural capital (Johnson *et al.* 2024).

These principles connecting to local communities and stewardship are found to some extent across the Rio Conventions and Protocols and support the bottom-up development of the bioeconomy. Although it has no formal relation to the Rio Conventions, the bioeconomy has linkages across of them, particularly in terms of biobased and land-based measures and technologies. In addition to the obvious linkages with UNFCCC principles, the sustainable use of biodiversity and the restoration of degraded lands connect biobased technologies to the UNCBD and UNCCD. Among other international institutions concerned with governance of the bioeconomy, one key leadership institution is the IACGB, which conducts expert meetings, produces key reports and serves as the scientific committee for the Global Bioeconomy Summit (GBS), most recently held in Nairobi in October 2024 (Global Bioeconomy Summit, 2024). As shown in Table 5.4, many other international platforms and institutions are engaged in governance of the bioeconomy with different aims and structures (Bößner *et al.* 2021).

Digitalization offers new opportunities and also raises a variety of governance issues and challenges for small-scale actors. Rapidly expanding access to large databases, new applications for artificial intelligence and the digitalization of key biophysical and bio-economic data can facilitate the rapid advancement of biobased climate solutions. The digital economy, which is increasingly linked to the development of biobased markets and systems, has significant implications with respect to appropriate policies, regulations and governance (Pyka 2017). The transition from agriculture-based digital economy to a digital bioeconomy involves overcoming social and institutional barriers as well as technical and economic constraints (Eastwood *et al.* 2023). Crops which are key to the development of the bioeconomy such as cassava (see Appendix 2, Box 5) have innovation platforms that can be further extended through enhanced access to digital technologies. More generally, the shift from fossil fuel-based economies to renewable-based economies involves managing both the opportunities and the risks associated with regulation and governance of digital technologies (United Nations Environment Programme, n.d.).

Despite considerable progress over the ten years since the first GBS was held, global governance on the bioeconomy remains somewhat fragmented. Countries are therefore looking for greater coherence and international cooperation, calling for

> ***"A multi-stakeholder global bioeconomy partnership for sustainable agrifood systems to serve as a catalyst for the development of policies, strategies, and plans, building capacities, knowledge systems, and incentives at global, regional, national, subnational and local levels" (FAO 2024c and FAO 2024d).***

Drawing on an inclusive consultation process, FAO is facilitating the development of a proposal for such a partnership (GFFA 2025). Anchoring biobased technologies alongside agrifood system development in such partnerships helps to ensure that food security is enhanced (see Appendix 2, Box 6). This global momentum is also evident in the G20 Bioeconomy Initiative, launched under the presidency of Brazil in 2024 and carried forward under the presidency of South Africa in 2025, as well as the 2024 GBS Communiqué (IACGB 2024b), signalling a clear commitment towards structured, multilateral engagement.

One key governance issue for such multilateral cooperation is safeguarding the sustainability of a growing bioeconomy, since additional demands for biomass will put additional environmental pressures on natural resources (land, water and biodiversity). Sustainability frameworks, such as the FAO Aspirational Principles and Criteria for a Sustainable Bioeconomy (FAO 2021) as well as broader multilateral statements such as the G20 High-Level Principles on Bioeconomy (G20 2024), facilitate improved articulation and management of conflicting demands and trade-offs. Robust monitoring approaches underpinned by sound indicators and data are fundamental to assess the effectiveness of individual bioeconomy initiatives and to generate a strong evidence base that can help strengthen political commitment (e.g. through improved representation of biobased technologies within NDCs and attract greater investment in sustainable bioeconomy activities at scale) (Bracco *et al.* 2019; FAO 2025).

5.5 CONCLUSIONS

Policies, regulations and governance for the bioeconomy and/or biobased technologies exhibit considerable diversity and cover all levels from local to global. Some examples from national and subnational perspectives reveal that certain countries are acting as regional leaders and could serve as catalysts for regional and global efforts and upscaling. The differing visions among bioeconomy stakeholders (biotechnology, bio-ecology, bio-resources) affect the design of governance mechanisms and the capacity to reach consensus, as well as highlighting the fact that bioeconomy strategies and policies need to recognize local and national priorities and capacities. Despite and perhaps because of this heterogeneity, a wide array of international institutions and cooperation platforms have emerged, especially during the past decade or so, in recognition of the importance of enhancing capacity on bioeconomy strategy implementation and wider deployment of biobased technologies. This diversity of institutions has provided a testing field from which new initiatives can be formed to consolidate and strengthen bioeconomy governance. Future efforts through G20, FAO and other global platforms can complement national and subnational programmes and strategies by enhancing transnational technology learning and exchange.

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CHAPTER HIGHLIGHTS

- The bioeconomy in Latin America and the Caribbean follows diverse, context-specific pathways, shaped by the region's unique socio-ecological conditions.
- Latin America and the Caribbean hold exceptional potential for bioeconomic innovation, driven by rich biodiversity, diverse ecosystems, and strong agricultural systems. However, uneven institutional, infrastructural, and governance capacities across countries pose challenges to scaling innovation. Unlocking this potential requires targeted investments and support to foster inclusive, sustainable, and innovation-led bioeconomic transitions.
- Sectors in the bioeconomy, such as agriculture, forestry, fisheries, and biotechnology, form a strategic nexus between economic growth, sustainable development, and climate action. These sectors contribute meaningfully to Nationally Determined Contributions (NDCs) and other national climate plans, yet their integration into formal climate policies across Latin America and the Caribbean remains inconsistent and fragmented.
- Strengthening the link between bioeconomy strategies and NDC frameworks is essential to fully harness synergies between climate mitigation, adaptation, and sustainable production systems. A more systematic approach will enhance the region's capacity to deliver on climate goals while advancing inclusive and resilient bioeconomic development.
- Social inclusion is fundamental to building a just and resilient bioeconomy. Pursuing bioeconomic opportunities without recognizing indigenous rights, cultural heritage, and local livelihoods risks reinforcing existing inequalities. By contrast, pathways that integrate the knowledge and contributions of indigenous and local communities enhance legitimacy, strengthen socio-ecological resilience, and ensure that bioeconomic transitions are both ecologically sustainable and socially just.
- Regional cooperation and policy coherence are critical to aligning the region's ecological potential with inclusive and sustainable socio-economic outcomes.

Part II

6.

Regional focus – Latin America and Caribbean

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6.1 INTRODUCTION

The Latin America and the Caribbean region uniquely combines ecological richness with development challenges, positioning the region to become a leader in bioeconomy innovation and low-carbon, climate-resilient transitions. The bioeconomy in LAC encompasses diverse activities that contribute to climate change adaptation and mitigation, sustainable development and improved local livelihoods. These efforts present strategic opportunities to integrate bioeconomy initiatives, including biobased technologies, into national climate plans, reinforcing the role of LAC in global climate action while promoting inclusive growth.

To fully harness the transformative potential of the bioeconomy in addressing social inequality and ecological degradation, strategies must be inclusive and locally adapted. Tailored approaches can unlock the region's unique strengths and diverse opportunities, fostering more inclusive and effective outcomes. This includes aligning ecological integrity with socioeconomic aspirations and building on existing advancements, which again require enabling policy frameworks that foster innovation, equity and climate resilience on various scales (Lewandowski 2018; Sillanpää and Ncibi 2017; Gonzalez and Sanchez 2023).

LAC is home to over 40 per cent of global biodiversity (IPBES 2018), concentrated in ecosystems including the Amazon basin, the arid zones of Mexico, the savannas of Brazil, and the Andean páramo (Brassiolo *et al*. 2023; Sasson and Malpica 2018; Bergamo *et al*. 2022; Espinosa and Rivera, 2016). The region's biological resources, such as lignocellulosic biomass, tropical fruits, medicinal plants, aquatic biomass and ecosystem services such as carbon sequestration, water regulation and cultural preservation are foundational to its bioeconomy.

