Advancing the Bioeconomy:

Synergistic Transformation in Key Agro-Industrial Sectors

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Acronyms and abbreviations

BOD	Biochemical oxygen demand
COD	Chemical oxygen demand
CPO	Crude palm oil
ECF	Elemental chlorine-free
EFBs	Empty fruit bunches
EPR	Extended Producer Responsibility
EUDR	EU Deforestation Regulation
FAO	Food and Agriculture Organization of the United Nations
FFB	Fresh fruit bunch
GHG	Greenhouse gas
ILUC	Indirect land-use change
INBAR	International Bamboo and Rattan Organization
ISPO	Indonesian Sustainable Palm Oil
LBL	Laminated bamboo lumber
LCA	Life cycle assessment
MOE	Modulus of elasticity
MOR	Modulus of rupture
MPOB	Malaysian Palm Oil Board
MSPO	Malaysian Sustainable Palm Oil
NFPP	National Natural Forest Protection Program
NTFPs	Non-timber forest products
POME	Palm oil mill effluent
PVC	Polyvinyl chloride
RSPO	Roundtable on Sustainable Palm Oil
SDGs	Sustainable Development Goals
TCF	Totally chlorine-free

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Executive summary

The global bioeconomy's fundamental operating principles are undergoing a necessary structural realignment. Initially conceived as a straightforward strategy to replace fossil fuels with renewable biological resources, early bioeconomy policies aggressively pursued biomass expansion. This volume-driven approach, however, rested on the flawed premise that biological renewability automatically equates to environmental sustainability. Consequently, unchecked biomass cultivation has frequently exacerbated land-use conflicts, depleted freshwater reserves, and driven severe biodiversity loss. Recognizing these critical limits, the current global policy framework has decisively shifted toward a Circular Bioeconomy. This paradigm prioritizes systemic resource efficiency, closed-loop material flows, and strict adherence to planetary boundaries, ensuring that bio-based production balances ecological integrity with economic development. This report evaluates the developmental trajectories, technological advancements, and socio-environmental impacts of four highly diverse agro-industrial sectors: bamboo, palm oil, natural rubber, and duckweed. By analyzing these sectors, the report identifies the primary drivers of the bioeconomic transition and the systemic vulnerabilities that continue to impede sustainable global supply chains.

Bamboo has evolved from a localized subsistence resource into a highly engineered, strategic material capable of replacing high-emission structural steel and single-use plastics. Advanced thermo-mechanical processes, such as producing bamboo scrimber and biocomposites, have optimized resource use and created long-term carbon sinks in the built environment. However, the commercial success of bamboo is heavily compromised by the aggressive expansion of high-density monoculture plantations. Converting diverse natural forests into simplified bamboo stands has caused severe ecological deficits, including drastic reductions in soil bacterial and fungal diversity, habitat loss for endemic fauna, and localized hydrological stress from shallow, aggressive root systems. Furthermore, a spatial misalignment exists in global trade: developing nations often shoulder the environmental and carbon costs of manufacturing short-lived bamboo commodities, while the long-term carbon sequestration benefits of engineered products are predominantly captured by nations in the Global North.

As the most land-efficient vegetable oil crop, palm oil underpins both the global food industry and ambitious national biofuel mandates. Yet this unparalleled productivity has historically been achieved through the widespread clearing of tropical rainforests and the irreversible degradation of carbon-rich peatlands. Beyond land-use changes, the industrial processing of palm fruit generates vast volumes of Palm Oil Mill Effluent (POME). If poorly managed, anaerobic POME treatment releases massive quantities of methane, a potent greenhouse gas that severely undermines the industry's climate mitigation potential. Today, the sector is heavily scrutinized under stringent new market-access rules, such as zero-deforestation mandates. While environmentally necessary, these top-down regulatory frameworks impose prohibitive costs for geolocation auditing and certification. These financial burdens are routinely passed down the supply chain, threatening the economic survival of independent smallholders and risking their exclusion from international markets.

Natural rubber remains a strategically indispensable material for heavy-duty transportation and industrial manufacturing because of its unique physical properties. The industry relies almost entirely on millions of smallholder farmers across Southeast Asia and emerging frontiers. These rural producers endure the physical toll of intensive labor and agrochemical exposure, yet they remain highly vulnerable to volatile international commodity prices. The sector is further challenged by profound supply chain opacity. Most raw rubber cannot be traced to its specific harvest origin, allowing deforestation to continue largely unchecked. Ecologically, reliance on monoculture rubber cultivation degrades soil health, while primary processing facilities discharge highly acidic, nutrient-loaded wastewater that threatens regional aquatic ecosystems.

Representing a radical departure from terrestrial agriculture, duckweed demonstrates the immense potential of aquatic biomass. Free from competition for arable land, duckweed exhibits explosive vegetative growth, yielding protein and starch in amounts that far exceed those of conventional staple crops. Crucially, duckweed serves as an active agent of environmental remediation. Cultivated in municipal or agricultural wastewater, it efficiently removes excess nitrogen, phosphorus, and even heavy metals, preventing possible downstream eutrophication. With its recent regulatory approvals as a safe nutritional source in major economies, duckweed offers a highly scalable, circular solution that addresses food

security, resource recovery, and water purification. However, its potential massive aquatic cultivation may create ecological risks if non-native species escape, block waterways or alter oxygen dynamics.

A synthesis of these four industries reveals critical, systemic flaws that must be addressed to secure a sustainable bioeconomy. Ecological deficits of intensive monocropping: The financialization of agricultural commodities has entrenched reliance on single-species plantations. This landscape homogenization disrupts natural nutrient cycles, depletes soil microbiomes, reduce biodiversity, and leaves global supply chains dangerously exposed to climate change-induced shocks. Carbon leakage and unequal burden sharing: The physical and ecological tolls of biomass extraction are disproportionately concentrated in the developing world. Conversely, the economic premiums and climate benefits of advanced bio-based materials flow toward industrialized nations. This inequity distorts the fundamental objectives of global climate mitigation.

Socio-Economic blind spots in environmental governance: Current compliance mechanisms, particularly strict traceability and zero-deforestation laws, function primarily as auditing barriers rather than capacity-building tools. Without restructuring the underlying economics of the supply chain to provide equitable financial support and technology transfer, these mandates risk penalizing the most vulnerable rural actors, potentially diverting non-compliant commodities to less-regulated secondary markets without reducing aggregate global environmental harm.

To ensure the bioeconomy operates sustainably within planetary boundaries, global policies must shift from linear extraction to regenerative, circular systems. This requires moving beyond sterile monocultures toward diverse, mixed-species agroforestry to strengthen ecological and economic resilience. Furthermore, supply chains must implement mandatory, inclusive traceability, using equitable cost-sharing to protect vulnerable smallholders. Industries must also adopt closed-loop biomanufacturing, transforming agricultural waste into high-value feedstocks and energy. Finally, biomass generation must decouple from arable land through innovative aquatic cultivation and controlled-environment systems. Bioeconomic success depends on resource efficiency, social equity, and biodiversity conservation rather than sheer extraction volume.

1 Introduction

1.1 Concepts and policy evolution trends of bioeconomy

1.1.1 From bioeconomy to circularity of bioeconomy: core concepts

The bioeconomy is commonly defined as an economic system that relies on biological resources, biological processes, and biotechnological innovation to produce food, energy, materials, and chemicals, with the aim of substituting fossil-based resources (Yang et al., 2021). At its core, the bioeconomy has been promoted as a growth-oriented strategy that leverages renewable biomass to support industrial development, enhance competitiveness, and contribute to energy security. In recent years, the bioeconomy has attracted growing global attention as a strategic pathway for climate mitigation, industrial transformation, and sustainable development. Many countries and regions have introduced bioeconomy strategies and policy frameworks, positioning biomass-based innovation as a key component of long-term economic and environmental transitions (Dietz et al., 2024).

Early bioeconomy policies largely emphasized expanding biomass supply, advancing biotechnology, and scaling up bio-based industries. However, a resource-substitution-oriented bioeconomy does not automatically ensure environmental sustainability. The renewability of biological resources is inherently conditional on land availability, water resources, ecosystem integrity, and management practices. Without systemic constraints, expanding biomass production may intensify land-use change (Wang et al., 2023), exacerbate biodiversity loss, and increase pressures on water and soil systems. These limitations show that replacing fossil resources with biological ones, by itself, is insufficient to address broader sustainability challenges.

The circular economy addresses these challenges from a different perspective. Rather than focusing on the type of resource used, it emphasizes systemic efficiency and the restructuring of material and energy flows. Its core principles include reduction, reuse, recycling, and efficiency improvements, aiming to close material loops, extend product lifetimes, and minimize waste generation (Muscat et al., 2021). Within this framework, sustainability is pursued through structural changes in production and consumption systems, regardless of whether resources are biological or non-biological.

The circular bioeconomy emerges at the intersection of these two approaches. Unlike traditional bioeconomy strategies, the circular bioeconomy does not treat biomass as inherently sustainable or an unlimited substitute for fossil resources. Instead, it integrates circular economy principles into bio-based systems, explicitly recognizing ecological boundaries and long-term sustainability constraints. Central to this concept are life-cycle thinking, cascading biomass use, and multi-objective governance that balances environmental, economic, and social goals. In practice, circular bioeconomy strategies prioritize allocating biomass to high-value, long-lived products before converting it to energy at the end of the life cycle. This cascading hierarchy seeks to maximize resource efficiency and carbon retention while minimizing environmental impacts. As such, the circular bioeconomy represents a shift from a quantity-driven expansion of bio-based activities toward a quality- and efficiency-oriented development pathway. The following chapters build on this perspective by examining bamboo, palm oil, natural rubber, and duckweed in relation to resource use, circular practices, environmental pressures, livelihood effects, and climate-related risks.

1.1.2 Policy evolution trends

The transition from the bioeconomy to the circular bioeconomy reflects a gradual process of conceptual deepening and governance expansion. This evolution can be broadly characterized by three stages.

In the first stage (early 2000s—2010), the bioeconomy was framed primarily as a growth strategy. Policies during this period focused on promoting bio-based industries, fostering technological innovation, and increasing the use of biological resources (Dietz et al., 2024). The bioeconomy was expected to generate economic growth, enhance industrial competitiveness, and support energy transitions. Environmental considerations were often treated as co-benefits rather than binding constraints. This growth-oriented framing was evident in early national bioeconomy strategies adopted in several industrialized economies, where bio-based sectors such as bioenergy, biofuels, and industrial biotechnology were promoted as engines of innovation and rural development. For example, bioenergy policies in the European Union and other regions initially emphasized expanding the renewable energy supply through biomass, with limited differentiation among feedstocks regarding land use or ecological impacts (Bruckner et al., 2019; Vogelpohl, 2023). Similarly, national bioeconomy roadmaps in countries such as Germany and the United States highlighted biotechnology, bio-refineries, and biomass valorization primarily as tools for economic modernization and global competitiveness (Federal Ministry of Food and Agriculture, 2014; White House, 2012). In this stage, sustainability was often assumed to follow automatically from the use of renewable biological resources.

In the second stage (around 2010—2018), sustainability safeguards were progressively integrated into bioeconomy policies. As evidence mounted on the environmental and social risks of large-scale biomass expansion, policymakers recognized that bio-based development is not inherently sustainable. Issues such as land-use change, greenhouse gas emissions, water stress, and ecological degradation were increasingly addressed through regulatory standards, certification schemes, and environmental assessment tools. This phase marked a shift from an assumption of sustainability to a more cautious, risk-aware policy approach. Concrete examples of this shift include the introduction of sustainability criteria for bioenergy and biofuels, which require accounting for lifecycle greenhouse gas emissions and restrict feedstocks linked to deforestation or high-carbon-stock land. Certification systems for agricultural and forestry biomass, such as those applied to palm oil, timber, and bio-based materials, also emerged as governance tools to mitigate biodiversity loss and social risks in global supply chains (Bracco et al., 2018; Carlson et al., 2018). In this phase, environmental assessments and reporting requirements increasingly accompanied bioeconomy-related investments, signaling a move away from the assumption that all bio-based pathways are environmentally benign. Policy discourse thus shifted toward a more cautious, risk-aware approach, emphasizing a sustainable bioeconomy rather than bioeconomy expansion per se.

In the third stage (2018—present), the circular bioeconomy has increasingly been articulated as a multi-objective governance framework. Rather than focusing on individual sectors or isolated policy goals, this stage emphasizes systemic coordination across climate mitigation, resource efficiency, ecosystem protection, and social inclusion. Circularity principles are explicitly embedded in bioeconomy strategies, highlighting the importance of life-cycle management, cross-sectoral integration, and policy coherence (Gottinger and Proestou, 2025). This integrative orientation is reflected in policy frameworks that link bioeconomy development with circular economy action plans, climate strategies, biodiversity objectives, and livelihoods improvement. For instance, recent policy approaches in the European Union increasingly frame biomass use within a hierarchy of cascading applications, prioritizing material uses and resource efficiency before energy recovery (Dietz et al., 2024). Similarly, international organizations such as the OECD and FAO have emphasized that bioeconomy strategies should be evaluated against multiple objectives, including environmental integrity, social equity, and long-term resilience, rather than output growth alone (Diakosavvas and Frezal, 2019b; Olivier Dubois and Marta Gomez San Juan, 2016). In this stage, governance attention shifts toward managing trade-offs, coordinating policies across sectors, and ensuring that circular bioeconomy pathways remain compatible with planetary and social boundaries. The three-stage policy evolution is summarized in Fig. 1.1.

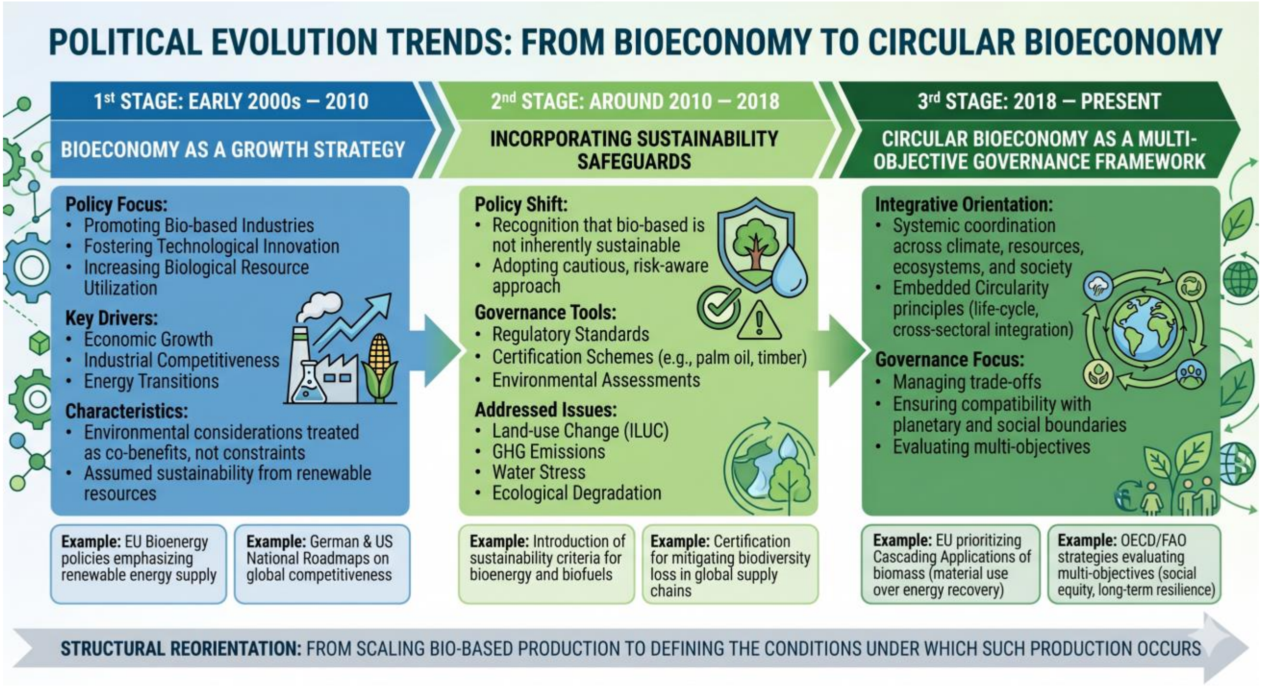


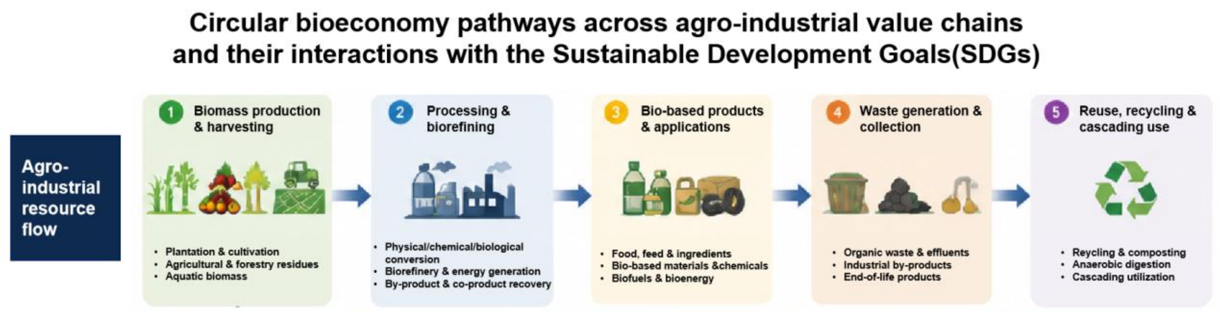
Fig. 1.1 The evolution of bioeconomy policy paradigms

1.2 Circular bioeconomy and SDGs

The circular bioeconomy has emerged as a strategic framework integrating biological resources, circularity principles, and sustainability objectives to address multiple global challenges simultaneously (Warchold and Pradhan, 2025). By promoting the efficient, renewable, and regenerative use of biomass across food, energy, materials, and industrial systems, the circular bioeconomy is increasingly recognized as a potential driver of progress toward the United Nations Sustainable Development Goals (SDGs). Unlike linear bio-based development pathways that focus primarily on resource substitution, the circular bioeconomy emphasizes resource efficiency, cascading use (sequential utilization of biomass for multiple purposes), waste valorization (converting residual biomass and waste streams into valuable products or energy), and systemic integration across sectors (Dam et al., 2025).