The ecological complexity of LAC also underpins distinct patterns of economic specialization across its industrial sectors, offering diverse entry points for bioeconomy contributions. Argentina and Brazil have developed large-scale production systems for soybean and sugarcane, supporting global biofuel markets (Sillanpää and Ncibi 2017; Islam and Hossen 2025). In contrast, Andean and Central American countries maintain smallholder-led agroforestry and shade-grown coffee systems that sustain biodiversity and rural livelihoods. Chile has invested in sustainably managed forest plantations that integrate wood production with ecosystem stewardship (Balocchi *et al.* 2023). Ecuador and Peru operate robust fisheries and aquaculture sectors, leveraging nutrient-rich coastal upwelling zones (Sasson and Malpica 2018).

Recognizing and managing these bio-assets is essential for integrating LAC into global bioeconomy and trade systems (Olmos and Mulder 2024). Biodiversity, forests, agricultural biomass and marine resources are vital for livelihoods, industrial development and the transition to low-carbon economies (Calicioglu and Bogdanski 2021). The transition pathways in LAC are deeply rooted in local socioecological systems, featuring innovations such as sustainable agriculture, circular biobased products, nature-based solutions (NbS) and indigenous-led value chains. Notable examples include the community forestry in Peru (Capello *et al.* 2022; Christmann *et al.* 2025), the bioproduct clusters in Colombia (Van Hoof *et al.* 2023; Henry *et al.* 2018), and the RenovaBio and Combustível do Futuro programmes in Brazil promoting low-carbon fuel certification.

Several LAC countries have already identified a role for biobased technologies and related strategies in their Nationally Determined Contributions. For example, Colombia includes bioeconomy innovation clusters in its NDC (Colombia 2020), Uruguay highlights bioeconomy as a key strategy for sustainable development, linking low-carbon production, innovation and circular resource use to climate goals (Uruguay 2024), Costa Rica positions bioeconomy and nature-based solutions as core strategies for achieving low-emission development, enhancing ecosystem resilience and promoting inclusive green growth (Costa Rica 2022) and Peru highlights the bioeconomy as a pathway to promote low-carbon growth, biodiversity conservation and rural development, especially in Amazonian and Andean regions (Peru 2020). Expanding these linkages through measurable targets and reporting frameworks can help mainstream biobased technologies within national climate agendas and unlock international finance and technology transfer (Calicioglu and Bogdanski 2021; Van Hoof *et al.* 2023). Biobased technologies often offer measurable contributions to both mitigation and adaptation. One example of strong synergetic linkages in a country's NDC is the Strengthened First NDC published by Chile in 2022. This includes a broad set of measures under its integrated mitigation and adaptation chapter, reflecting the country's commitment to synergistic climate action that links the reduction of emissions with building resilience (Chile 2022).

Recognizing these diverse systems, technologies and innovations, which range from climate-smart practices and forestry to waste-to-resource approaches, as "climate technologies" under the UNFCCC framework not only highlights their mitigation and adaptation potential but also facilitates their integration into NDCs. Their explicit inclusion in NDCs strengthens national adaptation planning, aligns with responsible resource management strategies and opens pathways to international support mechanisms and financing as elaborated upon in Chapter 4 of this report.

This chapter provides a regional assessment focused on the LAC region, with particular attention to biobased technologies. As a region which is rich in biodiversity and biomass resources, understanding the dynamics of technology development and transfer in biobased solutions is essential to enhance and accelerate the implementation of climate technology.

6.2 PROGRESS ON IMPLEMENTATION OF BIOBASED TECHNOLOGIES IN THE REGION

6.2.1 Key trends on implementation status

Biomass conversion technologies in Brazil and Argentina have made notable progress in second-generation bioethanol derived from lignocellulosic feedstocks such as sugarcane bagasse, straw and forestry residues (Faria et al. 2024; Igwebuike et al. 2024). Biomass conversion contributes to mitigation through substitution and sequestration. Biobased fuels and materials replace high-emission fossil-fuel derived alternatives, yielding substantial lifecycle reductions in GHGs (Dias *et al.* 2019). Furthermore, improved management of agricultural residues and forest by-products enhances soil carbon retention and avoids methane emissions from unmanaged organic waste (Cherubini and Strømman 2011). The RenovaBio policy in Brazil promotes the expansion of biofuels to reduce carbon intensity in the transportation sector (Brazil, Ministério de Minas e Energia 2021).

It supports biobased technologies such as ethanol (from sugarcane and corn), biodiesel (from soybean oil and animal fats), biomethane (from organic waste) and emerging biojet fuels. Producers voluntarily certify their biofuel production using the RenovaCalc tool, which applies life cycle analysis to determine carbon intensity and assigns an energy-environmental efficiency score. This score determines the number of CBIOs (decarbonization credits) a producer can issue, incentivizing low-carbon production. RenovaBio thus integrates environmental performance with market mechanisms to drive sustainable biofuel development. Mexico and Argentina implement biogas and composting systems for municipal organic waste, reducing methane emissions and replacing synthetic fertilizers. Agro-industrial residues are valorized for bioenergy and biomaterials, supporting circular economy goals. Both countries reference these actions in their NDCs as key strategies to reduce emissions and for energy security (Mexico 2022; Argentina 2021).

From an adaptation perspective, diversified bioenergy systems provide decentralized access to energy in rural and peri-urban areas, contributing to energy security, enhancing local economies and reducing vulnerability to the price volatility of fossil fuels. Additionally, anaerobic digestion processes produce digestate co-products that can serve as biofertilizers, enhancing nutrient cycling, soil health and crop productivity under climate stress (Möller and Müller 2012).

Box 6.1: Statistical and geographical system for the evaluation of the energy potential of biomass resources in the countries of the Central American Integration System

Latin America has a wealth of biomass resources which are as yet unexploited and, in some cases, unaccounted for. The Central American Integration System (SICA) comprised of Belize, Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, Panama and the Dominican Republic, in conjunction with multiple partners, has supported the development and implementation of the Statistical and Geographical System for the Evaluation of the Energy Potential of Biomass Resources in the countries of the Central American Integration System.

The platform's functionalities include indicating geographical zones of interest, what type of resource (classified as forest biomass, agriculture and agro-industrial residue, fishing residues, urban residues and energy crops), sustainability criteria (for example, location of Natural Protected Areas, areas with steepness greater than 10°), technologies for transformation (for example, transforming raw material into heat, electricity and/or fuels), final users (current and potential bioenergy users), optimization (for example, optimizing the location of electric generation plants), simulations and personalized reports. These functionalities help tailor the calculations to specific needs, for example, using different types of residue based on where the nearest roads are, as well as existing electricity transmission and distribution lines. The tool enables calculations to be made in real time incorporating the specific parameters or needs of users. These functionalities thus enable considerations of climate change mitigation, climate change adaptation and sustainable development to be properly analysed and planned for.

The Economic Commission for Latin America and the Caribbean (ECLAC), together with the developers of the National Autonomous University of Mexico (UNAM) and its research institutes, have worked with actors in each member country, not only to deliver multiple training sessions to government officials and other actors but also to transfer the tool and enable governments to upload data and improve functionality to suit evolving needs. This has enabled governments to better plan and has remained a priority for SICA's Council of Energy Ministers.

This tool has been used to create publications of biomass potential for several SICA member countries and has influenced the energy planning of the respective countries.

Source: ECLAC website.

Bio-CCUS technologies are increasingly being implemented and are embedded in national climate strategies across the LAC region, reflecting a convergence of nature-based and engineered approaches to carbon management. Prominent nature-based solutions include mangrove and wetland restoration in Colombia and Panama, forest conservation in Peru, and silvopastoral systems in Mexico, which integrate woody perennials with pasturelands to enhance biomass carbon sinks while supporting biodiversity, rural livelihoods and land productivity. Engineered solutions such as biochar, produced from pyrolysed agricultural residues, are gaining traction in countries like Brazil, where studies show its potential for soil carbon sequestration and emission reduction (Lefebvre *et al.* 2020). In Colombia, the National Bioeconomy Strategy promotes agroecological models in coffee production that enhance carbon sequestration and climate resilience (Colombia, Ministério de Ciencia, Tecnología e Innovación 2020). Additionally, countries like Mexico and Brazil are exploring bioenergy with BECCS and biomethane systems, supported by regional initiatives such as EUROCLIMA+ and national CCUS road maps, which aim to integrate Bio-CCUS into long-term decarbonization pathways (Hennig *et al.* 2023; EUROCLIMA+ 2022).

Sustainable agriculture and land-use technologies constitute a critical component of climate strategies by offering co-benefits that span mitigation, adaptation, food security and biodiversity conservation (Smith *et al.* 2019; Altieri and Nicholls 2017; Vrabcová 2024). These biobased technologies are increasingly being promoted across countries such as Uruguay, Costa Rica and Cuba to transform agrifood systems towards resilience and sustainability while contributing to circularizing the economy (Lal 2020; Tittonell 2014). Their climate mitigation potential lies in reducing GHG emissions, particularly nitrous oxide from fertilizers and methane from livestock, while enhancing soil organic carbon stocks and water retention capacity (Paustian *et al.* 2016). These biobased technologies also contribute to system-wide resilience, buffering agricultural productivity against extreme climate events such as droughts, floods and temperature anomalies (Howden *et al.* 2007). Importantly, biobased technologies within sustainable agriculture and land-use technologies are already reflected in the climate strategies of several LAC countries and are poised for scale-up. For example, the Strengthened First NDC from Costa Rica incorporates climate-smart agriculture, agroecological zoning and watershed-based land planning as key pillars of its adaptation framework (Costa Rica 2022). Similarly, the third NDC developed by Uruguay commits to sustainable grazing practices and enhanced soil carbon monitoring in pastoral systems, linking agricultural transitions directly to national mitigation targets (Uruguay 2024). These country-level commitments exemplify the integration of biobased technologies within the operationalization of the Paris Agreement, underscoring their relevance in shaping long-term sustainability pathways. Additionally, advanced monitoring systems, combining satellite-based measurement, reporting and verification (MRV), geospatial analytics and carbon accounting tools, are essential for tracking outcomes and ensuring transparency in implementation of these technologies (Harris *et al.* 2021).

Biobased materials derived from agricultural residues, forestry waste, algae and crop by-products are emerging as a strategic technological domain within the LAC bioeconomy (Ashothaman 2023; Bertram *et al.* 2021). Recent initiatives in Colombia and Paraguay underscore the potential of biodegradable packaging and textile fibres sourced from starch- and cellulose-based bioplastics derived from agricultural waste streams such as banana peels, cassava and pineapple. These materials have demonstrated high biodegradability and functional properties suitable for food packaging (Coratchia *et al.* 2024; Ishara *et al.* 2024; Othman *et al.* 2020). Chile and Uruguay have taken the lead in sustainable forestry through certified plantations; cascading biomass use and ecosystem stewardship. For example, the CMPC Group in Chile transforms forestry residues into advanced biobased products (Balocchi *et al.* 2023; CMP 2023). These models enhance carbon sequestration, reduce pressure on native forests and provide renewable inputs for bioindustries. Uruguay includes sustainable forestry in its NDC, while Chile integrates forestry innovation into its carbon neutrality road map.

From an adaptation perspective, biobased materials support income diversification in rural areas and strengthen resilience by embedding circular principles into local production systems (Proestou *et al.* 2025). This reduces dependency on imported synthetic inputs, mitigates price volatility and fosters community-level innovation through inclusive and socially driven bioeconomy models (Bryden *et al.* 2017; Celik *et al.* 2023). Table 6.1 provides examples of key advanced biobased technologies in LAC that contribute to climate change mitigation and/or adaptation.

Table 6.1 Examples of climate-related biobased technologies in Latin America and the Caribbean

Technology area	Technology	Climate change aspect	Examples	References
Biomass conversion technologies	Sugarcane ethanol and biorefineries	Reduces GHG emissions and replaces fossil fuels in transport and power sectors	In Brazil, 2G ethanol plants reduce up to 80-90 % of CO_2 emissions compared to gasoline. Bagasse cogeneration supplies ~3% of national electricity. In Costa Rica, Viogaz converts pineapple waste into bioenergy.	Matos et al. 2024; Liu *et al.* 2023; Coelho Junior *et al.* 2024; Chen *et al.* 2020
Bio-CCUS	Biochar for soil and carbon sequestration	Sequesters CO_2 in soil and reduces the need for synthetic fertilizers	Biochar trials in Brazil, Argentina and Peru show 30–50% increases in soil carbon over three to five years, supporting sustainable intensification	Lefebvre et al. 2020; Vijay et al. 2021;Aquije *et al.* 2021
Sustainable agriculture and land-use technologies	Crops with no-till and precision agriculture, biofertilizers	Improves soil health, reduces emissions and enhances climate resilience	In Argentina, genetically modified soy with no-tillage reduces GHG emissions by up to 50% compared to conventional practices. In Colombia, a sustainable yam biotech project increased yields by 25% using local innovation	Pelekh et al. 2023; Villadiego-del Villar *et al.* 2021
Biobased materials	Bioplastics from agro-waste and natural compounds	Reduces fossil dependency and supports biodegradable alternatives	In Mexico, Biofase produces 500 tons/month of avocado seed bioplastics	BIOFASE 2023; Gámez 2005

6.2.2 Synergies between biobased technologies and SDGs in the LAC region

Biobased technologies offer significant potential to advance multiple SDGs in the LAC region, reinforcing the integrated vision of the 2030 Agenda. In a region rich in biodiversity and biomass resources, these technologies can support SDG 8 (Decent Work and Economic Growth) by fostering rural entrepreneurship, creating green jobs and revitalizing local economies, particularly in agricultural and forest-dependent communities, through sustainable value chains (D'Amato *et al.* 2019). Table 6.2 summarizes selected biobased technology initiatives across LAC, including their links to the SDGs.
Biobased technologies also contribute to SDG 9 (Industry, Innovation and Infrastructure) by enabling technological upgrading and enhancing biomanufacturing capabilities, especially in emerging bioeconomy hubs such as Brazil, Colombia and Argentina. Localizing innovation and production systems can reduce dependency on imports and strengthen regional resilience (Asheim and Gertler 2009).

In addressing SDG 12 (Responsible Consumption and Production), biobased technologies promote circularity in biomass use, reduce resource intensity and minimize waste, key concerns in LAC countries facing growing urbanization and waste management challenges. Moreover, they are central to SDG 13 (Climate Action), offering lifecycle greenhouse gas mitigation, carbon sequestration through sustainable land use and greater resilience to climate variability, which is particularly critical for vulnerable ecosystems and communities in the region (Wesseler and von Braun 2017).