However, the relationship between the circular bioeconomy and the SDGs is neither uniformly positive nor free of tension. While circular bioeconomy strategies can generate substantial co-benefits for climate mitigation, energy transitions, rural development, and sustainable consumption (Heimann, 2019), they may also introduce new trade-offs related to land use, water depletion, biodiversity, social equity, and labor conditions (Badgujar et al., 2025). These interactions are highly context-specific and depend on governance frameworks, technological choices, regional resource endowments, and socio-economic conditions.

This section examines interactions between the development of the circular bioeconomy and selected SDGs, focusing on both its positive contributions and potential risks and trade-offs. By highlighting synergies as well as tensions, the analysis aims to provide a balanced, evidence-based understanding of how circular bioeconomy pathways can support sustainable development while avoiding unintended consequences. Fig. 1.2 provides a schematic overview of the stage-specific relationships between circular bioeconomy development and selected SDGs, including synergies, potential support, and potential conflicts.



Impacts on SDGs

	Biomass production & harvesting	Processing & biorefining	Bio-based products	Waste generation	Reuse recycling & cascading use	Typical mechanisms & examples
SDG 1 NO POVERTY	Synergy	Potential support	Potential support	Potential support	Synergy	Rural livelihood improvement
SDG 2 ZERO HUNGER	Synergy	Potential support	Potential support	Potential support	Synergy	Sustainable food systems
SDG 3 GOOD HEALTH AND WELL-BEING	Potential support	Potential support	Synergy	Potential support	Synergy	Human health protection
SDG 6 CLEAN WATER AND SANITATION	Potential conflict	Potential conflict	Potential support	Potential conflict	Synergy	Water resource management
SDG 7 AFFORDABLE AND CLEAN ENERGY	Potential support	Synergy	Synergy	Synergy	Synergy	Bioenergy production
SDG 8 DECENT WORK AND ECONOMIC GROWTH	Synergy	Synergy	Synergy	Potential support	Synergy	Green economic growth
SDG 9 INDUSTRY, INNOVATION AND INFRASTRUCTURE	Potential support	Synergy	Synergy	Synergy	Synergy	Industrial bio-innovation
SDG 10 REDUCED INEQUALITIES	Potential support	Potential conflict	Potential conflict	Potential support	Synergy	Inclusive value chains
SDG 12 RESPONSIBLE CONSUMPTION AND PRODUCTION	Synergy	Synergy	Synergy	Potential support	Synergy	Resource circularity
SDG 13 CLIMATE ACTION	Potential support	Potential support	Synergy	Potential support	Synergy	Climate change mitigation
SDG 14 LIFE BELOW WATER	Potential conflict	Potential conflict	Potential support	Potential conflict	Synergy	Marine pollution reduction
SDG 15 LIFE ON LAND	Potential conflict	Potential support	Potential support	Potential conflict	Synergy	Ecosystem conservation
SDG 17 PATNERSHIPS FOR THE GOALS	Potential support	Synergy	Potential support	Potential support	Synergy	Multi-stakeholder partnerships

Type of interaction

- Synergy
- Potential support
- Potential conflict

Note:

The colored indicators represent conceptual, literature-informed relationships rather than quantified causal effects.

Definitions:

Synergy: The stage directly and consistently contributes to achieving the SDG through well-established positive pathways.

Potential support: The stage may contribute to the SDG under appropriate technological, policy, or management conditions, but the positive effects are context-dependent.

Potential conflict: The stage may create trade-offs or adverse impacts on the SDG under certain conditions, requiring appropriate mitigation or governance measures.

Fig. 1.2 Circular bioeconomy–SDGs interactions across agro-industrial resource flows

1.2.1 Positive contributions to SDGs

SDG 7: Affordable and clean energy

The circular bioeconomy can support SDG 7 (Affordable and Clean Energy) by expanding the production and use of renewable bioenergy from agricultural residues, forestry by-products, and organic waste. These bio-based energy sources provide electricity, heating, and transport fuel, thereby reducing reliance on fossil fuels and enhancing energy security and diversification (Heimann, 2019). In the context of a bioeconomy, investments in bioenergy technologies, decentralized processing facilities, and biomass supply chains can create both direct and indirect opportunities to strengthen local energy access and infrastructure.

However, the benefits of bioenergy depend on the sustainable management of biomass resources. Unsustainable biomass production or inefficient energy conversion could lead to competition with other land uses, degrade ecosystem services, or strain water and nutrient resources. To fully realize the circular bioeconomy's potential for SDG 7, it is essential to implement measures that ensure sustainable feedstock sourcing, efficient energy technologies, and the integration of bioenergy into local energy systems, thereby maximizing clean energy availability while minimizing environmental pressures.

As shown in Fig. 1.2, the contribution of SDG 7 is closely linked with several other SDGs, particularly SDG 13 through fossil-fuel substitution and climate mitigation, SDG 9 through bioenergy infrastructure and technological innovation, and SDG 12 through the productive use of agricultural residues and organic waste.

SDG 8: Decent work and economic growth

The development of the circular bioeconomy has the potential to support SDG 8 (Decent Work and Economic Growth) by creating jobs across biomass supply chains, processing industries, and associated services. Compared with fossil-based industries, bio-based systems tend to be more labor-intensive, particularly in feedstock production, collection, and decentralized processing.

In rural areas, circular bioeconomy activities can create new livelihood opportunities by linking agriculture, forestry, and waste management with bio-based industries. These opportunities may include jobs in biomass logistics, bio-refining, bioenergy production, maintenance of processing facilities, and environmental services (Salvador et al., 2023). When supported by adequate skills development and institutional frameworks, such employment can contribute to inclusive economic growth and poverty reduction. At the same time, the circular bioeconomy can stimulate innovation and entrepreneurship by fostering new business models focused on resource efficiency, waste valorization, and local value creation. This dynamic is particularly relevant for small and medium-sized enterprises, which play a central role in many bio-based sectors. However, as indicated in Fig. 1.2, these employment and growth benefits may be accompanied by potential challenges, particularly when bio-based value chains rely on low-paid, seasonal, or informal labor. Without adequate labor protection, skills training, and inclusive governance, the circular bioeconomy may reinforce job insecurity or unequal benefit distribution rather than fully supporting decent work.

SDG 9: Industry, innovation, and infrastructure

The circular bioeconomy directly supports SDG 9 (Industry, Innovation, and Infrastructure) by fostering innovation in bio-based technologies and creating new value-added industries. Investments in biorefineries, biomass processing facilities, and bio-based product development stimulate technological advancement, enhance industrial productivity, and promote the adoption of resource-efficient production methods. These activities strengthen industrial infrastructure, diversify economic outputs, and contribute to resilient and innovative industrial systems, demonstrating a clear alignment between circular bioeconomy development and SDG 9.

SDG 12: Responsible consumption and production

SDG 12 (Responsible Consumption and Production) is central to the circular bioeconomy concept. By design, circular bioeconomy strategies aim to decouple economic growth from resource depletion by improving efficiency and promoting reuse, recycling, and the regeneration of biological resources (Salvador et al., 2023). Cascading biomass use, combined with integrating waste and by-product streams into productive cycles, reduces material losses and environmental burdens. Organic waste from households, agriculture, and industry can be transformed into valuable bio-based products, reducing landfill use and associated emissions while enhancing overall system efficiency. Furthermore, circular bioeconomy approaches promote systemic thinking across value chains, encouraging producers and consumers to consider life-cycle impacts and material flows. This contributes to more sustainable consumption patterns and supports the transition toward low-waste, low-emission production systems.

1.2.2 Potential support to SDGs

The circular bioeconomy offers multiple pathways to support key social Sustainable Development Goals, particularly SDG 1 (No Poverty), SDG 2 (Zero Hunger), and SDG 3 (Good Health and Well-Being). By promoting the sustainable use of biomass, enhancing agricultural productivity, and creating value-added opportunities along bio-based supply chains, the circular bioeconomy can improve livelihoods, food security, and health outcomes. At the same time, these benefits are not guaranteed and may be constrained by factors such as resource competition, land-use pressures, and inequitable access to economic opportunities (Neogi et al., 2022). The following sections provide a detailed discussion of the potential positive effects and associated trade-offs for each of these goals, highlighting the net potential for support while acknowledging the contextual challenges.

SDG 1: No poverty

The circular bioeconomy can offer multiple pathways for poverty alleviation. By creating value-added opportunities in rural and peri-urban areas, activities such as collecting and processing agricultural residues, developing small-scale biorefineries, and producing bio-based products diversify income sources for farmers and local communities. These opportunities can reduce dependence on single cash crops, increase household resilience to market shocks, and provide employment along biomass supply chains, including logistics, processing, and maintenance (Mak et al., 2020).

However, these benefits depend on equitable access to technologies, markets, and financing. Without inclusive policies, larger or better-capitalized enterprises may capture most of the economic gains, while smallholder farmers or marginalized communities receive limited benefits. Additionally, increased demand for biomass could shift labor allocation or intensify competition for land. Despite these constraints, when social and institutional frameworks support fair participation, the circular bioeconomy has the potential to contribute to poverty reduction, creating pathways for economic empowerment and inclusive rural development.

These considerations are also closely related to SDG 10 (Reduced Inequalities). The circular bioeconomy can promote more inclusive development by creating employment and income opportunities in rural and marginalized regions. Nevertheless, unequal access to technologies, investment, and markets may concentrate economic benefits among larger enterprises, widening existing disparities. Consequently, achieving positive outcomes for SDG 10 requires inclusive governance, equitable benefit-sharing mechanisms, and targeted policy support.

SDG 2: Zero hunger

Circular bioeconomy approaches can enhance food security by improving the efficiency and sustainability of agricultural systems. Using crop residues, organic waste, and by-products as biofertilizers or bioenergy feedstocks strengthens soil fertility, enhances nutrient cycling, and improves water retention (Srivastav et al., 2025). These interventions stabilize crop yields, increase resilience to climate variability, and reduce smallholder farmers' vulnerability to harvest fluctuations. Additionally, bio-based processing and local value chains generate income that can be reinvested in agricultural inputs or food access, thereby indirectly improving food availability and affordability.

Nonetheless, trade-offs exist. Competition for biomass among food, energy, and industrial uses can create resource constraints, particularly if first-generation crops are diverted from food production. Indirect land-use changes may also occur, potentially affecting local food systems. Yet prioritizing residues and non-food biomass for energy and industrial uses, together with integrated nutrient and waste management practices, can mitigate these conflicts (Hadley Kershaw et al., 2021). In this way, circular bioeconomy initiatives offer conditional but tangible support for SDG 2, enhancing both productivity and food system resilience.

Beyond its contribution to agricultural productivity, circular bioeconomy practices also have important implications for SDG 6 (Clean Water and Sanitation). The recycling of organic waste, recovery of nutrients, and adoption of sustainable biomass management can reduce nutrient leakage and improve water quality by limiting excessive fertilizer application and agricultural runoff. However, these benefits depend on appropriate management practices, as intensive biomass cultivation and processing may increase water consumption or contribute to water pollution if poorly regulated. Therefore, the contribution of the circular bioeconomy to SDG 6 is generally regarded as potential support under sustainable implementation conditions.

SDG 3: Good health and well-being

The circular bioeconomy can improve health outcomes through multiple interlinked pathways. Improved rural incomes from bio-based livelihoods can expand access to healthcare, nutrition, and sanitation. Sustainable management of agricultural residues and organic waste reduces environmental pollution, lowers exposure to harmful chemicals, and supports cleaner nutrient cycles, all of which contribute to healthier communities. Stable and diversified food systems resulting from bio-based interventions also enhance nutrition and dietary quality, supporting both child development and adult health.

Potential constraints include risks from unsustainable agricultural practices, fertilizer overuse, or inequitable distribution of economic benefits, which could exacerbate exposure to environmental hazards or create social disparities. Nonetheless, when circular bioeconomy initiatives are guided by sustainability criteria and equitable frameworks, the cumulative health effects are positive, indicating a net potential to support SDG 3.

1.2.3 Potential conflicts with SDGs

Despite its potential benefits, the circular bioeconomy may also involve context-dependent trade-offs and implementation risks that could affect progress toward certain SDGs if not carefully managed.

SDG 13: Climate action

As illustrated in Fig. 1.2, the contribution of the circular bioeconomy to SDG 13 (Climate Action) varies across different stages of the agro-industrial value chain. While bio-based products and reuse pathways provide clear climate benefits, the contributions of biomass production, processing, and waste management are generally regarded as potential support because their climate performance depends on sustainable implementation. For example, expanding biomass production to meet energy and industrial demands may create indirect pressures on land use, water resources, and agricultural systems, potentially leading to competition with food production (Kakadellis and Rosetto, 2021). Intensive biomass cultivation may also trigger land-use change elsewhere, resulting in unintended greenhouse gas emissions through deforestation, soil carbon loss, or the displacement of agricultural activities. Conversely, advanced bioenergy pathways can substantially contribute to climate mitigation by generating renewable energy while achieving net carbon removal, illustrating that climate outcomes depend on technological pathways and sustainability governance.

Moreover, inefficient biomass conversion or unsustainable sourcing can limit the anticipated climate benefits, as energy losses, transportation emissions, and lifecycle impacts may offset reductions in fossil fuel use. Overall, consistent with the stage-specific assessment presented in Fig. 1.2, the contribution of the circular bioeconomy to SDG 13 should be regarded as conditional rather than universally positive or negative. Achieving meaningful climate benefits requires sustainable biomass sourcing, efficient conversion technologies, effective waste management, and supportive governance to maximize synergies while minimizing unintended environmental impacts.

SDG 14 and SDG 15: Life below water and life on land

The expansion of biomass production and bio-based industrial activities associated with the circular bioeconomy can place significant pressure on both terrestrial and marine ecosystems, potentially undermining SDG 14 (Life Below Water) and SDG 15 (Life on Land). On land, increased demand for biomass may drive deforestation, habitat loss, and land conversion, reducing species diversity, degrading soil quality, and increasing vulnerability to pests and diseases. Intensive cultivation of monocultures or non-native species can further exacerbate ecosystem degradation and increase the risk of desertification.

In aquatic and marine systems, agricultural runoff from intensified biomass cultivation can transport nutrients, sediments, and agrochemicals into rivers and coastal waters, causing eutrophication, hypoxia, and the degradation of aquatic habitats. Unsustainable sourcing of marine biomass or aquaculture inputs can disrupt food webs, reduce biodiversity, and undermine the resilience of fisheries. Additionally, land-use changes for biomass production can alter hydrological flows and sediment transport, affecting estuarine and coastal ecosystems.

These dynamics highlight that, without sustainable management and monitoring, circular bioeconomy initiatives may inadvertently degrade terrestrial and marine ecosystems. Careful planning and resource stewardship are essential to minimize negative environmental impacts and manage the trade-offs between bio-based production and the conservation of biodiversity and ecosystem services.

Across all SDGs discussed above, the successful implementation of the circular bioeconomy also relies heavily on SDG 17 (Partnerships for the Goals). Effective collaboration among governments, industries, researchers, farmers, and international organizations is essential to promote technology transfer, policy coordination, investment, and knowledge sharing throughout bio-based value chains. Such partnerships facilitate the adoption of sustainable practices, strengthen governance, and help balance synergies and trade-offs across different stages of the circular bioeconomy.

1.3 Main agro-industries of the circular bioeconomy

Fig. 1.3 presents the framework used to organize the selected agro-industrial value chains.

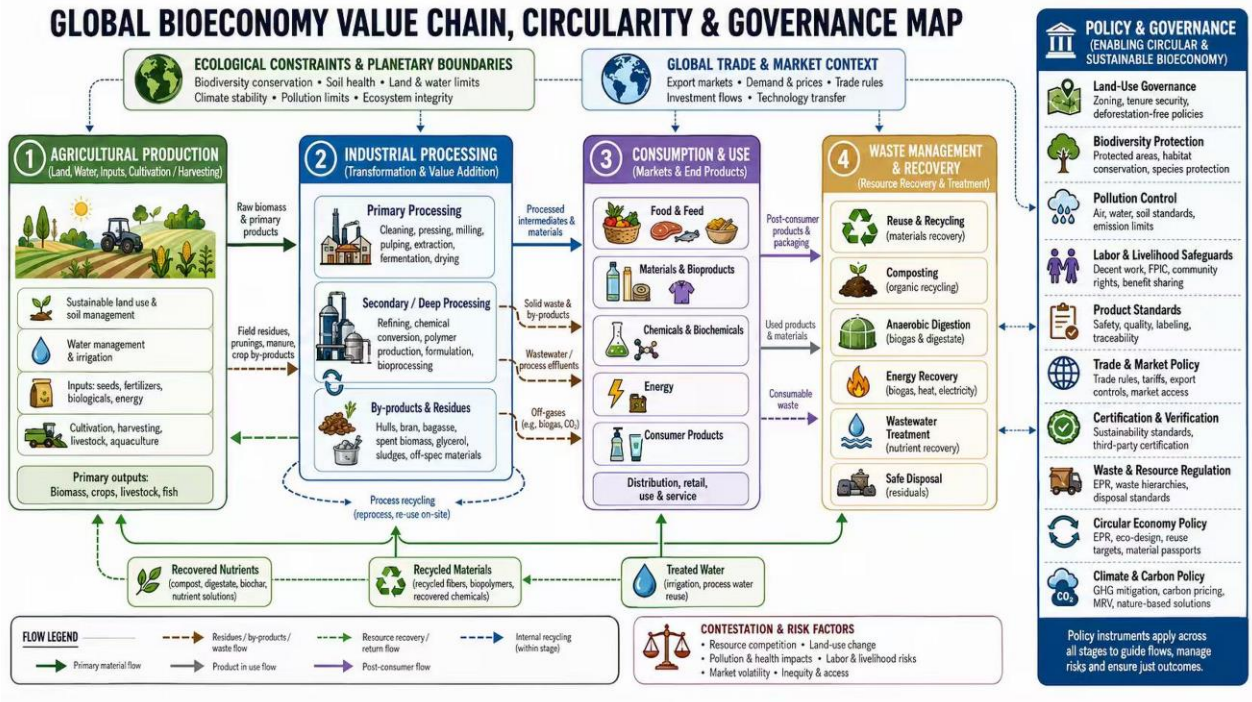


Fig. 1.3 Framework of agro-industry's circularity

Because the agricultural sector is at the core of the bioeconomy, we focus on its life cycle within the bioeconomy. Fig. 1.3 presents a schematic map of agro-industrial circularity across the full life cycle of the circular bioeconomy. It spans the entire chain from biomass production through processing, consumption, recovery, and return flows (FAO, 2014). In the upstream stage, bioresources such as palm oil, soybeans, rubber, rapeseed, cotton, bamboo, and algae are cultivated or collected under land, water, and input conditions, while interacting with ecological red lines, including biodiversity hotspots, protected areas, and wetlands. These activities generate pressures on land and water use, fertilizer and pesticide use, energy demand, and local livelihoods. In the midstream stage, biomass undergoes primary and deep processing, during which it is converted into oils, pulp, latex, fibers, chemicals, biofuels, and biomaterials. At the same time, by-products and waste streams such as effluents, shells, residues, bagasse, and biomass can be recirculated within industry through cascading use, reuse, recycling, and valorization. In the downstream stage, processed biomass supports global food, feed, energy, chemical, textile, and biomaterial industries. After consumption, end-of-life pathways, including reuse, recycling, composting, anaerobic digestion, and energy recovery, redirect materials back into production systems or into soils through biogeochemical cycling. Across all stages, global trade, certification, carbon and forest-related policies, and anti-deforestation regulations shape market access and sustainability outcomes, making circular agro-industry a system of interconnected material flows and environmental feedback.