Table 6.2 Examples of biobased technology initiatives, including linkages to SDGs

Country/ economy	Example/project	Key outcome/benefit	Relevant SDGs	Reference
Argentina	Corn ethanol, biogas from livestock manure	Agro-industrial synergy and GHG reduction	SDGs 7, 12, 13	United States Department of Agriculture (USDA) 2024
Argentina	Precision agriculture and genetically modified crops	GHG mitigation and soil restoration	SDGs 2, 12, 13	USDA 2024
Barbados	Biobased tourism packaging	Eco-labelling and export image	SDGs 8, 12, 14	INBAR 2025
Brazil	Sugarcane ethanol, bioelectricity from bagasse	Global leader in biofuels and energy diversification	SDGs 7, 9, 12, 13	Coelho Junior *et al.* 2024
Chile	Marine biomass for bioplastics	Seaweed valorization and packaging innovation	SDGs 9, 12, 14	Almeida and Vieira 2025
Chile	Bioplastics from salmon and seaweed waste	Marine circular economy	SDGs 12, 14	Pérez-San Martín *et al.* 2025; SalmonChile 2024
Colombia	Silvopastoral systems and tropical afforestation	Enhanced soil C+ productivity	SDGs 2, 13, 15	Chará *et al.* 2023
Colombia	Natural fibre panels (fique, plantain)	Green construction materials	SDGs 9, 11, 12	Gomez et al. 2021 ; García Sánchez *et al.* 2021
Costa Rica	INBio Payment for Ecosystem Services (PES) schemes for forests	CO_2 removal and biodiversity protection	SDGs 13, 15	World Bank 2025
Cuba	Biocomposites from sugarcane and forestry	Closed-loop sugar agro-industry	SDGs 9, 12, 13	Palomo-Briones *et al.* 2018
Dominican Republic	Small-scale biodigesters in rural farms	Decentralized energy access	SDGs 7, 13, 1	UNEP 2024c
Ecuador	Regenerative Amazonian farming	Soil carbon and biodiversity gains	SDGs 2, 13, 15	INBAR 2025
El Salvador	Climate-smart agriculture in coffee	Reduced erosion and yield stability	SDGs 2, 12, 13	Fernandez-Kolb *et al.* 2019
Guatemala	Community-managed forest projects for carbon markets	Indigenous inclusion and climate change mitigation	SDGs 13, 15, 16	Rainforest Foundation US 2022
Haiti	Agroecology with vetiver and tubers	Soil restoration and market access	SDGs 2, 8, 15	Groundswell International 2023
Honduras	Agroforestry with cacao and timber	Livelihood and forest cover gains	SDGs 1, 13, 15	Ramírez-Argueta *et al.* 2022
Jamaica	Waste-to-energy via sugarcane bagasse	Renewable energy and waste reduction	SDGs 7, 11, 13	Richards and Yabar 2022
Mexico	Agave and maize biomass valorization	Circular agave biorefineries in arid zones	SDGs 8, 9, 12	Honorato-Salazar *et al.* 2021
Mexico	Insulation from agave bagasse	Housing innovation and waste reuse	SDGs 9, 11, 12	Mora 2023
Panama	REDD+ pilots in Darién	Forest carbon market entry	SDGs 13, 15	Mateo-Vega 2017
Peru	Bamboo (Guadua spp.) forest projects	Carbon sinks and green construction	SDGs 9, 11, 13	Camargo García *et al.* 2023
Uruguay	National Bioinput Strategy 2025	Input circularity and farmer resilience	SDGs 2, 9, 12	COMBIO 2024

6.3 ENABLING CONDITIONS

Several enabling conditions have catalysed bioeconomy innovation across the LAC region, reflecting a convergence of institutional leadership, financial mechanisms and technological capacities.

6.3.1 Governance and institutions

A critical driver for advancing the bioeconomy and biobased technologies in the region has been the articulation of national bioeconomy strategies that integrate intersectoral governance and long-term planning. Countries such as Colombia, Costa Rica and Brazil have developed comprehensive visions that align biodiversity conservation with inclusive development. The 2018 Bioeconomy Strategy in Brazil, implemented through the Brazilian Agricultural Research Corporation (EMBRAPA), has notably advanced second-generation ethanol technologies, bioinputs and forest-based bioproducts (Trigo *et al.* 2019; Bastos Lima 2021). In Mexico, INIFAP has spearheaded advances in biobased technologies such as agroecology, precision farming and climate-resilient crops.

Multilateral and regional initiatives such as the Ibero-American Programme of Science and Technology for Development (CYTED), the Regional Fund for Agricultural Technology (FONTAGRO), and the Cooperative Programme for the Technological and Agrarian Development of the Southern Cone (PROCISUR) have played a pivotal role in fostering transnational collaboration among countries in the Southern Cone and Andean regions (FONTAGRO 2025). These platforms have facilitated the exchange of knowledge, joint research and capacity-building across national borders, particularly in areas critical to climate resilience and sustainable development. Their support has enabled the diffusion of climate-smart agricultural practices, which help farmers adapt to changing climate conditions while maintaining productivity. Additionally, they have promoted circular economy principles, encouraging the reuse and valorization of agricultural and biological waste streams. Importantly, these initiatives have also driven innovation in bioprocessing technologies such as bioinputs, bioplastics and biofertilizers and have supported the development of biodiversity-based value chains, which leverage native species and ecosystems for sustainable economic opportunities. These efforts contribute not only towards environmental sustainability but also to inclusive rural development and regional integration.

Inclusive governance, community engagement and coordinated action are essential to building resilient bioeconomy ecosystems across the region. Financial instruments, including blended finance vehicles, results-based payment schemes and green bond markets, play a critical role in de-risking investments and scaling deployment. At the same time, strengthening regional research and development platforms and public-private consortia is vital for developing and transferring technologies suited to local biophysical and socioeconomic conditions.

Institutionalizing MRV systems is key to tracking outcomes, attracting climate finance and ensuring transparency. Together, these mechanisms position bioeconomy-based innovations as high-impact, cross-sectoral climate solutions that can elevate the region's role in multilateral negotiations while supporting just transitions, nature-based solutions and equitable low-carbon development.

Table 6.3 below provides examples of how the enabling conditions for biobased technologies in the LAC region is advancing. Box 6.2 also provides insights from CTCN technical assistance to advance bioeconomy initiatives, including biobased technologies, in the LAC region.

Table 6.3 Examples of enabling conditions for biobased technologies in LAC region

Technology area	Policy & Regulatory enablers	R&D and Knowledge Transfer
Biomass Conversion Technologies	Colombia, Chile, Costa Rica, Mexico, Peru, and Uruguay have adopted national circular economy strategies that promote biomass valorization and conversion technologies. These strategies include regulatory frameworks, monitoring systems, and incentives for the sustainable use of biomass. The Inter-American Development Bank (IDB) has supported policy design for renewable energy, including biomass, through energy auctions, net metering policies, and distributed generation incentives (López Soto *et al.* 2019). Argentina, Brazil, and Colombia have developed legal frameworks to support bioenergy markets (IRENA 2024).	Examples of institutions carrying out R&D in this area include the Brazilian Agricultural Research Corporation (Embrapa); the National Institute of Industrial Technology (INTI) and the National Institute of Agricultural Technology (INTA) in Argentina; the Production Promotion Corporation (PROVO) in Chile; university–industry consortia; and South–South cooperation initiatives.
Bio-Carbon Capture, Utilization and Storage	Payment for Ecosystem Services (PES) schemes, Reducing Emissions from Deforestation and Forest Degradation (REDD+) approaches, and national climate and biodiversity laws (e.g., Costa Rica, Brazil) incorporate NbS and carbon benefit accounting with safeguards (Costa Rica 2021).	EMBRAPA (Brazil) and INIFAP (Mexico) conduct research on agroforestry, soil carbon, and biochar, and also organize innovation challenges (EMBRAPA 2022; INIFAP 2021).
Sustainable Agriculture & Land Use	Brazil enacted the 2024 Bioinputs Law, establishing a comprehensive regulatory framework for the production, commercialization, and use of biological inputs in agriculture, with oversight by the Ministry of Agriculture and Livestock (MAPA 2024). Uruguay approved its National Bioinputs Plan in 2025, prioritizing the use of bioinputs in agricultural production and promoting sustainable development through the Ministry of Livestock, Agriculture, and Fisheries (MGAP 2025). In Chile, the Ministry of Environment has advanced the integration of NbS in irrigation and water management, supporting climate resilience and sustainable agriculture (Chile, Minsterio de Agricultura, INDAP 2022; Chile 2022).	The National Institute of Agricultural Technology (INTA), the Cooperative Program for the Technological Development of Agro-Food and Agro-Industry in the Southern Cone (PROCISUR), and the Regional Fund for Agricultural Technology (FONTAGRO) are engaged in research on agroecology, intercropping, and organic inputs (FONTAGRO 2022; PROCISUR 2021).
Bio-Based Materials	Progress in bio-based materials is supported by enabling policies such as national circular economy strategies, legal frameworks for bioenergy and biomass valorization, and incentives for sustainable innovation. Regional cooperation and funding mechanisms, including FONTAGRO and CYTED, further strengthen the policy environment for R&D and commercialization of bio-based materials (CYTED 2022; FONTAGRO 2022).	National Science, Technology, and Innovation (STI) agendas in LAC countries support research and development for biobased materials. Regional initiatives such as FONTAGRO and the Ibero-American Program on Science and Technology for Development (CYTED) promote R&D on bio-based fibers, genomics, and materials innovation, with active participation from countries like Argentina, Brazil, and Mexico (CYTED 2022; FONTAGRO 2022).