1.3.1 Major bioresources and supply chains

Agro-industry relies heavily on biomass feedstocks. These feedstocks are highly sensitive to land and water availability and are closely linked to rural employment, income, and local livelihoods. At the same time, expansion, monocropping, and intensive input use create strong coupled risks to biodiversity and ecosystem services. The Food and Agriculture

Organization of the United Nations (FAO) defines the bioeconomy as the production, use, and conservation of biological resources. It supports all economic sectors through knowledge, technology, and innovation. This makes agro-industry a key carrier for bioeconomy implementation (FAO, 2018).

Globally, major agro-industrial bioresources include palm oil, soybeans, rapeseed, sugarcane, natural rubber, cotton, bamboo, and duckweed, among others. Oil crops (EIA, 2024) and sugar crops (Voora et al., 2023) support food and feed systems. They also serve energy uses, such as biodiesel and ethanol. In addition, they supply chemical value chains, including oleochemicals and surfactants. In the long term, global oilseed production and trade are becoming more concentrated in a few crops, especially soybeans, oil palm, and rapeseed (FAO, 2003).

These bioresources can be understood through a generalized value-chain framework that links four stages: upstream biomass production, midstream processing and biorefining, downstream product use, and end-of-life management. Across these stages, governance challenges are shaped by five cross-cutting dimensions: land and water use, rural livelihoods, biodiversity impacts, market concentration, and circularity potential. This framework helps distinguish several representative patterns. First, food–energy–chemical crops, such as palm oil, soybeans, rapeseed, and sugarcane, are mature commodity chains in which food, fuel, and industrial uses increasingly compete for the same feedstocks. Second, plantation-based industrial materials, such as natural rubber and cotton, are embedded in global manufacturing networks but often face low supply-chain transparency and land-use risks. Third, fast-regenerating lignocellulosic resources, such as bamboo, are promoted as substitutes for fossil-based and mineral-intensive materials in construction, fibers, packaging, and consumer products. Fourth, frontier aquatic biomass, such as duckweed, represents emerging bio-based pathways for protein, feed, wastewater treatment, and biomanufacturing, but remains constrained by immature standards, safety assessment, and commercialization systems.

These resources are often tightly coupled with livelihoods, land, water, and biodiversity. For example, the expansion of natural rubber has been identified as a major driver of tropical forest loss in Southeast Asia. High-resolution mapping studies suggest that rubber-related deforestation has been underestimated over long periods (Wang et al., 2023). Bamboo is valued for its high biomass productivity and rapid regeneration. It is seen as a promising resource for construction materials, fibers, and bio-based products. Its fast growth supports carbon sinks and long-term carbon storage (Ahmad et al., 2025). Duckweed and other aquatic biomass represent more frontier pathways. They grow rapidly on water surfaces, accumulate biomass quickly, and can be used for food and feed protein, among other applications (Takács et al., 2025).

Overall, these key bioresources support major sectors, including food and feed, energy and biofuels, chemicals and materials, consumer goods, and emerging bio-based materials and biomanufacturing. Building on this, agro-industrial supply chains exhibit clear spatial inequalities in the distribution of value. Upstream production is often concentrated in tropical and subtropical regions of the Global South. In contrast, refining, branding, and market bargaining power are more likely to be captured by a small number of processors and trading networks in the developed world. As a result, producer countries are more exposed to price volatility, extreme weather, and rising input costs (Deconinck et al., 2021).

At the same time, the use of agricultural feedstocks is expanding in a competitive manner. For oil crops, statistics from the U.S. Energy Information Administration show that biofuel production increasingly consumes soybean oil, rapeseed oil, palm oil, and other vegetable oils. This strengthens energy-sector demand for agricultural biomass and further affects oil prices and land pressure (EIA, 2025).

These industries also play a strong livelihood role, which adds to governance complexity. For example, palm oil requires timely post-harvest processing, as fresh fruit bunches must be delivered rapidly to nearby mills to maintain oil quality (Molenaar et al., 2013). At the same time, the sector is closely linked to rural employment and extensive smallholder participation. As a result, governance interventions in palm oil production influence not only deforestation and biodiversity outcomes but also local incomes, labor conditions, and the distribution of value along the supply chain (World Bank, 2023). Studies show that sugarcane cultivation and processing support employment and income for more than 100 million people across about 120 sugar-producing countries (Voora et al., 2023).

Building on this framework, the later case studies focus on palm oil, natural rubber, bamboo, and duckweed because they represent distinct value-chain patterns, stages of industrial maturity, and governance challenges. Palm oil represents a mature but highly contested food–energy–chemical commodity chain, where deforestation, smallholder livelihoods, and biofuel demand are closely intertwined (Voora et al., 2023). Natural rubber represents a globally traded industrial feedstock with strong links to forest conversion, tire manufacturing, and limited traceability. Bamboo represents a fast-growing lignocellulosic resource with high circularity and substitution potential, especially in construction, packaging, fibers, and bio-based materials (Ahmad et al., 2025). Duckweed represents an early-stage aquatic biomass pathway, with potential for protein production and wastewater-linked circular systems but with regulatory, safety, and market standards still under development (Jurga et al., 2026). Together, these cases cover a gradient from mature global commodities to emerging bio-based innovations.

Therefore, the core challenge for agro-based industries is not only to increase the output of individual commodities but also to shift bioeconomy expansion away from the depletion of natural capital. The focus needs to move toward joint gains in ecological resilience and local livelihoods (FAO, 2022b).

1.3.2 Circularity across the agro-industrial chain

In this study, the agro-industrial chain is structured into three stages based on a supply chain and product life cycle framework (FAO, 2014). Upstream processes involve the production and collection of biomass feedstocks, using land, water, labor, and material inputs. Midstream processes include transportation, primary and secondary processing, and manufacturing, which transform raw biomass into tradable intermediates and final products while generating energy demand, by-products, and waste streams. Downstream processes include product distribution, consumption, use, and post-consumption recovery, including recycling, cascading use, composting, and other circular end-of-life options.

Within this framework, circularity across agro-industrial value chains can be summarized into four representative pathways. The first is regenerative feedstock management, which focuses on maintaining soil quality, water resources, biodiversity, and long-term biomass productivity at the upstream stage. The second is by-product and residue valorization, through which processing residues, wastewater, biomass residues, or secondary materials are converted into energy, fertilizers, feed, biochar, or industrial inputs. The third is material substitution and cascading use, where bio-based products replace fossil-based or high-carbon materials and are used across multiple product cycles before final disposal. The fourth is post-consumption recovery and nutrient recirculation, which links downstream consumption with recycling, composting, energy recovery, or the return of nutrients to agricultural and aquatic production systems. These pathways show that circularity in agro-industry is not limited to waste treatment, but connects land-use governance, industrial processing, product design, consumption patterns, and end-of-life management.

The relationship between agro-industrial value chains and the Sustainable Development Goals (SDGs) also differs across product categories. Food, feed, and protein chains are closely linked to food security, nutrition, rural income, and responsible consumption, and therefore relate mainly to SDGs 2, 3, 8, and 12. (FAO, 2022b) Bioenergy and biochemical chains contribute to renewable energy and industrial decarbonization, but may also create land-use and biodiversity trade-offs, linking them to SDGs 7, 9, 12, 13, and 15.(Diakosavvas and Frezal, 2019a) Bio-based material chains, including construction materials, fibers, packaging, and rubber-based industrial products, support low-carbon substitution and resource efficiency, and are therefore associated with SDGs 9, 11, 12, and 13. Wastewater-based or residue-based chains, such as duckweed cultivation and biomass residue recovery, are particularly relevant to water quality, nutrient recovery, and circular production, connecting SDGs 6, 12, 13, and 15. (World Bank, 2020) However, without credible traceability, inclusive certification, land-right protection, and safety standards, circular bioeconomy pathways may shift environmental burdens, exclude smallholders, or create new trade barriers.

Based on this framework, bamboo, palm oil, natural rubber, and duckweed are selected as representative cases because they capture different resource characteristics, stages of industrial development, and degrees of governance complexity. The palm oil industry is relatively mature but highly contested. Natural rubber shows rapid demand growth but has very low supply-chain transparency. Bamboo is widely promoted as a green substitute for fossil-based products, such as plastics. Duckweed protein remains in the early stages of commercialization, with regulatory and safety standards still under development. The selected cases and their main characteristics are compared in Table 1.1.

Table 1.1 Example selection rationale12

Example	Resource type	Industrial maturity	Major products	Geographic concentration	Circularity potential	Main sustainability risks
Bamboo	Fast-growing lignocellulosic biomass	Moderately mature; rapidly expanding in engineered materials and plastic-substitution applications	Construction materials, packaging, fibers, utensils, panels, bio-based substitutes	Naturally distributed in tropical, subtropical and mild temperate regions, especially Asia, Africa and Latin America	High: fast regrowth, cascading use, biodegradable products, potential substitution for fossil-based materials	Land-use change, monoculture expansion, certification gaps, durability and end-of-life standards
Palm oil	Perennial oil crop / plantation commodity	Mature, globally traded and institutionally governed through certification schemes	Edible oils, processed foods, cosmetics, oleochemicals, biodiesel	Highly concentrated in Indonesia and Malaysia, which are projected to account for about 81% of global production	Medium: residue valorisation, bioenergy, oleochemical cascading, but limited by land-use lock-in	Deforestation, peatland conversion, biodiversity loss, GHG emissions, labor and smallholder traceability issues
Natural rubber	Tree-crop latex biomass	Mature material input, but demand is rising and supply chains remain fragmented	Tyers, gloves, medical products, industrial components, adhesives	Concentrated in Southeast Asia; Thailand and Indonesia are major producers, with demand growth led by China and India	Medium: product reuse and tyre recycling possible, but primary latex supply remains plantation-based	Underestimated rubber-driven deforestation, biodiversity loss, land conflicts, low first-mile transparency

Example	Resource type	Industrial maturity	Major products	Geographic concentration	Circularity potential	Main sustainability risks
Duckweed protein	Aquatic biomass / novel protein	Early-stage commercialization	Protein concentrate, fresh vegetable, animal feed, functional ingredients	Potentially less geographically fixed because cultivation can occur in controlled aquatic systems	High: nutrient recovery from wastewater or agricultural effluents, rapid biomass growth, protein substitution	Food-safety approval, heavy-metal or nutrient accumulation, compositional variability, immature standards and consumer acceptance

The palm oil industry is marked by a complex dichotomy between high industrial maturity and intense international political friction (FAO, 2013). At the upstream level, cultivation in tropical forests and peatlands remains a primary environmental flashpoint, driving significant deforestation and the release of soil carbon. This has triggered stringent regulatory responses such as the EU Deforestation Regulation (EUDR), which mandates advanced traceability and geolocation evidence (Godard et al., 2024). However, major producing nations such as Malaysia and Indonesia perceive these measures as discriminatory trade barriers and have consequently escalated disputes with the WTO (Jong et al., 2023; Mai et al., 2024). A critical dimension of this conflict is the potential for smallholder exclusion. While certification schemes such as the Roundtable on Sustainable Palm Oil (RSPO) aim to mitigate environmental and labor risks, smallholders face prohibitive structural disadvantages, including high certification fees, complex land tenure documentation, and rigorous auditing requirements (Brandi et al., 2015; Ekaputri et al., 2025; RSPO, 2025). In the midstream, while the processing of crude palm oil and the utilization of by-products—such as empty fruit bunches and wastewater treatment—are technically feasible, the primary governance constraint remains the equitable allocation of compliance costs and responsibility (FAO, 2013). Downstream, as consumers increasingly prioritize deforestation-free and ethically sourced products for food, cosmetics, and biodiesel, brands are under immense pressure to ensure full supply chain compliance. Nevertheless, stakeholders in the Global South argue that the financial and technical burden of these compliance systems should not fall on the most vulnerable producers, advocating for longer transition periods or exemptions to ensure that global emission reduction goals do not exacerbate social inequality (Gregory et al., 2025).

The natural rubber industry operates through a complex supply chain that begins upstream with cultivation primarily managed by smallholders in Southeast Asia. In the midstream phase, natural latex must be rapidly processed into sheet or block rubber using chemicals such as ammonia and formic acid (Fry et al., 2021). The sector also generates circular value through by-products such as rubberwood for furniture and by recycling rubber waste into reclaimed rubber or fuel. Downstream, these materials are converted into essential goods such as tires, footwear, gloves, and industrial products (CalRecycle et al., 2024). However, the industry faces severe governance challenges rooted in weak supply-chain transparency and hidden deforestation risks. Indeed, ZSL SPOTT assessments indicate that many processors and traders lack traceability even at the processor level, with very few reporting back to specific harvest areas (Ginger et al., 2023a). This lack of accountability is exacerbated by two primary factors: first, although plot-level traceability is technically feasible, its high implementation costs and the absence of robust financial or public support may trigger "trade diversion," where compliant rubber is funneled to the EU while non-compliant rubber shifts to less regulated markets, resulting in risk leakage rather than actual reduction (Yarlagadda et al., 2025); second, the sustainability commitments of major downstream tire companies often remain performative, frequently failing to set traceability targets that fully encompass the smallholder-dominated upstream sources (Ginger et al., 2023b).

The bamboo industry is notable for its carbon sequestration potential and renewability, yet its path to global integration is marked by distinct challenges across the value chain. Upstream, bamboo's rapid growth and self-regenerating root systems support soil carbon storage and erosion control without replanting (Ahmad et al., 2025). However, this biological advantage is shadowed by potential ecological risks; surging demand may trigger overharvesting or the expansion of monocultures, which can compromise habitat quality and biodiversity (Pulitzer Center, 2023). Furthermore, in the Global South, unclear land tenure often undermines community participation, prompting institutions like UN-REDD to stress that sustainable management must prioritize community land-use rights to avoid a cycle of short-term economic gain followed by long-term environmental degradation (UN-REDD Programme, 2021; REDD, 2021). In the midstream, bamboo's high cellulose and lignin content enables diverse processing into construction materials, cellulosic fibers, and pulp, as well as conversion into biofuels and biochar. This stage is further enhanced by waste circularity, in which processing residues are transformed into biogas or biochar through gasification and fermentation (Ahmad et al., 2025). Downstream, durable bamboo products serve as sustainable substitutes for plastics and timber while contributing to water purification and soil improvement (Ahmad et al., 2025). Despite these multi-sectoral benefits, the industry's governance remains hampered by immature markets and fragmented standards that frequently exclude small-scale operators (Li et al., 2024). Consequently, the sector requires more than material innovation; it necessitates the development of verifiable, tradable governance tools and standardized certification frameworks recognized by international markets to ensure equitable benefit sharing and long-term ecological resilience (GGGI, 2023; Li et al., 2024).

The duckweed industry is emerging as a highly resource-efficient sector with significant circularity potential, structured around a versatile value chain. Upstream, duckweed cultivation uses various species that thrive in freshwater ponds, rice fields, or nutrient-rich wastewater, where duckweed uses livestock manure or effluents as nitrogen sources; however, integrating duckweed with wastewater management introduces critical risks from heavy metals, pathogens, and algal toxins that must be rigorously addressed (European Commission, 2025). In the midstream, duckweed's dense nutritional profile—containing 20–35% protein along with essential sugars, lipids, and minerals—supports diverse processing pathways, ranging from direct animal feed and human-grade protein extraction to the fermentation of biofuels and biofertilizers (World Bio Market Insights, 2026).

Downstream, surging global demand for plant-based proteins, particularly in Europe, North America, and Southeast Asia, has successfully introduced duckweed protein powder into food and beverage markets (Tanikawa et al., 2021). Its use as a soybean substitute in the feed industry helps reduce deforestation pressures typically associated with large-scale soy expansion (Baghban-Kanani et al., 2023). Despite these advantages, the industry's scalability is constrained by stringent regulatory frameworks. The EU's recent classification of duckweed as a "novel food" has accelerated market entry but requires firms to navigate rigorous standards for ingredient safety, contaminant limits, and standardized production (Lambert et al., 2025; Takács et al., 2025). Consequently, while these regulatory thresholds provide a competitive edge for technologically advanced firms in the Global South, they also serve as technical barriers, underscoring that the long-term viability of duckweed depends on harmonizing food safety protocols with the complex requirements of water-environment management (Takács et al., 2025; European Commission, 2025).

These four industries were selected for case analysis because they represent the global bioeconomy across three key dimensions. First, they span a broad ecological spectrum, from tropical woody perennials (palm oil and rubber) to giant arborescent grasses (bamboo) and aquatic macrophytes (duckweed), reflecting varied carbon sequestration potentials and resource use patterns across ecosystems. Second, they illustrate a wide range of industrial maturity and transition pathways; while palm oil and rubber are mature global commodities currently embroiled in "deforestation" controversies and intense trade conflicts, bamboo and duckweed represent emerging green sectors with high substitution potential but fragmented governance standards. This contrast enables a comprehensive exploration of both "legacy asset transformation" and "new bio-industrial development." Finally, all four sectors are at the frontier of global sustainability regulations—such as the EU Deforestation Regulation (EUDR) and Novel Food classifications—effectively capturing the systemic tensions among rigorous environmental compliance, smallholder livelihood protection, supply chain transparency, and the equitable distribution of responsibility between the Global North and South. This study systematically analyzes these four agro-industrial sectors across five interrelated analytical dimensions, with the specific research content elaborated as follows: first, the evolutionary trajectories of core policies and industrial practices are examined; second, the inherent correlations among industrial development, land use patterns, and biodiversity conservation are summarized; third, the multidimensional impacts of agro-industrial expansion on rural and local livelihoods are empirically revealed; fourth, the predominant environmental constraints and critical ecological problems associated with large-scale agro-industrial development are analyzed; and finally, the bidirectional mechanisms between climate change dynamics and agro-industrial development processes are delineated.

2 Bamboo Industry

The bamboo industry represents an important and rapidly evolving component of the global bioeconomy. As a fast-growing perennial grass, bamboo can provide a renewable biomass supply within short harvest cycles while regenerating through its rhizome system without repeated replanting. Traditionally used for rural housing, household goods, handicrafts, food, and fuel, bamboo has increasingly entered higher-value industrial applications, including engineered boards, pulp and paper, textiles, furniture, packaging, bio-composites, charcoal, and plastic-substitution products. This transformation is particularly relevant for many countries in Asia, Africa, and Latin America, where bamboo resources are closely linked to rural livelihoods, small-scale enterprises, and community-based value chains. At the same time, expanding global markets have positioned bamboo as a potential low-carbon alternative to timber, plastics, and other emissions-intensive materials. However, realizing this potential requires careful attention to land use, biodiversity, processing emissions, product standards, value distribution, and climate vulnerability. The following section therefore examines the bamboo industry through its policy evolution, technological development, market expansion, environmental implications, and livelihood impacts.

2.1 Historical evolution of key policies and practices in the bamboo industry

The development and maturation of the bamboo industry constitute a important case within the broader global macroeconomic transition toward a sustainable bioeconomy. Historically marginalized within academic and industrial discourses and frequently relegated to a subsidiary role within traditional forestry frameworks, where it was primarily used for basic rural construction, agricultural implements, or low-value artisanal crafts, the bamboo sector has undergone a substantial repositioning over the preceding three decades. The global academic community, alongside international environmental governance bodies, increasingly acknowledges bamboo as a fast-growing, exceptionally versatile, and strategic biomass resource (Rao et al., 2026). This formal recognition is fundamentally predicated on the material's unique biological and morphological advantages, specifically its high strength-to-weight ratio and rapid maturation. Unlike most conventional timber species, which require several decades to reach maturity, sympodial and monopodial bamboos typically reach a harvestable physiological state within four to five years. Furthermore, due to its extensive rhizome network, systematic and cyclical harvesting stimulates rather than depletes the proliferation of new shoots, ensuring a continuous and robust regeneration mechanism.

Consequently, bamboo is now considered instrumental in driving modern bioeconomic paradigms, serving as a compelling, scalable, and technically viable substitute for high-emission, fossil-based feedstocks and traditional structural materials (FAO, 2022a). Its robust carbon sequestration capabilities, significantly exceeding those of comparable fast-growing hardwood species on a per-hectare basis, directly underpin global objectives related to climate resilience, ecosystem restoration, and deep industrial decarbonization. This sector-wide transformation is not an accidental phenomenon resulting from passive market forces; rather, it is the cumulative, systemic outcome of highly calculated macroeconomic policy interventions, advanced technological innovation in sophisticated industrial processing methodologies, and rapidly evolving global environmental standards. These intertwined factors have collectively and deliberately elevated the resource from an era of mere subsistence extraction to one characterized by highly integrated, large-scale industrial application and international trade (Rao et al., 2026).

This section examines the evolution of the bamboo sector through policy change, technological development, market diffusion and international trade over the past forty years. Addressing prior conceptual ambiguities and moving beyond simplistic analytical frameworks, the analysis charts the progression from resource-based exploitation to knowledge-intensive value addition. Furthermore, it incorporates a Life Cycle Assessment (LCA) perspective and industrial ecology principles to evaluate the true environmental efficacy of various processing routes. The analysis uses China as the primary empirical reference case owing to its preeminent position in the global market, its vast managed plantation resources (exceeding 7 million hectares), and its pioneering, decades-long role in industrializing bamboo processing technology. Concurrently, it draws comparative institutional insights from other significant bamboo-producing regions in the Global South, offering a holistic perspective on the globalization of this strategic resource.

2.1.1 Policy paradigm shift: from subsistence forestry to strategic bioeconomy resource

The policy landscape governing the cultivation, harvesting, trade, and industrial use of bamboo has evolved dramatically from localized, fragmented agricultural management strategies to complex, multi-sectoral frameworks that are now foundational to the emerging global bioeconomy. As articulated by key global organizations such as the Food and Agriculture Organization (FAO), the United Nations Environment Programme (UNEP), and the International Bamboo and Rattan Organization (INBAR), contemporary bioeconomy policies worldwide have deliberately moved beyond the simple, linear extractive model of resource exploitation (FAO, 2022a). Modern policy frameworks actively seek to address overarching, existential global challenges, notably climate change mitigation, sustainable land management, and the imperative for responsible, low-carbon material sourcing.

Within the bamboo sector, the precise trajectory of policy development in China, which accounts for a large share of global commercial bamboo production and processing, provides an illuminating, replicable roadmap for industrial maturation. This policy evolution can be clearly divided into three major, sequential historical phases, each closely intertwined with shifting national macroeconomic objectives, pressing forestry conservation imperatives, and broader environmental strategies (Fig. 2.1).

Phase I: The Resource-Based Era (Pre-1998). During the 1980s and early 1990s, bamboo's conceptualization and administration within national policy were largely subsumed within broader rural development and basic agricultural poverty-alleviation frameworks. Following the implementation of the Household Contract Responsibility System in the early 1980s, management of previously collective bamboo forests was decentralized and entrusted directly to local farmers. The policy objective during this era was singular, straightforward, and localized: maximizing biomass supply to support rural energy needs (primarily fuelwood for heating and cooking), basic housing construction, and the production of low-value, labor-intensive handicrafts. During this period, bamboo was often indiscriminately classified alongside minor non-timber forest products (NTFPs), lacking a distinct, recognized industrial identity. State interventions were largely limited to basic silvicultural guidelines and localized poverty-relief subsidies. There was virtually no systemic policy attention to value-added deep processing, international trade standards, or the long-term environmental implications of specific cultivation practices, resulting in a highly fragmented, low-efficiency industrial landscape heavily reliant on wild harvesting (Perez et al., 1999).

Phase II: Industrialization and Market Expansion (1998–2020). The decisive inflection point in the industrialization of the bamboo sector occurred in 1998, catalyzed by the implementation of the National Natural Forest Protection Program (NFPP). The central government implemented the NFPP in direct response to severe ecological degradation and devastating regional flooding in the Yangtze and Yellow River basins. It instituted a strict, comprehensive, and unprecedented ban on the commercial logging of natural forests across vast regions of China. This sudden, massive regulatory shift immediately created an urgent domestic timber deficit, necessitating the rapid identification and development of fast-growing, renewable substitutes to supply the construction and furniture sectors. Given its rapid regeneration rate and excellent physical strength, bamboo became the immediate focal point of state-sponsored substitution strategies. Policy frameworks began to strategically decouple bamboo from general forestry, granting it specific industrial priority. Subsequent national policies, most notably the National Bamboo Industry Development Plan (2011-2020), established highly specific financial incentives for high-yield plantation expansion, provided heavy capital subsidies for advanced processing machinery, and strongly encouraged the creation of specialized, densely integrated industrial clusters (such as Anji County in Zhejiang Province and Jian'ou in Fujian Province). During this period, the focus shifted decisively from the raw resource end to the deep-processing end. Policies emphasized the establishment of large-scale "Dragonhead" enterprises—corporations capable of dominating supply chains and driving regional economic growth through technology adoption. This period saw a massive scaling of production capacity, particularly in engineered bamboo flooring, heavy reconstituted bamboo boards, and basic bamboo pulp production, completely transforming the sector into a highly lucrative, multi-billion-dollar industry geared toward both expanding domestic consumption and massive global export volumes (State Forestry Administration of China, 2013).

Phase III: The Bioeconomy and "Plastic Substitution" Era (2021–Present). The contemporary phase is defined by the strategic integration of the bamboo industry into global climate governance architectures and the urgent global fight against plastic pollution. Following the formal introduction of China's "Dual Carbon" goals (aiming to peak carbon emissions before 2030 and achieve carbon neutrality by 2060), recent policy frameworks characterize bamboo not merely as a convenient timber substitute but as a critical, strategic material essential to ecological civilization and a low-carbon economic transition. The landmark release of the "Three-Year Action Plan for Accelerating the Development of Bamboo as a Substitute for Plastic (2023–2025)" by the National Development and Reform Commission, alongside multiple other ministries, exemplifies this strategic, top-down pivot. This highly specific policy employs a sophisticated combination of strict regulatory instruments, substantial financial incentives for advanced material research and development, and mandated green public procurement protocols to drive systemic market transformation. Crucially, current policies focus heavily on Life Cycle Management, increasingly integrating mandatory LCA methodologies to scientifically verify the carbon footprint benefits of bamboo products and rigorously prevent corporate "greenwashing." Furthermore, these modern policies are fostering deep cross-sectoral integration, linking bamboo industry development directly with plastic pollution control initiatives, emerging national carbon trading markets (CCERs), and green finance mechanisms, thereby demanding complex, cross-ministerial coordination to fully manage the sector's ecological and economic potential (National Development and Reform Commission of China, 2023).

While China has played a leading role in bamboo industrialization and commercialization, other producing nations in the Global South are actively reforming their traditional regulatory frameworks to stimulate their domestic bamboo bioeconomy. For instance, in India, bamboo was historically and problematically categorized under the colonial-era Indian Forest Act of 1927 as a "tree," a highly restrictive legal classification that imposed severe bureaucratic hurdles, complex transit passes, and heavy restrictions on felling, thereby stifling commercial cultivation by private farmers (Government of India, 2018). Recent pivotal legislative amendments have officially deregulated bamboo grown on non-forest lands, reclassifying it as a grass to incentivize private plantation forestry and spur rural industrialization. Similarly, nations in Sub-Saharan Africa, such as Ethiopia and Kenya, have begun explicitly incorporating bamboo into their national Biomass Energy Strategies and Green Economy trajectories (Alemayehu & Hido, 2023), recognizing its potential for land restoration and economic development, though their processing sectors largely remain in the transitional space between Phase I and Phase II development paradigms. Vietnam and Indonesia have also expanded export-oriented bamboo processing, although processing depth and standardization remain uneven across products and regions (INBAR, 2023).

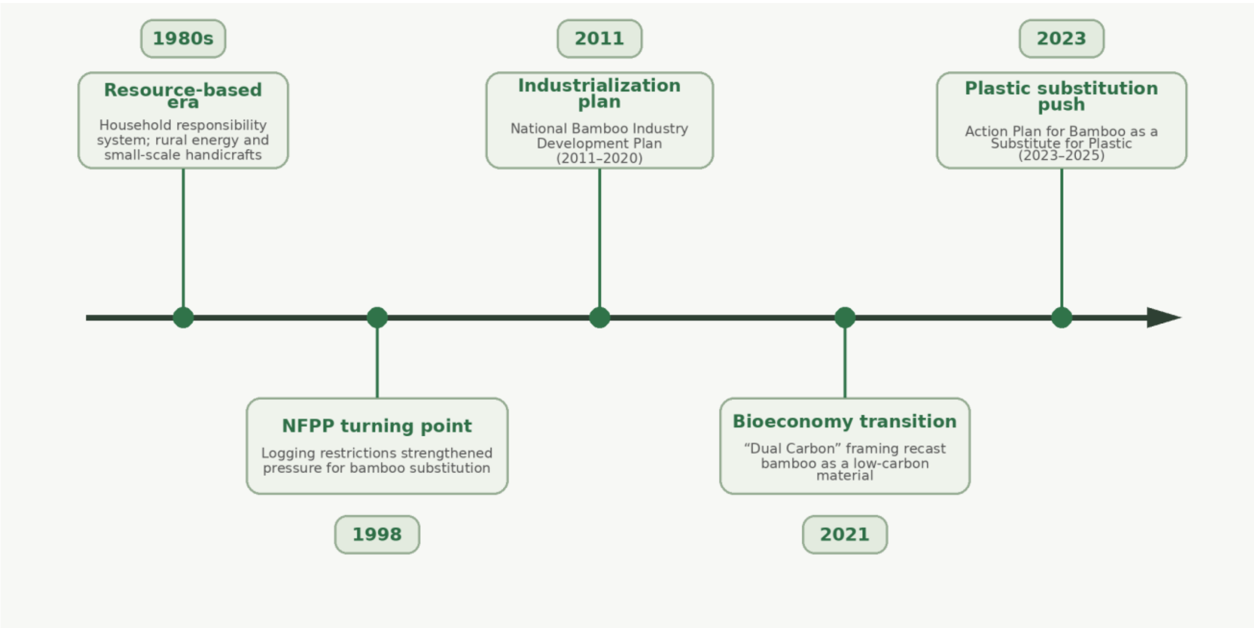


Fig. 2.1 Evolution of China's Bamboo Industry Policies (1980s-Present).

2.1.2 Technological trajectories: processing routes, modernization, and LCA optimization

Technological advancement and deep industrial engineering have been the crucial drivers of the bamboo bioeconomy's maturation. This continuous progress has been instrumental in enabling a massive and highly valuable transition: moving away from the simple, structurally limited, and low-value use of raw, round bamboo culms toward the creation, optimization, and widespread global adoption of sophisticated, high-performance engineered materials, technical bioplastics, and high-purity biochemicals. Based strictly on the physical properties, lignocellulosic chemical composition (cellulose, hemicellulose, and lignin ratios), and morphological characteristics of the varying biomass inputs—ranging from mature, thick-walled culms to processing residues like sawdust, shavings, and even bamboo shoots—modern bamboo industrial processing is rigorously categorized into several distinct, highly optimized conversion pathways (Fig. 2.2). Across these routes, LCA results depend on the system boundary, including biogenic-carbon accounting, land-use change, processing energy, adhesive inputs, product lifetime and end-of-life assumptions. The major bamboo processing routes are compared in Table 2.1.

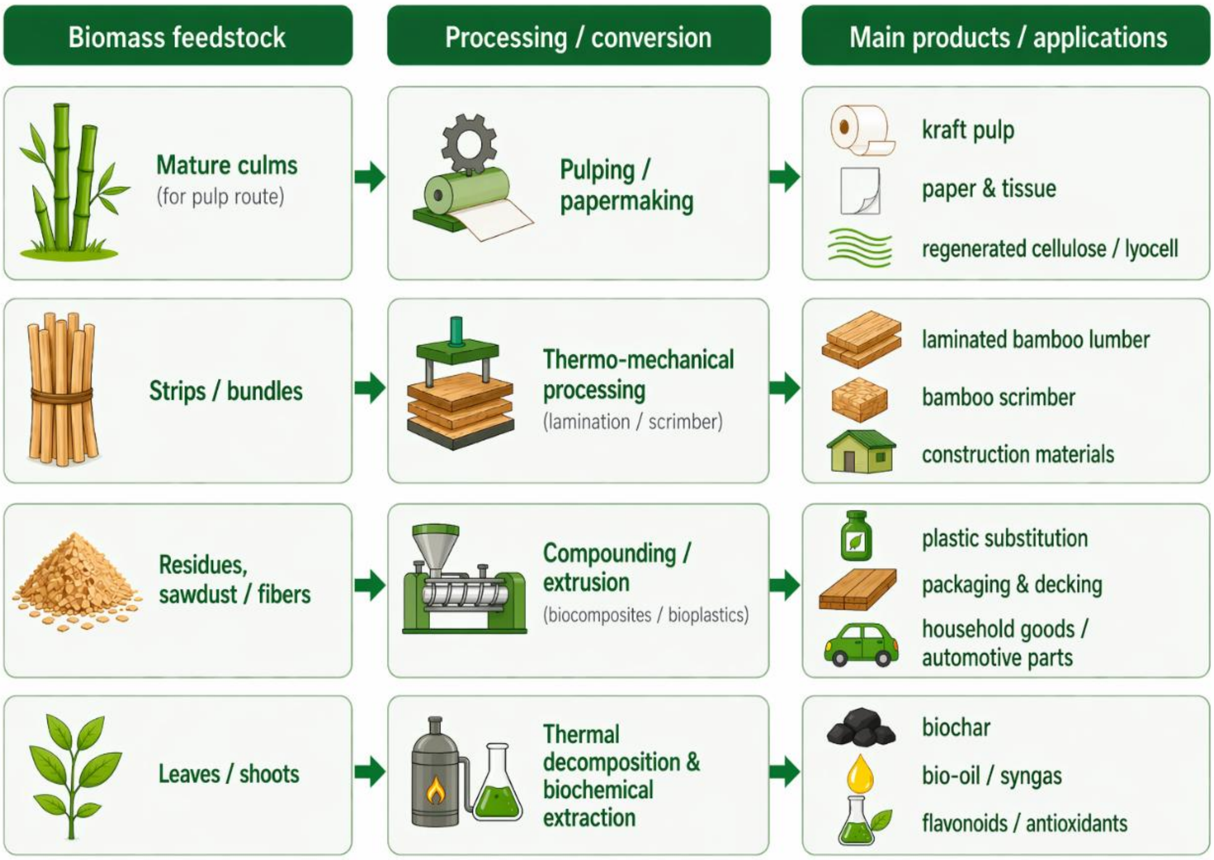


Fig. 2.2 Pathways for the industrial utilization of different bamboo biomass resources.