6.3.2 National strategies and regulations

Several LAC countries have made significant strides in integrating bioeconomy into their national development and climate strategies. Costa Rica has adopted a National Bioeconomy Strategy (2020-2030) that emphasizes biodiversity-based innovation, circular economy principles and rural inclusion. Argentina has developed a national bioeconomy framework focused on biotechnology, sustainable agriculture and biomass valorization, supported by public-private partnerships and regional planning. Mexico promotes biobased technologies through its National Strategy for Climate Change Adaptation and Mitigation in the Agricultural Sector, which includes silvopastoral systems and agroecological practices. Uruguay has incorporated bioeconomy into its climate and agricultural policies, particularly through sustainable livestock and forestry initiatives. Peru is advancing bioeconomy through its forest conservation programs and community-based agroforestry, often linked to REDD+ and climate resilience goals.

At the regional level, the Latin American Bioeconomy Network, coordinated by the Institute Interamericano de Cooperación para la Agricultura (IICA), has established guiding principles to harmonize bioeconomy strategies across countries.These principles emphasize biodiversity conservation, innovation, circularity and social inclusion and serve as a foundation for policy alignment and investment attraction. Additionally, ECLAC has published a regional vision for a sustainable bioeconomy, highlighting the need for integrated governance, capacity-building and cross-sectoral collaboration.

Brazil has formalized its commitment to the bioeconomy through its National Bioeconomy Strategy (Brazil 2024). It promotes the sustainable use of biodiversity, regenerative agriculture and bio-industrialization. Key components include the development of the National Bioeconomy Development Plan (PNDBIO) and the creation of the National Bioeconomy Commission, which oversees policy alignment and stakeholder engagement. The strategy is closely linked to the country's broader industrial and climate goals, including the New Industry Brazil (NIB) initiative and supports innovation ecosystems focused on biodiversity-based products, bioenergy and circular economy models.

The Colombian National Bioeconomy Strategy, launched in 2020, aims to transform the country into a knowledge-based economy rooted in biodiversity (Colombia, Ministério de Ciencia, Tecnología e Innovación 2020). It focuses on generating high value-added products through science, technology and innovation, with strategic sectors including agriculture, health, cosmetics and renewable energy. The strategy is supported by institutions such as AGROSAVIA, which promotes sustainable agricultural innovation. This approach emphasizes regional development, public-private partnerships and the integration of bioeconomy into climate resilience and rural transformation efforts in Colombia.

6.3.3 Research and development

Similarly, Uruguay demonstrates the role of enabling frameworks by leveraging its robust research and development infrastructure and agricultural expertise to advance biobased industrial innovation. The UPM biorefinery exemplifies this approach by converting forestry biomass into pulp and bioenergy, showcasing synergies between technological advancement, circular economy principles and climate-smart production systems (Scarlat *et al.* 2015).

In contrast, Bolivia and Guatemala are in earlier stages of bioeconomy development. Their efforts focus on foundational investments in community-based forest economies, Indigenous food systems and small-scale agro-industrial innovation. These initiatives often rely on support from regional development banks and international technical assistance, reflecting a bottom-up orientation towards territorial sustainability and cultural resilience (Bracco *et al.* 2019).

Institutions such as EMBRAPA in Brazil, INTA in Argentina and INIFAP in Mexico have developed technologies in agroecology, biofertilizers, precision agriculture and climate-resilient crops, fostering the emergence of dynamic biobased sectors and public-private innovation platforms (Trigo *et al.* 2019). The EMBRAPA bioinput platform, for example, has become a cornerstone for small- and medium-sized enterprise (SME) incubation and private-sector collaboration, accelerating commercialization and technology dissemination (EMBRAPA 2025).

Collectively, these examples underscore the importance of enabling institutions, public-private partnerships and international cooperation in fostering inclusive bioeconomic transitions. They also highlight the need for adaptive policy frameworks that align industrial capacities, including biobased technologies, with socioecological priorities across the LAC region (D'Amato *et al.* 2020).

6.3.4 Finance

Governments in LAC are increasingly using public development banks to channel climate finance into biomass conversion. These banks offer green loans, guarantees and technical assistance to reduce investment risks and attract private capital (European Investment Bank, 2024a).

The Development Bank of Latin America and the Caribbean (CAF) has issued sustainable bonds aligned with its new Sustainable Finance Framework, mobilizing billions in funding for green infrastructure, including biomass conversion technologies (CAF 2025). The Uruguayan National Bioinputs Plan includes public funding and incentives for biomass-based inputs. This supports farmers and SMEs in adopting sustainable technologies for biomass conversion.

Financial innovation has also played a transformative role. Blended finance instruments facilitated by the Green European Foundation, the IDB Lab, and the CAF have helped derisk early-stage bioeconomy ventures. In Costa Rica, the Bioeconomy and Green Growth Fund, supported by the United Nations Development Programme BIOFIN initiative, has provided catalytic capital for enterprises in biobased energy, food systems and biorefineries (Correa *et al.* 2022).

Box 6.2 provides an example of regional efforts to finance a just circular transition in Latin America, highlighting insights from the CTCN multi-country technical assistance initiatives focused on biobased technologies.

Box 6.2: Financing a just circular transition in Latin America: insights from multinational technical assistance on biobased technologies

Countries in the LAC region are increasingly embracing circular economy (CE) principles to address climate and development challenges. Recognizing the region's rich biodiversity and potential for biobased innovation, the CTCN launched two multi-country technical assistance (TA) projects aimed at integrating CE into national strategies and financial systems (CTCN 2021; 2022).

The first TA, involving Chile, Brazil, Mexico and Uruguay, focused on assessing the current status of CE and developing national road maps. The second TA supported Ecuador, Dominican Republic, Cuba, El Salvador and Paraguay in defining long-term CE visions. A separate initiative in Costa Rica targeted local-level CE development. Across all projects, the emphasis was on the climate benefits of circularity, particularly in sectors such as bioinputs, regenerative agriculture and biomass reuse, key pillars of a biobased economy.

Support from CTCN focused on advancing CE strategies, including biobased technologies, across the LAC region. Through its technical assistance, participating countries gained access to rich and regionally diverse information, with national assessments extending beyond major urban centres to capture sector-specific opportunities for biobased technologies. These efforts helped to establish strong baselines for CE integration, enabling countries to measure progress and assess future impacts. Equally important was the facilitation of cross-country knowledge exchange, allowing governments and institutions to share experiences, learn from successes and setbacks and adapt best practices to their local contexts. Collectively, these contributions have strengthened the region's capacity to implement NDCs and advance the goals of the Paris Agreement, positioning LAC countries as leaders in climate-smart, inclusive bioeconomy transitions.