Table 2.1 Comparison of major bamboo processing routes.

Processing route	Key products	Circularity opportunities	Main environmental concerns	Technology maturity
Pulping and papermaking	Kraft pulp, paper, tissue and dissolving pulp	Chemical recovery, black-liquor energy recovery and water reuse	Energy and chemical demand, bleaching emissions and wastewater	Commercial and mature
Thermo-mechanical processing	Laminated bamboo lumber, scrimber and structural products	High culm utilization, offcut reuse and long-lived carbon storage	Drying and pressing energy, adhesive use and emissions	Commercial and mature
Biocomposite production	Bamboo-plastic composites and molded products	Use of sawdust and fibres; reduced virgin polymer demand	Coupling agents, polymer matrices and end-of-life recyclability	Commercial to emerging
Thermochemical conversion	Biochar, bio-oil and syngas	Valorization of low-grade residues and energy recovery	Feedstock drying, process emissions and residue quality	Pilot to commercial
Biochemical extraction	Flavonoids, antioxidants and bio-based chemicals	Valorization of leaves, shoots and processing liquors	Solvent use, purification energy and wastewater	Emerging

Bamboo Pulp and Papermaking Technologies: Converting raw bamboo chips into cellulosic pulp is among the most technologically mature, capital-intensive, and scale-driven routes in the sector. Bamboo fiber has highly advantageous morphological characteristics; specifically, its fiber length (averaging 1.5–2.0 mm) and excellent slenderness ratio effectively bridge the gap between short-fiber hardwoods (like eucalyptus) and long-fiber softwoods (like pine). This unique morphology makes bamboo pulp an exceptional raw material for manufacturing both high-strength, unbleached packaging paper and highly absorbent premium tissue paper (Khantayanuwong et al., 2023). Technologically, the industry has undergone a massive, enforced modernization, largely transitioning away from highly polluting, small-scale traditional alkaline processes toward advanced, high-efficiency continuous Kraft (sulfate) pulping processes. To address the unique challenges of bamboo—namely its high silica content and dense, impermeable outer epidermis—modern mills employ advanced pre-steaming and pre-hydrolysis Kraft (PHK) cooking technologies to optimize delignification. Furthermore, from a rigorous LCA perspective, the environmental footprint of this massive sector has been drastically improved through the mandatory implementation of totally chlorine-free (TCF) and elemental chlorine-free (ECF) bleaching sequences, which have largely eliminated the historically severe emissions of toxic chlorinated compounds and dioxins into local water systems. Additionally, state-of-the-art bamboo pulp mills now uniformly utilize sophisticated chemical recovery boilers to combust the lignin-rich black liquor. This critical closed-loop technology not only recovers highly valuable pulping chemicals (sodium hydroxide and sodium sulfide) but also generates massive amounts of biogenic thermal energy (steam) and electricity to power the entire plant. This energy self-sufficiency significantly drives down the overall cradle-to-gate carbon emissions, aligning the pulping process with modern industrial ecology standards. Beyond conventional papermaking, highly purified dissolving bamboo pulp (characterized by very high alpha-cellulose content) is chemically extruded to produce regenerated cellulose fibers, such as conventional viscose and advanced Lyocell. The Lyocell process, in particular, represents a technological pinnacle, utilizing a closed- loop organic solvent system (N-methylmorpholine N-oxide, or NMMO) that recovers and reuses over 99% of the solvent, offering a highly sustainable, bio-based, and biodegradable alternative to both highly water-intensive conventional cotton and petroleum-derived synthetic textiles like polyester(G. Zhao et al., 2010).

Engineered Bamboo Boards and Thermo-mechanical Processing: Traditional structural use of bamboo in construction was inherently and severely limited by the bamboo culm's hollow, cylindrical geometry, the frequent presence of structural nodes, and its varying wall thickness along the length of the pole. Modern engineering technologies have fully overcome these morphological constraints through sophisticated "deconstruction and reconstitution" manufacturing strategies. The primary technology route for Laminated Bamboo Lumber (LBL) involves precision-slicing raw culms into uniform rectangular strips, aggressively boiling or carbonizing them to remove vulnerable starches and free sugars (thereby greatly increasing resistance to fungal decay and insect attacks), drying them to a precise moisture content, and finally laminating them under high pressure with specialized structural adhesives (such as phenol-formaldehyde or melamine- urea- formaldehyde). This creates a standardized, orthotropic material comparable in performance to engineered wood products like glulam timber(Bala & Gupta, 2023). A significantly more advanced leap is Bamboo Scrimber (frequently referred to as Strand Woven Bamboo). This disruptive technology crushes entire bamboo bundles into interconnected, continuous fibrous mats, which are then deeply impregnated with weather-resistant phenolic or advanced bio- based resins and compressed under controlled elevated temperature and pressure (frequently exceeding 140°C and 10 MPa). This thermo-mechanical process uses approximately 80–90% of the raw biomass—significantly reducing waste compared to the strip-making process of LBL—and yields a highly densified (exceeding 1.1 g/cm3), highly dimensionally stable material. The mechanical properties of Bamboo Scrimber, such as its modulus of rupture (MOR) and modulus of elasticity (MOE), frequently and dramatically exceed those of conventional structural concrete, mild steel, and premium, slow- growing tropical hardwoods. From an LCA perspective, while the intensive manufacturing phase consumes considerable thermal and electrical energy and introduces adhesive- related chemical emissions, the final engineered bamboo products function as exceptional, long- term carbon sinks. They store atmospheric carbon within the built environment for decades, representing a highly effective carbon storage mechanism within the construction sector(Churkina et al., 2020; Liu et al., 2024; X. Xu et al., 2022).

Melt Compounding and Bamboo Biocomposites (Bioplastics): Aligned directly and strategically with the global "substitute for plastic" initiative and the imperative to reduce marine and terrestrial microplastic pollution, the biocomposites pathway represents the frontier of bamboo valorization and industrial ecology. This route efficiently uses low-value processing residues—such as bamboo sawdust, fine milling flour, or mechanically extracted microfibers—thereby achieving near 100% resource utilization efficiency across the supply chain. Because natural bamboo lignocellulosic fibers are highly hydrophilic (water-absorbing due to surface hydroxyl groups) and common polymer matrices are typically hydrophobic (water-repelling), the core technological and chemical challenge is achieving strong interfacial compatibility. Modern processing strictly uses chemical coupling agents, most notably maleic anhydride-grafted polypropylene (MAPP), to surface-modify the bamboo fibers and ensure they bond effectively with the plastic. These modified fibers are then compounded with thermoplastic polymer matrices (ranging from conventional petrochemical plastics like polypropylene and polyethylene to fully biodegradable biopolymers like polylactic acid) via high-shear melt compounding and advanced twin-screw extrusion techniques. These bamboo plastic composites (BPCs) not only divert massive volumes of industrial waste from landfills or open incineration but also significantly reduce the volumetric consumption of fossil-based plastics. The resulting materials exhibit high stiffness, excellent dimensional stability, and reduced thermal expansion, making them widely used in automotive interiors (e.g., door panels), exterior decking, heavy-duty logistics pallets, and rigid, durable packaging (D. Xu et al., 2023).

Thermal Decomposition and Biochemical Extraction: To achieve a true zero-waste, fully circular processing model, advanced thermal decomposition technologies are increasingly deployed at the industrial scale. Pyrolysis and gasification processes convert completely unutilizable bamboo biomass residues (such as roots, small branches, and fine processing dust) into valuable biochar, bio-oil, and combustible syngas in oxygen-deprived, carefully controlled high-temperature environments. The resulting bamboo biochar is highly porous, possesses a massive specific surface area, and serves as an excellent soil amendment and carbon sequestration agent, effectively returning fixed carbon to the soil in a highly stable, recalcitrant form that resists microbial degradation for centuries. Concurrently, advanced biochemical extraction and fractionation techniques are used to isolate high-value secondary metabolites—including bamboo leaf flavonoids, potent antioxidants, antimicrobial compounds, and lactic acid—from bamboo shoots, foliage, and processing liquors (Nirmala et al., 2018). These highly purified biochemicals cater directly to the high-margin, heavily regulated pharmaceutical, cosmetic, and food-additive markets, demonstrating the ultimate realization of the cascade utilization principle in the biomass sector.

2.1.3 Market dynamics and application diffusion: sectoral substitution

The strategic, targeted diffusion of highly engineered bamboo products has systematically penetrated downstream economic sectors that have traditionally been dominated by high-carbon, energy-intensive, non-renewable materials. By successfully disrupting these entrenched markets, the modern bamboo industry acts as a highly practical, economically viable, and scalable mechanism for global climate mitigation, fundamentally shifting massive consumption patterns toward renewable, bio-based alternatives with significantly lower lifecycle carbon footprints. Substitution benefits should be assessed under functional equivalence, considering product application, durability, adhesive use, transport distance, the local energy mix and end-of-life treatment.

Crucially, the successful initial market diffusion of these novel, sustainable products often hinges entirely on decisive, intentional leadership from the public sector. Government offices, municipalities, and state-backed institutions possess unique financial leverage and regulatory authority to create foundational demand, mitigate the severe initial market risks of scaling new technologies, and set powerful new normative standards for public consumption. By formally requiring public institutions to pilot, specify, and procure "bamboo-for-plastic" or "bamboo-for-steel" products within their supply chains, a stable, highly predictable initial market is intentionally established. This guaranteed baseline demand significantly reduces the inherent financial and commercial risk—often termed the "green premium"—for manufacturers who are heavily investing in transitioning production lines or developing new, sustainable material technologies (Krieger & Zipperer, 2022).

Construction, Architecture, and Heavy Infrastructure: The global construction sector, historically responsible for a significant 39% share of global energy-related carbon dioxide emissions, has become the primary, highest-impact target for engineered bamboo materials. High-density bamboo scrimber, cross-laminated bamboo (CLB), and bamboo glulam beams are increasingly substituting high-emission concrete, energy-intensive steel framing, and scarce solid wood in load-bearing structural frameworks, exterior architectural cladding, heavy-duty bridge decking, and premium interior flooring. Because these highly durable, weather-resistant products have a physical lifespan spanning several decades—often guaranteed for 25 to 50 years—they effectively serve as massive, long-term carbon reservoirs (classified as the S4 stage in rigorous LCA frameworks). This prolonged physical existence delays the re-emission of biogenic carbon into the atmosphere, generating significant, verifiable carbon displacement credits. Furthermore, industrial infrastructure applications represent a major application area for volume utilization. Breakthrough technologies like bamboo-winding composite pipes, currently being deployed for massive urban water drainage systems and high-pressure agricultural irrigation networks, leverage bamboo's extraordinary tensile strength and natural corrosion resistance. These winding pipes offer a highly disruptive, remarkably lower-carbon, and highly durable alternative to traditional polyvinyl chloride (PVC), cast iron, and pre-cast concrete pipes, signaling the full maturation of bamboo as an industrial-grade engineering material (M. Chen et al., 2021).

Pulp, Paper, and Regenerated Textiles: As global demand for cellulosic fiber continues to rise sharply amid severely restricted logging in natural forests and shrinking arable land for timber plantations, bamboo serves as a vital, rapidly renewable non-wood fiber source. It is used extensively and efficiently in the mass production of unbleached kraft packaging paper, heavy corrugated cardboard, and premium, highly absorbent sanitary tissue paper, directly substituting for chemically intensive wood pulp. In the global textile sector, bamboo-derived regenerated cellulose fibers—specifically viscose, modal, and Lyocell—have gained a growing market share. These fibers directly substitute highly water-intensive and pesticide-heavy cotton, as well as petroleum-based synthetic fibers like polyester and nylon. The newer, advanced closed-loop solvent systems (such as the Lyocell process) represent a definitive shift towards cleaner production technologies that are perfectly aligned with stringent circular bioeconomy standards, drastically reducing water pollution and energy consumption compared to legacy textile manufacturing processes (Guo et al., 2021).

Packaging, Disposables, and the FMCG Sector: Driven by the rapid global proliferation of single-use plastic bags and stringent municipal waste regulations, bamboo is rapidly capturing a large share of the fast-moving consumer goods (FMCG) and disposables market. Products such as high-precision bamboo-based molded-pulp packaging (used for electronics and cosmetics), thermoformed food-delivery containers, disposable biodegradable cutlery, and extruded bamboo-fiber straws are aggressively replacing expanded polystyrene (EPS) foam and polyethylene terephthalate (PET) plastics. Government-mandated green procurement policies, coupled with impending Extended Producer Responsibility (EPR) financial schemes, play a pivotal role in this sector, legally enforcing the phase-out of petrochemical plastics and mandating the rapid adoption of bio-based, compostable alternatives, despite their currently higher unit production costs (Barone et al., 2025).

2.1.4 Globalization of the bamboo value chain, trade misalignment, and standardization

The globalization of the bamboo industry over the past three decades is overwhelmingly defined by an economically significant shift: moving away from the highly localized, informal trade of raw, unprocessed culms toward the highly organized, standardized international export of value-added finished goods. Within this complex global value chain, China currently holds a dominant position. Accounting for over 75% of the global bamboo export market, China's official trade volume in this sector significantly exceeded $2.2 billion annually as of 2022, making it the primary supplier to North American and European consumer markets (INBAR, 2023). Nevertheless, a growing number of developing nations in the Global South—notably Vietnam and Indonesia in Southeast Asia, India in South Asia, and Ethiopia and Kenya in Sub-Saharan Africa—are increasingly integrated into this international network. These nations are actively seeking to replicate China's successful industrialization and cluster-based model to foster local bioeconomy development, alleviate rural poverty, and generate vital foreign exchange reserves.

Despite the impressive growth in aggregate export volume and total economic value, a deep dive into global trade flow data reveals a profound, highly problematic spatial misalignment between life-cycle carbon assets and international environmental burdens. A large share of bamboo exports from developing manufacturing nations (most notably China) to specific, highly saturated East Asian markets (such as Japan and South Korea) consists of extremely short-lived products. These primarily include single-use bamboo skewers, disposable chopsticks, and basic, low-value food packaging. From a rigorous LCA and industrial ecology perspective, exporting these products represents a massive, rapid "carbon source" flow. The substantial amounts of fossil-based thermal and electrical energy consumed during domestic manufacturing (representing locked-in, unavoidable carbon emissions during the manufacturing and use LCA stages) are not offset by long-term carbon storage. This is because these disposable products are quickly incinerated or landfilled in the destination country, often within weeks or months of export, immediately releasing biogenic carbon back into the atmosphere. The producing nation bears the severe ecological cost and emissions burden of manufacturing, while the carbon is rapidly released overseas. Conversely, the high-value, long-lived engineered bamboo products—such as heavy structural scrimber beams, durable flooring, and solid bamboo furniture, which act as true, long-term carbon sinks—are disproportionately absorbed by affluent Western markets, primarily the United States and the European Union. Addressing this severe structural trade imbalance—strategically shifting national export reliance away from low-end, short-lived commodities that act as rapid carbon sources and pivoting heavily toward durable, carbon-locking engineered materials—is essential for maximizing the climate mitigation potential and long-term economic resilience of the producing nations.

To successfully navigate, regulate, and optimize these highly complex global trade dynamics, international standardization is the ultimate, indispensable market enabler. International organizations, primarily the International Bamboo and Rattan Organization (INBAR), are instrumental in addressing structural market imbalances by facilitating robust South-South cooperation, coordinating international technology transfer programs, and spearheading the development of critical international ISO standards. The successful harmonization of global customs codes (specifically 6-digit HS Codes) dedicated to bamboo and rattan products has drastically improved global trade data visibility, finally allowing governments and researchers to implement targeted tariff policies, combat illegal logging, and accurately track material flows. Furthermore, the rigorous establishment of engineering standards, most notably ISO 22156 for bamboo structural design and testing, is actively dismantling long-standing technical barriers to trade. This critical standardization allows engineered bamboo products to legally enter highly regulated, immensely lucrative commercial construction markets in Europe and North America by providing architects, civil engineers, and building code officials with reliable, standardized, and legally defensible load-bearing and fire-safety data (International Organization for Standardization, 2021).

In essence, the formal recognition of bamboo in global environmental governance documents permanently cements its status as a foundational pillar of the transition to a global, low-carbon bioeconomy. By offering a rapidly renewable, scientifically validated, and highly scalable alternative to finite, high-emission materials, bamboo is now firmly positioned as a multifunctional tool for advancing the United Nations Sustainable Development Goals (SDGs). Specifically, bamboo provides a localized, highly circular supply chain model essential for achieving SDG 12 (Responsible Consumption and Production) by minimizing industrial waste and replacing persistent plastics. Simultaneously, it serves as a massive mechanism for terrestrial carbon sequestration and industrial displacement, directly supporting the targets of SDG 13 (Climate Action). This profound strategic repositioning permanently transitions bamboo's global identity from a niche topic of localized ecological conservation and rural handicraft to a central, structural, and indispensable pillar of global climate resilience and sustainable industrialization (FAO, 2022a).

2.2 Bamboo plantation, water use, land use and biodiversity

Bamboo forests provide substantial ecosystem benefits by improving water regulation, stabilizing soils, sequestering carbon, and supporting habitat complexity that can enhance local biodiversity. However, intensive, poorly planned monocultural plantations can degrade soil structure, simplify biological communities, alter hydrological regimes, and, in some cases, cause long-lasting or effectively irreversible losses of ecosystem function and species diversity. The main interactions among bamboo plantations, water, land, and biodiversity are summarized in Fig. 2.3.