6.4 ROLE OF INDIGENOUS AND LOCAL KNOWLEDGE

Indigenous and local communities across the LAC region have long engaged in biobased technologies rooted in Traditional ecological knowledge (TEK), biodiversity stewardship and the circular use of natural resources.

Examples of Indigenous-led biobased innovation include the Shipibo-Conibo people of Peru, who engage in the culturally regulated production of ayahuasca for traditional medicinal purposes and ethical biotrade (Gonzalez et al. 2021). Another example is provided by the Kichwa communities in Ecuador, whose chakra agroforestry systems safeguard agrobiodiversity and support local food sovereignty (Álava-Núñez *et al.* 2025). Finally, the Xingu Seed Network in Brazil links indigenous seed collectors to ecological restoration markets, thereby enhancing biocultural resilience and providing sustainable livelihoods (International Network for Seed-Based Restoration 2017).

The Valhalla Macadamia Farm in Guatemala exemplifies an Indigenous- and locally-led bioeconomy rooted in biodiversity-based value chains and nature-based solutions. Founded in 1989, the farm's mission is to restore degraded lands through macadamia agroforestry, promoting reforestation, carbon sequestration and soil regeneration, while enhancing local food systems and climate resilience (McGrail 2023). Through the free distribution of macadamia seedlings to Indigenous farmers, along with technical support and processing services, Valhalla empowers rural communities to develop equitable, regenerative value chains that integrate traditional knowledge with ecological stewardship (McGrail 2023). This model not only diversifies livelihoods and fosters rural innovation but also demonstrates how community-driven approaches can scale ecosystem restoration and inclusive climate action across the region. These initiatives deliver high co-benefits for biodiversity conservation, local livelihoods and cultural resilience, while simultaneously reducing deforestation and greenhouse gas emissions (Chazdon and Uriarte 2016).

Enhancing market access and strengthening certification schemes, such as fair trade, biodiversity-friendly labelling and origin-based certifications, can play a pivotal role in creating enabling environments for biobased technologies generated through indigenous and local knowledge. These mechanisms support the development of equitable value chains and facilitate access to premium markets for sustainably sourced products, thereby aligning conservation incentives with local livelihoods (Gardner *et al.* 2019). As policy instruments, these are not only essential for achieving the 2030 targets of the Global Biodiversity Framework, but also central to ensuring an equitable implementation of the Paris Agreement.

6.5 CONCLUSIONS

Advancing biobased technologies in the LAC region offers a strategic pathway to unlocking the full potential of the bioeconomy while addressing climate, biodiversity and development goals in an integrated manner. Building on pioneering national initiatives such as the RenovaBio in Brazil, the Amazonia Bioeconomy Hub in Colombia, the BioValor platform in Uruguay and the Indigenous-led bio-enterprises in Guatemala, LAC countries are well-positioned to scale transformative models that align bioeconomic innovation with inclusive and sustainable development.

To catalyse this transition, technology inclusive bioeconomy strategies should be embedded within national climate and development frameworks. Strengthening place-based innovation systems that leverage Indigenous knowledge, biodiversity assets and multi-stakeholder collaboration will be key to making progress on equitable and resilient biobased technologies.

Moreover, enhancing digital MRV systems, sustainability certification and regional standard-setting will be critical to ensure transparency, traceability and market access. Regional coordination through platforms such as the Community of Latin American and Caribbean States (CELAC), the Mercado Común del Sur (MERCOSUR) and IICA can accelerate policy harmonization and the co-development of metrics and instruments tailored to the diverse socioecological contexts in the region.

By consolidating successful experiences and investing in enabling environments and innovation systems for biobased technologies, the LAC region can emerge as a global leader in sustainable bioeconomy development, driving innovation, climate action and inclusive growth for decades to come.


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APPENDICES

APPENDIX 1

Box 1: FA for biomaterial in buildings

Wood has been traditionally used for low -rise buildings in the Global North in Northern Europe and Northern Americas, in particular in regions with sustainable forests. Wood, bamboo, straws and other biomaterials have also been used in developing countries with region with fast bamboo growth. Wood and bamboo in building as structural element in building is known since many years, mainly for low raise constructions, for example Japanese traditional houses. Wood has a high insulation, this improving the energy performances of buildings. More recently wood building elements are prefabricated allowing simpler construction process compared to other materials. Costs for wood-based construction are comparable construction with traditional materials such as concrete or bricks buildings, with regional variations due to material availability and constructions traditions. New technology developments and new building codes have facilitated the practical application of wood in multi-storey buildings, with several example around the world.

Biomaterials (e.g. cork, straw, etc.) are also used as insulation materials. An additional application is composite material, e.g. straw used to reinforce bricks, which are still widely utilized in the construction sector today.

Wood in construction could be carbon neutral only if it comes from sustainable forests, thus not contributing to deforestation. There is still a debate on the carbon neutrality potential of wood used in construction in large scale.

In areas where wood building is already deployed, users are favourable to the construction of multi-storey wood buildings, while in other areas there are still concerns about safety and durability. Local policy makers are mostly favourable to wood based new construction, are in introducing local policies for fostering the construction. Building codes (in the past one of the major barriers to high raise buildings) have been recently modified to allow wood multi storey buildings and in general are promoting policies to foster wood-based construction.

APPENDIX 2

Box 2: Regulating biobased technology - the case of BECCs in the European Union

The proposed 2040 European Union targets envision a carbon-neutral power sector that includes between 4 and 34 Mt of BECCS (European Commission 2024). This target is theoretically reachable by adding carbon capture and storage only to the existing European Union solid biomass bioelectricity and CHP plants. However, these plants are often small and geographically isolated (IEA Bioenergy n.d.), thus reducing the financial and logistic feasibility of converting all of them to BECCS. New BECCS installations are likely necessary to meet this ambition.

However, BECCS installation represent complex systems spanning multiple sectors, including agriculture and/or forestry, energy and/or industry, and carbon management (i.e., transport and storage of CO_2), all of which are subject to different regulations with competing policy goals (Tanzer *et al.* 2025). The cross-sectoral nature of BECCS and patchwork policy context creates a higher administrative burden for BECCS operators than for operators of fossil-based or other renewable energy installations. There are at least thirteen different European Union regulations and directives affecting BECCS operators (Tanzer et al. 2025). Biomass is a renewable but limited resource that is valuable both when it is harvested for use as material, energy carrier or source of carbon and when it is left standing, as a carbon sink and purveyor of critical ecosystem services and a source of beauty. The LULUCF net removal targets, the European Union Deforestation Regulation and the Nature Restoration Law all work to retain and increase standing biomass. In contrast, the European Renewable Energy Directive and Emission Trading Directive both incentivize the use of biomass, via zero-rating emissions from biomass that meets certain sustainability criteria. The tension between unintegrated policies that encourage the use and restrict the supply of biomass hinders the development of the stable biomass supply chains needed for BECCS and risks increasing undocumented uses of biomass, as suggested by the increasing discrepancy in known biomass supply and biomass use (Cazzaniga 2021). Similar sustainability regulations are, furthermore, not applied to fossil supply chains, creating an artificially unlevel playing field.

Through storage targets in the Net Zero Industry Act and funding through the Connecting Europe Facility, the European Union is incentivizing the creation of a CO_2 transport and storage infrastructure, which is needed for BECCS viability, although the infrastructure is also designed to support fossil-based CCS. However, the application of CCS to biomass installations is also not incentivized in the ETS, as it is for fossil-based installations, although inclusion of permanent removals in the ETS, potentially including BECCS, was announced as part of the 2040 target plans (European Commission 2025b). The carbon removal and carbon farming framework will establish a protocol for the creation of removal credits from BECCS but does not specify how they will be used or lead to compensation.