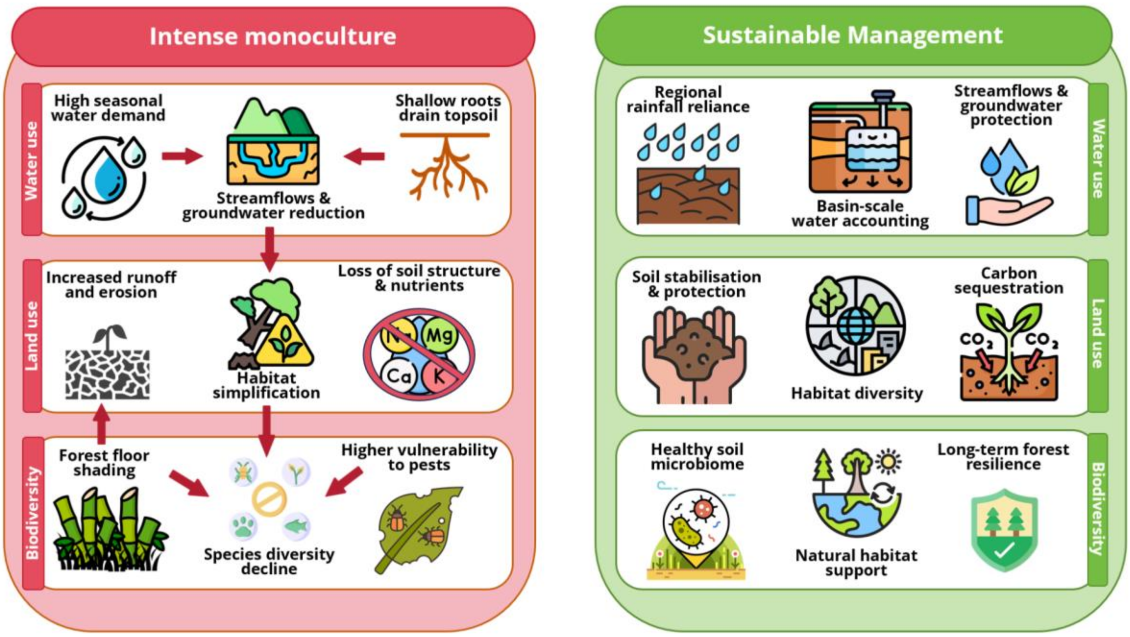


Fig. 2.3 Bamboo plantations: impact on water, land and biodiversity

Therefore, realizing bamboo's environmental potential requires site-appropriate design, mixed-use landscape planning, and governance that prevents unregulated expansion of monocultures.

2.2.1 Differences in water resource utilization due to regional variations

To better understand the possible consequences of bamboo plantation in a specific area, its water-use characteristics must be considered. These include canopy structure, evapotranspiration, and root system structure.

From the perspective of canopy structure and evaporative surface, bamboo stands commonly exhibit high leaf area indices (LAI) due to numerous small leaves distributed across dense culm cohorts. LAI increases the stand-level evaporative surface and, therefore, the potential for transpiration per unit ground area (Mei et al., 2016). Thus, canopy structure is a primary factor controlling stand-level transpiration potential.

Transpiration is another important indicator of bamboo's water use, but it is essential to distinguish the theoretical upper bound of water demand from the water use typically observed in the field. Irrigation-planning calculations cite a maximum annual transpiration of approximately 3,300 mm/year for dense, well-watered stands (Kleinhenz and Midmore, 2000). Fig. 2.2.4 represents a theoretical upper limit under continuous water supply and maximal LAI, roughly equivalent to 33 million liters per hectare per year. This marks a physiological ceiling: the fastest rate at which bamboo can dissipate water under continuous supply and maximal LAI. It is not the water use of an ordinary stand. However, stand-scale empirical measurements for Moso bamboo and similar species report interannual evapotranspiration of ~650–850 mm per year, and precipitation, soil moisture, and atmospheric demand drive the year-to-year variation (Zhang et al., 2019). This means that while bamboo can consume vast amounts of water if available, it is adaptable and can grow stably with approximately 1,500 mm of annual rainfall. The risk arises primarily when intensive irrigation pushes consumption toward that theoretical maximum during dry seasons.

Root distribution also affects water demand. Bamboo root systems are typically shallow and fibrous, concentrated in the upper soil horizon (commonly within 0–40 centimeters). This stratified root system predisposes bamboo to aggressively exploit surface soil moisture and promotes competitive exclusion of co-occurring species for shallow water (O'Keefe et al., 2019).

If plantations are intensively managed and irrigation sustains maximal productivity, the theoretical upper bound implies water withdrawals. Even if bamboo uses only part of that maximum, widespread monocultures can still increase overall water consumption in a river basin and alter streamflow and groundwater levels (Mei et al., 2016). The magnitude of the burden, therefore, varies with planting density, irrigation practices, and the alignment of growth phenology with dry seasons.

The concentration of demand during the shooting season causes sudden peaks in water use. If peak shoot growth occurs during a dry period, additional irrigation or groundwater extraction is usually required to sustain yield, thereby increasing seasonal stress on hydrological systems.

Therefore, increased water demand from irrigated bamboo systems may lead to conflicts with agricultural irrigation, drinking water supply, and ecological flow requirements. Consequently, the expansion of the sector should be integrated into basin-scale water accounting frameworks and governance arrangements that allocate water rights, preserve environmental flows, and mitigate adverse distributional outcomes.

In humid tropical and humid subtropical zones with abundant, well-distributed rainfall, water consumption associated with bamboo cultivation is generally moderate because rainfall can satisfy most transpiration requirements. Under these circumstances, the need for irrigation is often low. However, intensification of management, for instance, higher planting density and fertilization, can increase water consumption in such regions.

In monsoonal climates, where the rainy season is periodic, it must coincide with the bamboo growing season. If bamboo's peak growth occurs during the dry period, reliance on irrigation or stored soil moisture increases, creating marked seasonal pressure on water resources and heightened competition with food crops.

In temperate and cool-temperate zones, lower solar radiation and reduced evaporative demand constrain stand transpiration. Consequently, measured evapotranspiration in temperate contexts is typically lower than in warm climates. Commercial production remains feasible but requires careful management of planting density and irrigation regimes.

In arid and semi-arid landscapes, natural productivity is limited by moisture. Irrigated, intensive bamboo cultivation in these zones requires substantial water resources or groundwater withdrawals and is therefore high-risk for long-term hydrological sustainability. The relationship between rainfall and bamboo water demand is shown in Fig. 2.4.

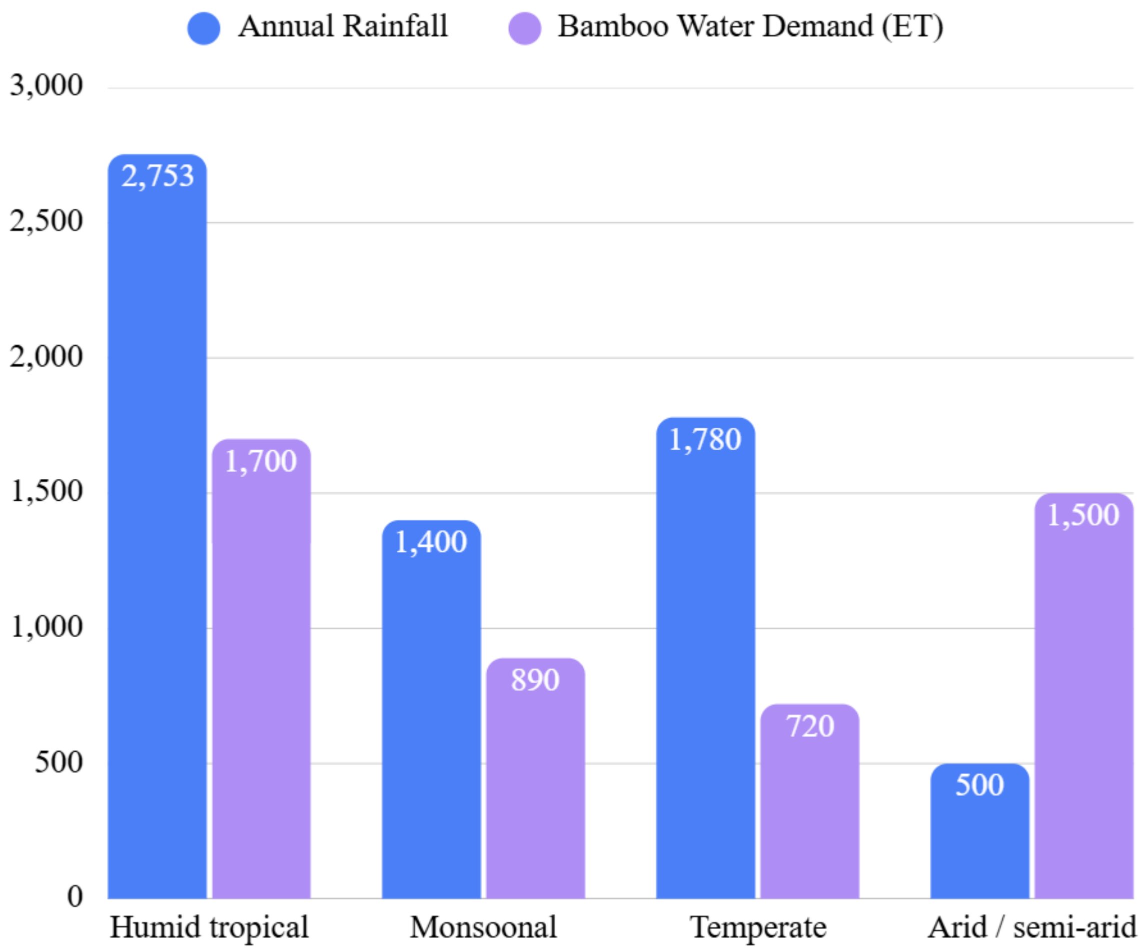


Fig. 2.4 Correlation between annual rainfall and bamboo water demand depending on climate

Bamboo processing also affects local water resources in different ways, depending on the industry. The manufacture of bamboo pulp and paper is highly polluting because it generates "black liquor," a highly alkaline, toxic effluent containing residues of caustic soda, ammonia, and dissolved organic matter. Raw wastewater from bamboo pulping can have high Chemical Oxygen Demand (COD) and Biochemical Oxygen Demand (BOD) (Chang et al., 2018). Bamboo bleaching wastewater is often highly acidic (pH ~4.49) and contains high levels of turbidity (28.7 NTU) due to the presence of bleaching agents like hypochlorite and residual bamboo chips (Akpan et al., 2022). Most bamboo fabric is "bamboo viscose," produced through a chemically intensive regeneration process that uses approximately 65 tons of freshwater, whereas the associated cotton pulp production requires 72 tons per ton, demonstrating that bamboo can be an environmentally friendly alternative to cotton (Zhu et al., 2020).

The industrial processing of bamboo into commercial products remains highly water-intensive, often ranking as the largest freshwater consumer after the agricultural sector. Although water use and wastewater characteristics vary significantly by industry, common issues across all sectors include high organic loading and the discharge of toxic chemical residues.

2.2.2 Land use change and environmental trade-offs of bamboo cultivation

Depending on the type of management, bamboo cultivation can lead to either land restoration or ecological risks. The impact mechanisms of bamboo plantations and industries are categorized into direct biological and industrial processes and indirect ecological and socioeconomic consequences. The main land-use pathways associated with bamboo cultivation are summarized in Fig. 2.5.

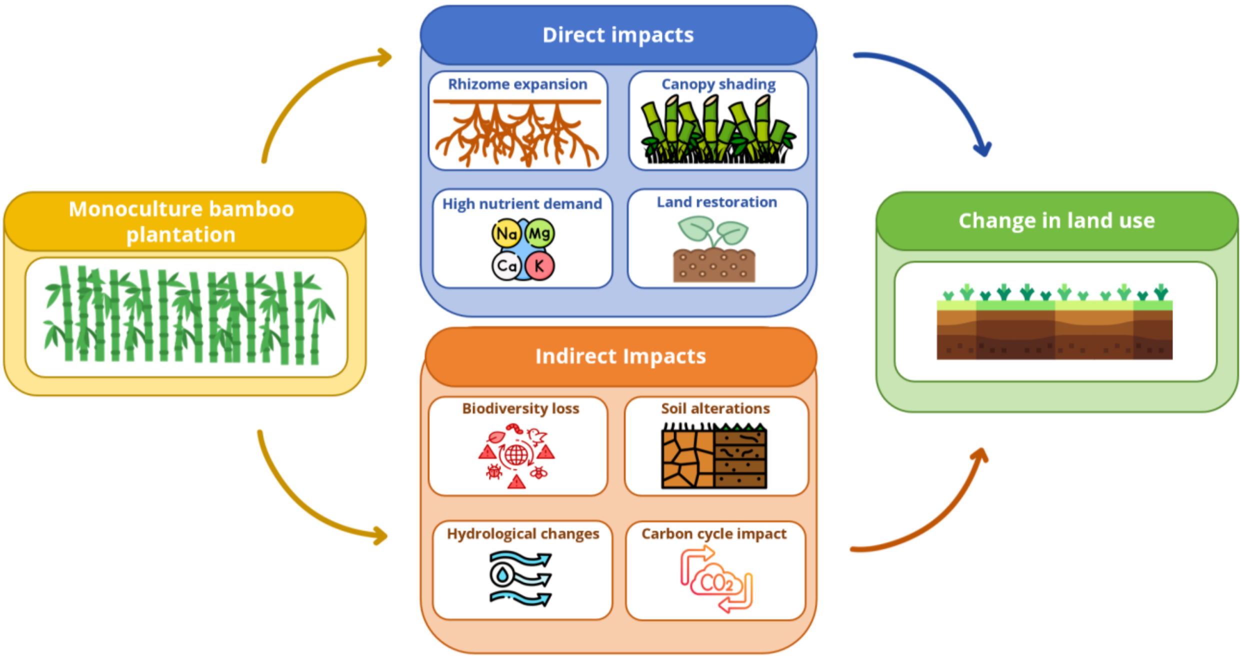


Fig. 2.5 Impact of bamboo cultivation on the land use

Direct Impacts of bamboo plantations on land use

Competition for Space: Running bamboo species utilize a vigorous underground rhizome system to rapidly invade adjacent territories, allowing them to expand horizontally and establish new shoots (Xu et al., 2020). This underground network forms a dense web that occupies soil space and outcompetes the root systems of neighboring native vegetation.

Shading: Bamboo's rapid vertical growth enables it to break through the canopy of neighboring trees and form a dense vegetation layer (Xu et al., 2020). This position shades the forest floor, suppressing the regeneration of native tree seedlings and eliminating light-sensitive understory vegetation.

High Nutrient and Water Demand: Due to its rapid growth and high biomass production, bamboo consumes large amounts of soil nutrients and water (Chen et al., 2024). This intensive uptake can lead to soil nutrient depletion in the topsoil layers.

Land Restoration: Controlled planting is used to stabilize slopes and reclaim degraded mining lands. For example, in India, bamboo plantations have restored areas destroyed by intensive brick production, resulting in a 10-meter rise in the water table over 20 years (FAO and INBAR, 2018). Bamboo's fibrous roots bind loose soil, reducing erosion and preventing landslides on steep terrain. Studies show that Moso bamboo forests stabilize soil 1.5 times more effectively than Chinese pine forests (Rebelo and Buckingham, 2015).

Indirect Impact Mechanisms

Biodiversity loss: Converting diverse forests into bamboo monocultures simplifies the landscape and eliminates specialized habitats. This reduces bird, insect, and mammal diversity as the variety of food sources and nesting sites declines.

Soil Structure Alterations: Bamboo expansion often increases soil pH and alters microbial community composition (Zhao et al., 2025). Replacing broadleaf forests with bamboo often reduces soil organic carbon and total nitrogen stocks due to rapid nutrient uptake and the removal of diverse forest litter (Xu et al., 2020).

Hydrological Changes: High-density bamboo root zones can increase soil water infiltration and flow connectivity. However, in some contexts, bamboo monocultures may increase surface runoff and sediment loading relative to diverse native forests.

Carbon Cycle: While bamboo rapidly sequesters carbon in its biomass, replacing old-growth broadleaf forests with bamboo can lead to a net decline in ecosystem carbon stocks, potentially resulting in CO_2 emissions to the atmosphere.

Thus, to achieve sustainable development, it is necessary to implement management strategies that preserve existing bamboo ecosystems and limit monoculture cultivation. It is recommended to create a spatial mosaic across the landscape by combining bamboo plantations with natural forests and using physical barriers to prevent bamboo invasion, especially in sensitive and small ecosystems (Xu et al., 2020).

2.2.3 Impact of bamboo cultivation on biodiversity

Biodiversity outcomes depend on which kind of bamboo system is in question. The systems fall into four types along a gradient of declining habitat value: natural bamboo forests, mixed bamboo systems that combine bamboo with native trees, managed single-species plantations, and intensive monocultures grown for maximum yield. Although bamboo plantations offer certain benefits, large-scale monoculture plantations cannot be equated with natural ecosystems that have high biodiversity.

Natural bamboo forests and managed plantations deliver different mixes of services. Natural stands provide measurable ecosystem services, including rapid biomass growth and carbon sequestration, natural habitat for local species, erosion control on slopes and riverbanks. Managed and mixed plantations add raw material supply, livelihood benefits, and potential for land rehabilitation on degraded sites. These functions vary across climate zones, bamboo species, planting methods, and management practices (Lobovikov et al., 2007). The biodiversity effects of bamboo monoculture are summarized in Fig. 2.6.

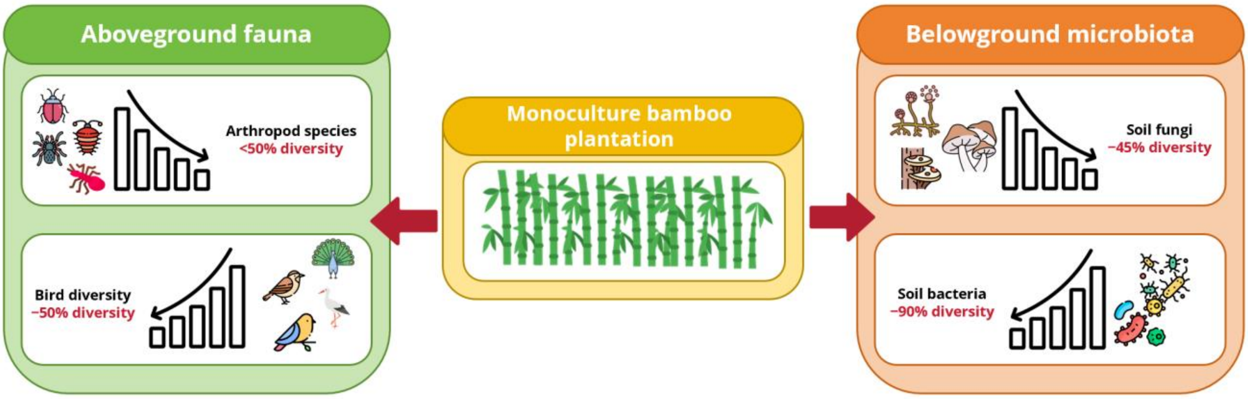


Fig. 2.6 Impact of bamboo monoculture cultivation on bird, arthropod, fungi and bacteria diversity

A direct comparison of biodiversity in natural forests and monoculture bamboo plantations shows a sharp decline in the latter across all biological domains. In the Hunan and Sichuan provinces intensive monoculture stands support lower bird diversity than adjacent mixed forests (Yiping and Henley, 2010). While monocultures raise higher short-term yields, but the loss of biodiversity compromises the stand's long-term stability, its resilience to adverse weather, and overall productivity.

Besides, monoculture bamboo plantations maintain less than half the richness of arthropod communities found in native forests and even in mixed-species plantations (Wang et al., 2019). Mixed-species systems therefore support a richer arthropod community than monocultures, which argues for mixed planting over monoculture where plantations replace forest.

Despite that, intensive management reduces both soil fungal and bacterial diversity. An 11-year case study in Fujian and Zhejiang provinces shows a 90% decline in soil bacterial diversity and a 45% decline in soil fungal diversity, driven by practices aimed at maximizing culm density and short-term yields. Such a dramatic reduction destroyed complex biological communities necessary for nutrient cycling and for maintaining soil quality (Zhao et al., 2025). This undermines the natural nutrient cycles maintained by the combined efforts of plants, insects, and microorganisms.

Moreover, unmanaged stands let Moso bamboo exhibit aggressive invasiveness, rapidly displacing native tree and shrub species in the wild. Its dense canopy blocks light, hindering the recovery of forest species, leading to 'simplification' of the ecosystem and threatening the survival of rare and endangered species(Xu et al., 2020).

In conclusion, the balance of benefits and risks associated with bamboo cultivation depends on several variables. With sustainable management practices, bamboo can contribute to erosion control, land rehabilitation, and rapid carbon sequestration without stressing the local environment. Conversely, the extensive cultivation of monocultures may lead to reduced streamflow, depressed groundwater levels, and reduced biodiversity.

2.3 Impact on livelihoods

Bamboo occupies a unique and increasingly recognized position in the livelihood portfolios of rural and peri-urban communities across tropical, subtropical, and temperate regions. As a versatile, rapidly renewable non-timber forest resource, bamboo underpins a wide range of economic activities. Its use spans localized subsistence that provides essential food and housing materials to advanced industrial processing for international trade, cementing its status as a socioeconomically vital pillar of the global bioeconomy (Bala and Gupta, 2023; Zhang et al., 2025). An estimated 2.5 billion people worldwide rely on the bamboo sector for their well-being, with bamboo contributing between 13 and 17 percent of household income in many bamboo-dependent communities (Alamerew et al., 2024). Understanding these livelihood dimensions is essential to evaluating bamboo's potential as a driver of inclusive and sustainable rural development.

2.3.1 Income generation and poverty alleviation

Bamboo's contributions to household income are particularly pronounced in lower-income, resource-dependent communities. A household survey of 12 remote mountainous villages in southern China found that bamboo was the single most valuable source of cash income, with lower-income households showing the greatest dependence on bamboo-derived earnings, suggesting that bamboo serves as an excellent pro-poor resource in areas with limited off-farm income opportunities (Belcher and Hogarth, 2013). This pattern reflects a broader finding across bamboo-producing regions: while higher-income households may derive higher absolute income from bamboo, the poorest and most marginalized populations depend on it most critically as a livelihood safety net.

In sub-Saharan Africa, similar dynamics are evident. In Ethiopia's Bale Mountains, bamboo accounts for about 38 percent of total annual earnings for low-income households, compared with just 16 percent for wealthier groups, making it the primary livelihood source for the poorest communities (Alemayehu and Hido, 2023; Tinsley, 2015). Across the country, bamboo-related economic activities provide livelihoods for about 750,000 Ethiopians (Alemayehu and Hido, 2023). In the Mekong sub-region, more than 400,000 people in Cambodia, Lao PDR, Myanmar, Thailand, and Viet Nam depend on bamboo for their livelihoods, with the potential to reach 800,000 beneficiaries through enhanced value chain development (Lee et al., 2021).

These figures underscore bamboo's exceptional relevance to achieving SDG 1 (No Poverty) and SDG 8 (Decent Work and Economic Growth), particularly in regions where formal employment opportunities remain limited and climate-induced agricultural disruptions are increasing the vulnerability of rural populations.

2.3.2 Employment across the value chain

The bamboo industry generates employment across the full value chain, from plantation establishment and culm harvesting to processing, manufacturing, trade, and export. It creates jobs for farmers, artisans, manufacturers, traders, and other stakeholders, contributing to income generation and poverty alleviation, particularly in rural areas where bamboo resources are abundant (Ayer et al., 2023). The diversity of bamboo applications, spanning construction materials, furniture, textiles, paper, charcoal, food products, and bio-composites, means that employment opportunities are distributed across multiple sectors and skill levels, thereby reducing dependence on single-commodity markets.

Critically, many segments of the bamboo value chain are accessible to low-capital actors. Many bamboo processing industries, including hand weaving and the manufacture of household products, require little investment and can build on technical knowledge already present in rural communities, providing a source of supplementary income for vulnerable groups. Artisanal industries such as bamboo charcoal and incense stick production can often be carried out at the household level (Binfield et al., 2022). This low barrier to entry distinguishes bamboo from many other industrial crops and positions it as a genuinely inclusive livelihood resource.

2.3.3 Gender dimensions and women's empowerment

The bamboo sector offers notable, though unevenly realized, opportunities for women's economic empowerment. Bamboo-based artisanal industries may particularly benefit women, who often face structural barriers to entering non-domestic industries yet can engage in bamboo processing activities within or near the home (Binfield et al., 2022). In Tanzania, charcoal briquette production and sales employ over 5,000 women, many of them single mothers, who have gained stable incomes through bamboo-based enterprises that simultaneously slow deforestation (Phimmachanh et al., 2015).

In India, where bamboo resources are distributed across 18 states, an estimated half of the more than 5 million people earning their livelihoods from bamboo processing and product manufacturing are women (Lund-Thomsen et al., 2021). National programs have sought to leverage this potential: India's Ministry of Micro, Small and Medium Enterprises clusters and the National Rural Livelihood Mission, in collaboration with the United States Agency for International Development and the Industree Foundation, have mobilized over 10,000 women into producer collectives, resulting in approximately $3 million in market orders since 2019.

Bamboo weaving, in particular, represents an important intersection of cultural heritage and economic livelihoods for rural women. As a traditional handicraft, it has significant economic value as a source of livelihood for households across large rural areas, while also serving as a renewable natural resource and an environmentally friendly alternative to carbon-intensive materials (Jiang et al., 2024). Integrating women's participation in bamboo value chains not only advances gender equity but also enhances household food security and reinvestment in children's education and health, generating outcomes that compound across generations and communities (Obiri et al., 2020).

2.3.4 Challenges and structural constraints

Despite its considerable potential, the realization of bamboo's livelihood benefits is constrained by structural barriers that require targeted policy and investment. Market access remains a critical limiting factor: rural producers frequently lack reliable sales channels, pricing information, and the logistics infrastructure needed to connect to regional and export markets. While value-added bamboo products can generate incomes well above minimum wage thresholds in contexts such as the Lao PDR, these models are often constrained by the absence of stable sales channels and require strengthened partnerships with local government agencies and market intermediaries (Lee et al., 2021).

Furthermore, the risk of resource over-exploitation presents a structural tension inherent in rapid commercialization. Rising external demand, particularly for semi-processed raw materials, can incentivize harvesting beyond sustainable yield thresholds, undermining the very resource base on which livelihoods depend. Governance frameworks that secure community tenure rights, enforce sustainable harvesting practices, and invest in plantation development are therefore foundational to translating bamboo's livelihood potential into durable outcomes.

A transformative approach to bamboo-based livelihoods requires moving beyond project-level interventions toward enabling policy environments that integrate bamboo into national strategies for rural development, the green economy transition, and climate adaptation. A resilient approach requires cooperative, participatory, and sustainable management methods that integrate scientific research with indigenous knowledge to harness bamboo's extensive social, economic, and ecological benefits (Alamerew et al., 2024). When embedded within bioeconomy frameworks, bamboo offers a compelling model for inclusive rural development that simultaneously generates sustainable income, conserves natural capital, and enhances community resilience amid compounding environmental and economic pressures.

2.4 The interaction between climate change and bamboo industry

Against the dual backdrop of intensified global climate action and the accelerated transition toward a bio-based economy, the bamboo sector is increasingly moving from a traditional resource-utilization domain to the forefront of sustainable development, owing to its distinctive ecological attributes and industrial potential (Ramakrishnan et al., 2020). However, the relationship between climate change and the bamboo industry is characterized by pronounced two-way interactions. On the one hand, bamboo, as a fast-growing and renewable biomass resource, exhibits substantial potential for climate change mitigation through bioenergy production, substitution of bio-based materials, and carbon sink formation. On the other hand, climate change–induced stressors, including rising temperatures, altered precipitation regimes, and the increasing frequency of extreme weather events, are posing new challenges to the stable supply of bamboo resources and the long-term sustainability of bamboo-based production systems. Systematically identifying the interaction mechanisms between climate change and the bamboo industry and clarifying the relationship between mitigation potential and climate-related risks are therefore critical prerequisites for building a resilient and low-carbon bamboo-based industry in the future. The interactions between climate change and the bamboo industry are summarized in Fig. 2.7.

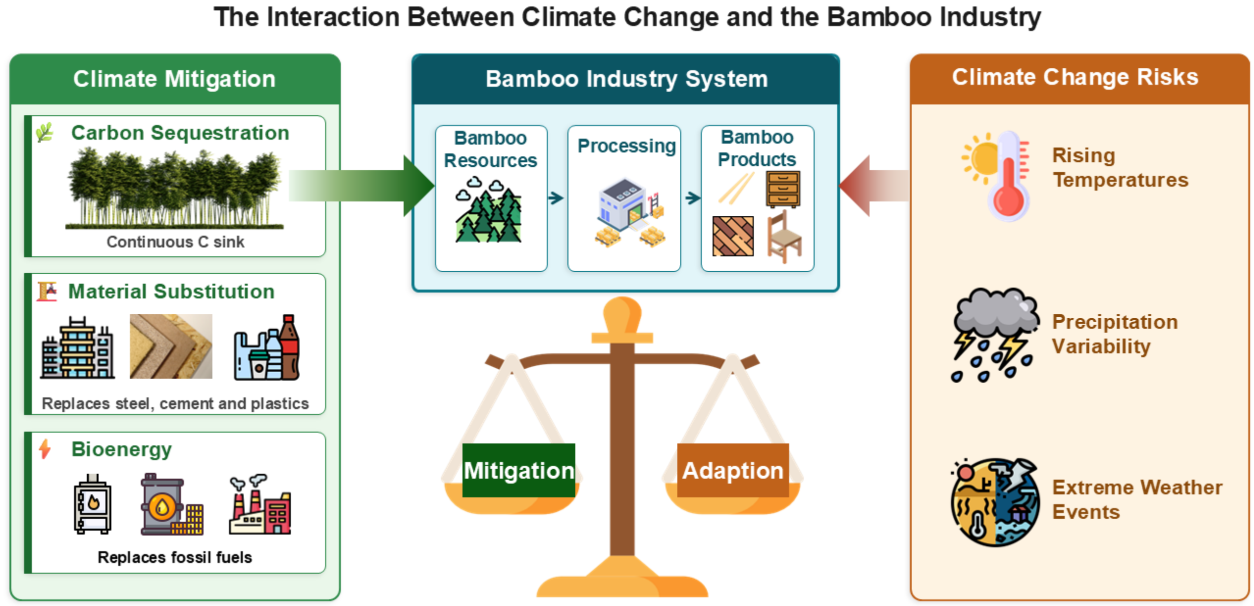


Fig. 2.7 The Interaction Between Climate Change and the Bamboo Industry

2.4.1 Bamboo as a climate change mitigation option

Bamboo is widely recognized as a biomass resource with significant climate change mitigation potential due to its unique biological and ecological characteristics (Ramakrishnan et al., 2020). Compared with conventional woody plants, most bamboo species have short growth cycles and high annual biomass accumulation rates (Kuehl et al., 2011), typically reaching harvest maturity within 3–5 years without replanting (Das et al., 2019; Terefe et al., 2019). This perennial, sustainably harvestable growth pattern helps maintain continuous land cover and ecosystem stability while reducing additional greenhouse gas emissions associated with land disturbance, regeneration, and management activities.

The climate mitigation effects of the bamboo industry span its entire life cycle—from bamboo forest cultivation and product processing to end use and end-of-life management—and are primarily reflected in two dimensions: direct carbon sequestration and carbon storage in bamboo products.

Regarding direct carbon sequestration, bamboo forests continuously absorb and fix atmospheric CO_2 through both aboveground biomass and extensive belowground rhizome systems, achieving relatively high carbon sink efficiency per unit area under favorable conditions (Ouyang et al., 2025; Terefe et al., 2019). For instance, well-managed Phyllostachys edulis forests can sequester up to 24.31 t CO_2 ha^{-1} yr^{-1}. Moreover, bamboo stands can rapidly regenerate after harvesting via underground rhizomes, allowing carbon sink functions to recover quickly. This characteristic makes bamboo highly applicable within nature-based solutions for climate change mitigation (Pan et al., 2023).

From the perspective of carbon storage through bamboo products, bamboo primarily contributes to mitigation through bioenergy use and substitution of bio-based materials. In the bioenergy domain, bamboo and its processing residues can be used to produce biofuels, biochar, or heat, partially replacing fossil energy sources such as coal and oil and thereby reducing fossil carbon emissions from energy systems. In some developing countries and rural regions, bamboo-based bioenergy also delivers co-benefits by improving energy access and supporting local economic development. With respect to material substitution, bamboo-based products are widely used in construction, furniture, packaging, and daily consumer goods, providing alternatives to carbon-intensive materials such as steel, cement, and plastics (Bundi et al., 2024; Chang et al., 2018; Zea Escamilla et al., 2018). By extending product lifespans and storing biogenic carbon, bamboo-based materials not only reduce life-cycle greenhouse gas emission intensities but also contribute indirectly to climate mitigation through avoided emissions. For example, life cycle assessment studies of food delivery systems show that both disposable and reusable bamboo cutlery exhibit lower global warming potential than plastic alternatives, with reusable bamboo products reaching carbon break-even after only a few uses (Wang et al., 2025). Similarly, dynamic life cycle assessment of bamboo bio-concrete buildings indicates that increasing the share of bamboo-based materials in building envelopes enhances carbon storage and reduces operational emissions, demonstrating the mitigation potential of bamboo construction systems in regions with abundant bamboo resources (Rosse Caldas et al., 2020).

Overall, bamboo exhibits substantial climate change mitigation potential across regions by combining carbon sequestration with material and energy substitution, while delivering co-benefits such as green employment and resource efficiency. Under optimized management, global bamboo ecosystems could therefore play a strategic role in advancing circular bioeconomy development and long-term decarbonization (Zhang et al., 2025).

2.4.2 Impacts of climate change on bamboo resources and production

Despite its positive role in climate change mitigation, bamboo growth and production are highly dependent on climatic conditions. Most bamboo forests are dominated by a single or a few species, with relatively simple stand structures. In addition, bamboo's hollow culm structure and comparatively low compressive strength make it particularly sensitive to climate variability and extreme weather events (Zhou et al., 2011). As global climate change intensifies, rising temperatures, increasing precipitation variability, and more frequent extreme climate events are significantly affecting the stability of bamboo resource production and the functioning of bamboo-based industrial systems (Qiuyue et al., 2024).

Temperature is a key climatic factor shaping bamboo growth, development, and geographic distribution. Moderate warming may enhance bamboo biomass accumulation in some regions by extending the growing season and improving photosynthetic efficiency (Chen et al., 2019; Li et al., 2021). However, when temperatures exceed optimal thresholds, heat stress can inhibit culm elongation and leaf function, reduce growth rates, and substantially increase the risk of pest and disease outbreaks. Extreme heat and heatwave events may also disrupt plant water balance by intensifying transpiration, thereby exacerbating physiological stress under drought conditions. Temperature changes can further alter bamboo growth cycles and phenological patterns, ultimately affecting productivity. Over longer time scales, sustained climate warming may drive spatial shifts in suitable habitats for bamboo species, reshaping regional bamboo resource distributions. Some low-latitude or low-altitude bamboo forests may experience declining suitability, whereas higher-latitude or higher-altitude regions could become newly suitable. Such shifts not only affect ecosystem structure but also pose new adaptation requirements for existing bamboo industry layouts and infrastructure. In China, for example, major bamboo-producing regions have experienced significant increases in extreme heat and anomalous precipitation events, with different areas facing distinct risks such as droughts, floods, and extreme cold events (Shan et al., 2025).

Changes in precipitation patterns strongly influence bamboo production. Increasing frequency and intensity of drought events can induce water stress, suppress shoot emergence and culm formation, and ultimately reduce yield per unit area (Li et al., 2019). In bamboo systems reliant on natural rainfall, prolonged drought may lead to forest degradation and substantially increase restoration costs. Conversely, extreme precipitation and flooding can cause root hypoxia, facilitate disease transmission, and intensify soil erosion, undermining ecosystem stability. Empirical studies suggest that intensified drought, together with enhanced human disturbances, may reduce soil carbon sequestration capacity in bamboo ecosystems (Ouyang et al., 2025). Beyond certain drought thresholds, the negative effects of water stress on bamboo productivity may offset the positive impacts of climate warming (Li et al., 2026).