The lack of a coherent policy landscape hinders the development of BECCS by increasing administrative and financial hurdles without mandating meaningfully consistent sustainability regulation to reduce the unsustainable extraction and consumption of both biogenic and fossil carbon. Critical elements to ensure the efficient and sustainable regulation of the bioeconomy include creating a policy that recognizes the complex interconnectedness of the land, industry, energy and climate sectors, particularly for technology systems such as BECCS, setting aligned targets for the land sink, technological removal and industrial biomass use that respect the implications of a changing climate and establishing at least parity of regulation for fossil carbon.

Box 3: Bio-based innovation in Thailand

In South-East Asia, Thailand is at the forefront of the bioeconomy and biobased innovation development. As the world's fourth largest sugar cane producer, the country has both dedicated bioeconomy policies and strategies in place (most notably the Bio Circular Green Economy 2.0 (BCG). The BCG provides the key driving force for the development of the bioeconomy in Thailand and the strategy follows its principles. In line with this strategy, an institutional infrastructure has developed over the past decade or so, most notably the Bioeconomy Development Office (BEDO), dedicated research units in the National Science and Technology Development Agency (NSTDA) and ministerial working groups and committees (Edyvean *et al.* 2023). Moreover, the government has recently made biotechnology, bioenergy and biomaterials a key priority of the Eastern Economic Corridor (EEC), a special industrial zone east of Bangkok which is designed to drive innovation in the Eastern seaboard region of the country. There, in what is known as the Biopolis Innovation hub, the country's first multifunctional biorefinery, the Bio Base Asia Pilot Plant (using a variety of feedstocks to produce a variety of outputs) was scheduled to be inaugurated in recent months (Biopolis Eastern Economic Corridor of Innovation 2021).

Box 4: The East African Community Regional Bioeconomy Strategy

According to a report by the World Bank, over 30 per cent of the East Africa region's GDP is biobased, pointing to the significant potential for contributions to sustainable development and economic growth (Virgin *et al.* 2024). The East African Community Bioeconomy Strategy is a key regional initiative that aims to leverage biological resources to drive sustainable development and address climate adaptation and mitigation challenges, with major policy implications (EASTECO 2022). The strategy promotes the sustainable conversion of biomass into value-added food products, feed, energy, fuels and other biobased products, reducing dependence on fossil fuels and supporting cleaner energy systems. This contributes to climate mitigation by lowering greenhouse gas emissions while also creating green jobs and enhancing rural livelihoods. By encouraging carbon capture through natural and technological solutions such as biochar, agroforestry and biobased carbon utilization, the strategy supports efforts to remove CO_2 from the atmosphere. These approaches help offset emissions and align with global carbon neutrality goals. The strategy also emphasizes climate-smart and regenerative agricultural practices that boost productivity, enhance resilience and restore degraded lands. These innovations improve soil health, increase carbon storage and reduce emissions from land use, aligning agriculture with climate adaptation and mitigation efforts. The development and use of biobased alternatives to conventional materials such as bioplastics, green construction materials and natural fibres reduces reliance on fossil-based inputs. These innovations support circular economies and contribute to lowering the carbon footprint of industrial and consumer products.

Box 5: The cassava bioeconomy: innovative clustering for climate and development

Cassava (Manihot esculenta) is a root crop native to the Amazon and is widely cultivated across tropical regions as a key bioeconomy resource (Trujillo *et al.* 2025). With its high starch content and drought resistance, cassava offers innovations across value chains to provide food, feed, biomaterials and bioplastics to substitute for fossil-based resources and support climate resilience. Several countries in Asia, Africa and Latin America have policies to leverage the potential of cassava to address climate challenges, diversifying markets and fostering local development.

In Thailand, the world's leading cassava starch exporter, the cassava bioeconomy has been strategically aligned with national goals for the Bio Circular Green Economy (Lilavanichakul and Yoksan 2023). The country has pioneered bioplastic innovations (Aung 2021), using cassava starch to produce biodegradable bags and packaging materials, responding to global concerns about plastic pollution. However, social and environmental challenges remain to be addressed, including moving beyond monocultures and social supports for small-scale cassava producers. Similar platforms have been used by the Thai programme to expand cassava initiatives through South-South collaboration across the Mekong region of South-East Asia.

In Colombia, cassava is a culturally important crop for smallholders, especially for traditional dishes and food security (Canales and Trujillo 2021). Emerging initiatives include biomaterials from cassava starch, bioplastics with biodegradable films and different types of packaging (Ortiz *et al.* 2023). One key challenge in Colombia is integrating smallholders into more sophisticated cassava value chains with a proper business organization (Trujillo *et al.* 2025).

In Africa, the world's leading cassava-producing region, countries such as Nigeria in West Africa and Kenya in East Africa, are advancing cassava-based bioeconomy initiatives. In East Africa, cassava is an important crop for poor and vulnerable communities and a potential building block for advancing the bioeconomy through transnational innovation systems along the cassava value chain (Lutta *et al.* 2024). Factors such as poverty, inequality and limited access to resources can hinder the participation of marginalized communities in the bioeconomy.

Tropical countries face common challenges in unlocking the full potential of cassava as a versatile bioresource for the bioeconomy. Key priorities include promoting biodiversity-compatible production, enabling generational renewal, improving knowledge transfer to small producers and strengthening business capacities. Addressing these issues is essential to advancing climate action, fostering local development, seizing opportunities for industrialization, job creation and value addition.

Box 6: The nexus of bioeconomy, climate technologies and agrifood systems

Agrifood systems – comprising crops, livestock, fisheries and aquaculture and forestry, from their production, processing and consumption – are at the heart of the bioeconomy, with great potential to help green other sectors of the bioeconomy with sustainably produced biological resources and services (FAO 2024a). In turn, bioeconomy science and technology can make agrifood systems more efficient, resilient and inclusive. The bioeconomy for sustainable food and agriculture is therefore a strategic priority for the United Nations Food and Agriculture Organization (FAO) with a dedicated programme of work that focuses on facilitating the deployment of sustainable bio-innovations and providing support to stakeholders in developing and implementing cross-sectoral and evidence-based bioeconomy strategies, policies and programmes (FAO 2021). Drawing on long-standing collaborations with governments including Namibia and Uruguay, the FAO Bioeconomy Toolbox offers step-by-step guidance to stakeholders seeking to develop bioeconomy strategies (Gomez San Juan 2024).

To fully leverage the potential of the bioeconomy in a changing climate that could affect food security, it is important that bio-economy policies, strategies and plans prioritize food security and nutrition for all and especially for vulnerable populations. The aim should be to mainstream the transformation of agrifood systems alongside bioeconomy development to ensure efficiency, equity and resilience (Albinelli et al. 2024). Safeguarding food security is impossible without decisive action to adapt to the impacts and mitigate the causes of climate change. Therefore, the development of comprehensive national renewable carbon management plans that integrate the bioeconomy as a key component and promote the diversification of biomass sources for multiple uses, sustainable land management, carbon capture and utilization, waste-to-energy processes and other bioeconomy options should be encouraged (FAO 2024b). This goes hand-in-hand with increased investments in bioeconomy science, technology and innovation, particularly in low- and middle-income countries. Climate funds such as the Adaptation Fund, the Global Environmental Facility (GEF), and the Green Climate Fund (GCF) have a critical role to play in scaling up bio-innovations for climate action. Coordinated policymaking and governance, international cooperation, sustainability monitoring and investment in scaling can realize the potential of the bioeconomy to make a substantial contribution to climate and biodiversity goals.

Photo: Pexels

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ACRONYMS

2G	Second-generation biofuels
AIF	Africa Investment Forum
AMZBio	Amazon Bioeconomy Initiative
AFOLU	Agriculture, Forestry and Other Land Use
AGROSAVIA	Corporación Colombiana de Investigación Agropecuaria
AR6	IPCC Sixth Assessment Report
ATJ	Alcohol-to-Jet
B2C	Business to Consumer
BAFU	Bundesamt für Umwelt (Swiss Federal Office for the Environment)
BCG	Bio-Circular-Green Economic Model
BCR	Bio-Circular-Regional economy
BECCS	Bioenergy with Carbon Capture and Storage
BEDO	Bioeconomy Development Office (Thailand)
BHCCS	Bio-Hydrogen with Carbon Capture and Storage
BIC	Bio-based Industries Consortium
Bio-CCUS	Bioenergy with Carbon Capture, Utilization and Storage
BioE3	Biotechnology for Economy, Environment & Employment
BioSSA	Bioeconomy Strategy for Southern South America
BioVolar	Latin American Bioeconomy Volar Programme
CABIO	Câmara Setorial da Bioeconomia (Brazil Bioeconomy Chamber)
CAF	Corporación Andina de Fomento (Development Bank of Latin America and the Caribbean)
CAP	Common Agricultural Policy
CBIOs	Créditos de Descarbonização (Brazilian Decarbonization Credits under RenovaBio)
CBD	Convention on Biological Diversity
CCUS	Carbon Capture, Utilization and Storage
CDR	Carbon Dioxide Removal
CDM	Clean Development Mechanism
CELAC	Comunidad de Estados Latinoamericanos y Caribeños
CE	Circular Economy
CHP	Combined Heat and Power
CIF	Climate Investment Funds
CLT	Cross-Laminated Timber
CMCP	Circular and Modern Circular Production
COP	Conference of the Parties (UNFCCC)
CSU	Carbon sequestration and utilization
CTCN	Climate Technology Centre and Network
CTPR	Climate Technology Progress Report
CYTED	Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo
DACCS	Direct Air Carbon Capture and Storage
DFC	U.S. International Development Finance Corporation
DFIs	Development Finance Institutions
DOE	Department of Energy (US)
DSHC	District Solar Heating and Cooling
EAC	East African Community
EBC	European Biochar Certificate
EBRD	European Bank for Reconstruction and Development
ECBF	European Circular Bioeconomy Fund
ECLAC	Economic Commission for Latin America and the Caribbean
EEC	Eastern Economic Corridor (Thailand)
EIF	European Investment Fund
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuária (Brazil)
EMBRAPII	Empresa Brasileira de Pesquisa e Inovação Industrial (Brazil)
ENVIS	Environmental Information System (India)
ESG	Environmental, Social and Governance
EU	European Union
EU ETS	European Union Emissions Trading System
EUROCLIMA	EUROCLIMA+ (EU–Latin America climate programme)
FA	Formic Acid
FAME	Fatty Acid Methyl Ester
FAP	Fundo - Amazon Research Fund
FbA	Forest-Based Adaptation
FONTAGRP	Fondo Regional de Tecnología Agropecuaria
FSC	Forest Stewardship Council
FT	Fischer–Tropsch
G20	Group of Twenty
GBEF	Global Bioeconomy Forum
GCF	Green Climate Fund
GCP	Global Carbon Project
GEF	Global Environment Facility
GFFP	Global Forest Financing Partnership
GHG	Greenhouse Gas
GIB	Green Investment Bank
GST	Global Stocktake
GovVC	Government Venture Capital
HEFA	Hydroprocessed Esters and Fatty Acids
HTG	Hydrothermal Gasification
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
IAM	Integrated Assessment Model
IACGB	International Advisory Council on Global Bioeconomy
IBF	International Bioeconomy Forum
ICAP	International Carbon Action Partnership
ICIPE	International Centre of Insect Physiology and Ecology
ICMA	International Capital Market Association
ICS	International Classification for Standards
IDB	Inter-American Development Bank
IEA	International Energy Agency
IMF	International Monetary Fund
INIFAP	Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias (Mexico)
INTA	Instituto Nacional de Tecnología Agropecuaria (Argentina)
INTI	Instituto Nacional de Tecnología Industrial (Argentina)
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPB University	Institut Pertanian Bogor University (Indonesia)
IPCC	Intergovernmental Panel on Climate Change
IPLC	Indigenous Peoples and Local Communities
IPM	Integrated Pest Management
IRENA	International Renewable Energy Agency
IRR	Internal Rate of Return
ISO	International Organization for Standardization
ITMO	Internationally Transferred Mitigation Outcome
IUCN	International Union for Conservation of Nature
IICA	Instituto Interamericano de Cooperación para la Agricultura
IITA	International Institute of Tropical Agriculture
KfW	Kreditanstalt für Wiederaufbau (German Development Bank)
LAC	Latin America and the Caribbean

LCA	Life Cycle Assessment
LT-LED	Long-Term Low-Emission Development Strategy
LVL	Laminated Veneer Lumber
MAPA	Ministério da Agricultura, Pecuária e Abastecimento (Brazil)
MEL	Monitoring, Evaluation and Learning
MERCOSUR	Mercado Común del Sur
MGAP	Ministerio de Ganadería, Agricultura y Pesca (Uruguay)
MMCF	Man-Made Cellulosic Fibres
MRV	Measurement, Reporting and Verification
MSMEs	Micro, Small and Medium-sized Enterprises
N2O	Nitrous Oxide
NABD	North American Development Bank
NAP	National Adaptation Plan
NBSAPs	National Biodiversity Strategies and Action Plans
NbS	Nature-based Solutions
NDC	Nationally Determined Contribution
NF	Nitrogen Fertilizer
NICRA	National Innovations in Climate Resilient Agriculture
NIB	Nordic Investment Bank
NIST	National Institute of Standards and Technology (US)
NTSDA	National Technology Strategy and Development Agency
NZE	Net Zero Emissions
OECD	Organisation for Economic Co-operation and Development
PE	Private Equity
PEFC	Programme for the Endorsement of Forest Certification
PES	Payment for Ecosystem Services
PHA	Polyhydroxyalkanoates
PLA	olylactic Acid
PM	Particulate Matter
PNDBIO	Programa Nacional de Desarrollo de la Bioeconomía
PPP	Public–Private Partnership
PROCISUR	Programa Cooperativo para el Desarrollo Tecnológico Agroalimentario y Agroindustrial del Cono Sur
PROVO	Programa de Bioeconomía Volar
R&D	Research and Development
RD&I	Research, Development and Innovation
REDD+	Reducing Emissions from Deforestation and Forest Degradation+
RSB	Roundtable on Sustainable Biomaterials
SAF	Sustainable Aviation Fuel
SBIR	Small Business Innovation Research (US)
SBTi	Science Based Targets initiative
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
SENAI Brazil	Serviço Nacional de Aprendizagem Industrial (Brazil)
SICA	Sistema de la Integración Centroamericana
SIP	Synthesized Iso-Paraffins
SLB	Sustainability-Linked Bond
SLL	Sustainability-Linked Loan
SME	Small and Medium-sized Enterprise
TA	Technical Assistance
TEC	Technology Executive Committee
TEK	Traditional Ecological Knowledge
UDD	Universidad del Desarrollo
UNEP	United Nations Environment Programme
UNEP-CCC	United Nations Environment Programme Copenhagen Climate Centre
UNAM	Universidad Nacional Autónoma de México
UNCBD	United Nations Convention on Biological Diversity
UNCCD	United Nations Convention to Combat Desertification
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America
UPM	Universidad Politécnica de Madrid
VC	Venture Capital
WBC	World Bioeconomy Council
WBEF	World BioEconomy Forum
WEF	World Economic Forum
WGII	IPCC Working Group II
WGIII	IPCC Working Group III
WIPO	World Intellectual Property Organization
WTO	World Trade Organization


UN environment programme
CTCN
UN Climate Technology Centre & Network
United Nations Climate Change
Technology Executive Committee
UN environment programme
copenhagen climate centre