The impacts of extreme climate events on the bamboo industry extend beyond ecosystem processes and may be amplified along the entire value chain. In upstream production stages, frequent extreme events increase uncertainty in forest management, raise disaster prevention and recovery costs, and intensify interannual variability in the quantity and quality of raw materials. In midstream processing stages, an unstable raw material supply can reduce processing facility capacity utilization and even lead to temporary shutdowns. Floods, storms, and other extreme events may also damage infrastructure such as roads, electricity, and communication networks, further amplifying climate shocks to processing systems. In downstream markets, fluctuations in bamboo product supply can trigger price volatility, weaken market confidence, and adversely affect small- and medium-sized enterprises and rural livelihoods that depend on the bamboo sector. In some regions, such impacts may exacerbate regional development inequalities and socioeconomic vulnerability.

2.4.3 Feedbacks, trade-offs and implications for a resilient bamboo-based agro-industry

Climate change impacts on the bamboo industry also prompt a reassessment of its long-term mitigation potential. Under ideal conditions, bamboo-based systems can consistently deliver emission reductions through energy and material substitution. However, as climate stress intensifies, uncertainties in bamboo resource supply may weaken mitigation performance and create trade-offs between mitigation and adaptation.

On the one hand, declines in bamboo biomass output directly constrain the resource base available for energy use and material substitution, thereby limiting the overall potential for emissions reductions. On the other hand, adaptation measures implemented to cope with climate risks may themselves entail additional energy consumption and greenhouse gas emissions. For instance, investments in irrigation systems, infrastructure reinforcement, and intensified management practices can enhance production stability, but if poorly planned, they may increase the long-term carbon footprint of the bamboo industry.

Therefore, enhancing the resilience of the bamboo industry under climate change should not be viewed as an alternative to mitigation objectives, but rather as a critical enabler of sustained low-carbon development. By systematically integrating climate risk considerations into bamboo industry planning and policy design and aligning adaptation strategies with emissions-reduction goals, it is possible to foster positive feedback between mitigation and adaptation, ultimately supporting the development of a resilient and climate-smart bamboo-based agro-industry.

2.5 Summary

The bamboo industry has undergone a profound transformation, evolving from a marginalized, subsistence-level agricultural practice into a strategic, highly engineered pillar of the global bioeconomy. Driven by proactive macro-level policy shifts and advanced processing technologies, bamboo is now positioned as a high-performance, low-carbon alternative to emissions-intensive materials such as plastics, steel, and conventional timber. However, realizing this environmental potential requires rigorous ecological governance. While sustainable bamboo management offers exceptional carbon sequestration and land restoration benefits, unregulated monoculture cultivation poses severe cascading risks to regional water resources, soil microbiomes, and local biodiversity.

Socioeconomically, the bamboo value chain serves as a vital safety net and an engine for inclusive rural development. It creates diverse employment opportunities and empowers marginalized groups, though structural market barriers and trade misalignments persist. The sector also has a complex, two-way relationship with global climate change. While bamboo systems offer robust mitigation pathways through direct carbon sinks and bio-based material substitution, the industry remains highly vulnerable to climate-induced stressors, including droughts and extreme weather events. Ultimately, advancing a sustainable bamboo bioeconomy requires carefully balancing these ecological trade-offs, ensuring equitable distribution of livelihoods, and implementing climate-smart adaptation strategies to cultivate a truly resilient agro-industrial landscape.

3 Palm Oil Industry

3.1 Policy evolution, production technologies, and trade patterns

Palm oil is one of the most widely used vegetable oils globally and plays a central role in food processing, oleochemicals, cosmetics, animal feed, and biofuel production. Its high oil yield per hectare makes it an economically attractive crop and an important source of export revenue, rural employment, and energy-security support in major producing countries. At the same time, the sector has become one of the most contested agro-industrial systems in the circular bioeconomy because its expansion, processing, trade, and waste streams are closely linked to land-use change, biodiversity loss, peatland degradation, greenhouse gas emissions, water pollution, and livelihood transformation. Against this background, this chapter examines the palm oil industry through a value-chain perspective, focusing on policy evolution and production technologies, land-use and biodiversity impacts, palm oil mill effluent as a key environmental issue, climate interactions, and social implications for different livelihood groups.

3.1.1 Evolution of key policies in the palm oil sector

The policy framework surrounding palm oil exhibits pronounced transnational and value-chain-specific characteristics. In major producing countries such as Indonesia and Malaysia, policies have long focused on plantation development, yield improvement, rural income generation, and export competitiveness. In recent years, policy priorities have gradually expanded toward biodiesel blending mandates and sustainability certification, aiming to absorb domestic palm oil supply and strengthen energy security while responding to growing international concerns over deforestation, greenhouse gas emissions, and supply-chain traceability. In contrast, regulatory markets such as the European Union have increasingly influenced the sector through market-access rules, renewable energy criteria, traceability requirements, and zero-deforestation regulations. Overall, the evolution of palm oil policies reflects a transition from an early emphasis on plantation expansion, total output growth, and demand creation toward a sustainability-oriented policy framework centered on sustainability certification, supply-chain traceability, emissions reduction, smallholder inclusion, and deforestation-free supply chains.

In the early stages, key policies in the palm oil sector primarily aimed to expand production and stimulate demand. In 1977, Indonesia, with support from the World Bank, implemented the Nucleus Estate and Smallholders / Perkebunan Inti Rakyat (NES/PIR) scheme, which integrated plantations, processing facilities, and smallholders. During the 1980s, this model was further combined with the Transmigration program to promote the expansion of oil palm cultivation. In 1998, Malaysia established the Malaysian Palm Oil Board (MPOB), consolidating previously fragmented functions related to registration, licensing, and research and development, thereby strengthening coordinated governance and promotion of the sector. To stimulate demand for palm oil-based biodiesel, Indonesia issued Ministerial Regulation No. 32/2008 on biofuel utilization. Subsequently, the biodiesel blending mandate has been progressively increased, culminating in the implementation of the B40 mandate as of January 1, 2025, positioning palm oil-based biodiesel as a key instrument to enhance energy security and reduce diesel imports.

As deforestation, peatland drainage, greenhouse gas emissions, labor issues, and land conflicts increasingly became focal points of international concern, palm oil governance entered a new phase characterized by certification schemes and sustainability standards. In 2004, the Roundtable on Sustainable Palm Oil (RSPO) was established, and the introduction of the RSPO Principles and Criteria in 2007 marked the formation of a global voluntary certification framework (Roundtable on Sustainable Palm Oil, 2007, n.d.). As a transnational and voluntary mechanism, RSPO relied largely on market recognition, corporate commitments, and supply-chain participation rather than legally binding state regulation. RSPO promotes the adoption of sustainable production practices to reduce deforestation, conserve biodiversity, and respect the rights and livelihoods of rural communities, workers, smallholders, and indigenous peoples.

Subsequently, Indonesia developed a regulatory framework centered on the Indonesian Sustainable Palm Oil (ISPO) certification system, aligned with forest and peatland governance policies. ISPO has evolved from an initial focus on upstream plantations to cover a broader segment of the supply chain, with certification requirements extended to both companies and producers. Malaysia has progressively implemented the Malaysian Sustainable Palm Oil (MSPO) certification scheme, which became mandatory in 2020. The MSPO system is characterized by full supply chain coverage, differentiated standards for various actors, and an emphasis on market acceptance and traceability. Compared with RSPO's voluntary and market-based approach, ISPO and MSPO represent producing countries' efforts to institutionalize sustainability requirements within national regulatory systems. Their strengthening also reflects the need to improve the international credibility of palm oil supply chains and respond to increasingly stringent expectations regarding legality, traceability, social responsibility, and deforestation-free production.

On the demand-side regulatory front, the European Union introduced a cap on food- and feed-based biofuels under the Renewable Energy Directive II (RED II) in 2018 and mandated the gradual phase-out of high indirect land-use change (ILUC)-risk fuels (European Union, 2018). This was further specified in the 2019 Delegated Regulation (EU) 2019/807, which classified palm oil as a high ILUC-risk feedstock (European Commission, 2019). In 2023, the EU Deforestation Regulation (EUDR) formally included palm oil among regulated commodities, requiring that products placed on or exported from the EU market be deforestation-free, compliant with the laws of the country of production, and subject to due diligence obligations, including the submission of traceability data such as geolocation information (European Union, 2023). These measures progressively incorporate palm oil into a more stringent framework of low-carbon fuel policies and green market access requirements. Unlike RSPO, ISPO, and MSPO, which operate as certification systems, RED II and EUDR function as consuming-market regulations that link sustainability performance directly to market access. Their implementation has increased pressure on both certification schemes and supply-chain actors to strengthen verification, traceability, emissions reduction, and zero-deforestation compliance.

In summary, the evolution of palm oil policies reflects a shift from a production-expansion paradigm to a sustainability-oriented governance framework. Producing countries have increasingly emphasized national certification systems and sectoral regulation, while consuming countries and import markets have reshaped international trade conditions through low-carbon and zero-deforestation requirements. The interaction among RSPO, ISPO, MSPO, RED II, and EUDR therefore reflects a shift from voluntary sustainability standards and producer-country certification toward a more stringent governance system shaped by both supply-side regulation and demand-side market-access requirements. As illustrated in Fig. 3.3.1, the policy trajectory of the global palm oil sector can be broadly divided into three phases: an initial phase of industrial expansion and demand cultivation; a transitional phase of certification and standardization; and a recent phase characterized by strengthened governance centered on traceability, emissions reduction, and zero-deforestation objectives. The key policy milestones are summarized in Fig. 3.1.

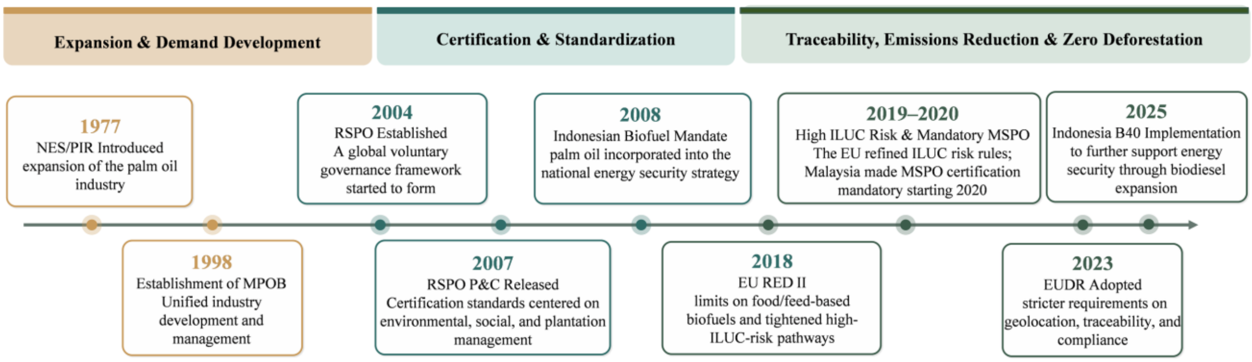


Fig. 3.1 Key policy timeline for the palm oil industry

3.1.2 Palm oil production technologies and sustainability measures

Southeast Asia is the core region for large-scale palm oil production, with Indonesia and Malaysia serving as the primary production and processing centers. In 2022, Indonesia operated 1,318 palm oil mills. According to the Malaysian Palm Oil Board (MPOB), as of December 2024, Malaysia had 453 fresh fruit bunch (FFB) processing facilities, 43 palm kernel crushing plants, 53 refineries, and 19 oleochemical factories. Of the palm oil processed domestically, 74% is used in the food sector and 24% in industrial applications.

Commercial oil palm plantations are typically established at a density of 120-150 trees per hectare. Peak fruit production is generally reached in the sixth to seventh year, with yields of approximately 35 tons of fresh fruit per hectare under optimal management. Yields gradually decline as trees age, and replanting is typically conducted after 20-25 years. As illustrated in Fig. 3.2, harvested fresh fruit bunches are transported to mills for processing into crude palm oil. Key processing stages include sterilization, fruit stripping, pulping, pressing, clarification, and drying. Initially, FFBs are sterilized under high-temperature, high-pressure conditions to inactivate enzymes and soften the fruit. The sterilized fruit then undergoes stripping to separate individual fruits from the bunch stalks, generating empty fruit bunches (EFBs). The separated fruits are subsequently pulped, heated, and homogenized to form a mash suitable for oil extraction. Pressing and separation processes, often involving screw presses and vibrating screens, yield oil, fiber, and kernel fractions, with fibers typically repurposed as boiler fuel. The oil phase is further clarified and dried to remove moisture and impurities, producing crude palm oil, which is then stored for subsequent use.

Palm oil production generates several biomass by-products, including EFBs, palm fibers, palm shells (Cheah et al., 2023), as well as palm oil mill effluent (POME) (Samavati et al., 2025). POME is generated in substantial quantities, typically at approximately 0.5–0.75 tonnes per tonne of fresh fruit bunches processed. When treated in open anaerobic ponds without gas recovery, methane emissions may reach approximately 12.36 kg CH_4 per tonne of POME (Yacob et al., 2006; Akhbari et al., 2020). By contrast, controlled anaerobic digestion has a reported biogas production potential of approximately 20–28 m3 per m3 of POME, while covered-lagoon systems can achieve chemical oxygen demand removal efficiencies of around 90%, depending on system design and operating conditions (Lok et al., 2020; Wadchasit et al., 2021). In the context of sustainable development, the industry is increasingly prioritizing the reuse and recycling of these by-products. Direct applications include combustion of waste as fuel and the use of shredded EFB and palm fronds as plantation mulch (Teh, 2016). Additionally, EFBs and other fiber-rich residues are being explored for conversion into composite materials (Mahardika et al., 2024; Mohtar et al., 2017; Lim et al., 2020). POME can undergo anaerobic digestion to produce biogas or fertilizer (Mohammad et al., 2012; Ohimain et al., 2017), or, following treatment, be reused in the production process (Cheah et al., 2023).

Current strategies to increase palm oil yields focus primarily on improving productivity within existing plantations rather than expanding the plantation area. Research indicates substantial potential for yield improvement, and closing yield gaps within existing plantations can reduce pressure to convert additional rainforest areas. Precision agriculture and expert systems are increasingly used to optimize crop, water, and soil management, shifting production practices from extensive to data-driven intensive management. From a supply chain perspective, achieving sustainability remains challenging due to long, complex, and fragmented chains. Efforts to enhance transparency and traceability aim to integrate information across cultivation, processing, trade, and procurement. The main palm oil production and waste-utilization pathways are summarized in Fig. 3.2.

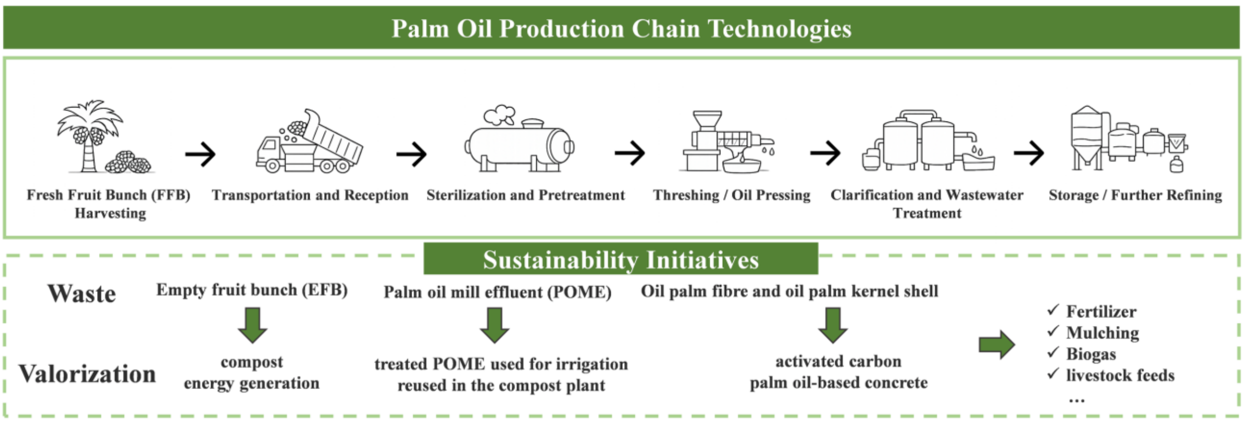


Fig. 3.2 Palm oil production technology and waste resource utilization approaches

3.1.3 International trade patterns of palm oil

Palm oil is the most widely traded vegetable oil globally, accounting for 42.5% of total vegetable oil exports in 2024. Exports are highly concentrated, with Indonesia accounting for 50% and Malaysia for 34% of global exports. Although production in Thailand, Colombia, Nigeria, and other countries continues to increase, Indonesia and Malaysia are expected to remain the principal exporters. This concentration makes global trade highly sensitive to producing countries' industrial and domestic consumption policies, as well as to compliance with sustainability standards. In Indonesia, approximately 45.98% of palm oil is consumed domestically, and programs such as B30 are gradually reshaping domestic demand structures. Exported products are increasingly downstream-oriented; the share of crude palm oil (CPO) in Indonesian exports declined from 37.5% in 2003 to 8.5% in 2021. Nevertheless, the total export value of palm oil products rose from USD 3.717 billion in 2002 to USD 47 billion in 2021, reflecting a gradual shift from primary resource exports toward processed products. Growing domestic demand for refined products, fractionated oils, oleochemicals, and particularly biodiesel may further reduce the volume available for export, with significant implications for global trade flows, international market supply, and pricing.

On the import and consumption side, Asia and Europe are key destinations. While the European Union was historically a major market for Malaysian crude palm oil, it has gradually been supplanted by India, China, Turkey, Pakistan, and Iran (Cheah et al., 2023). In Indonesia, the share of exports to the EU was approximately 11.48% of national vegetable oil exports in 2010, of which around 80% consisted of palm oil, compared with 30.78% to India and 19.57% to China (Rum et al., 2022). This highlights that India and China have become primary absorbing markets, whereas the EU retains strong regulatory influence despite a relatively smaller share of imports.

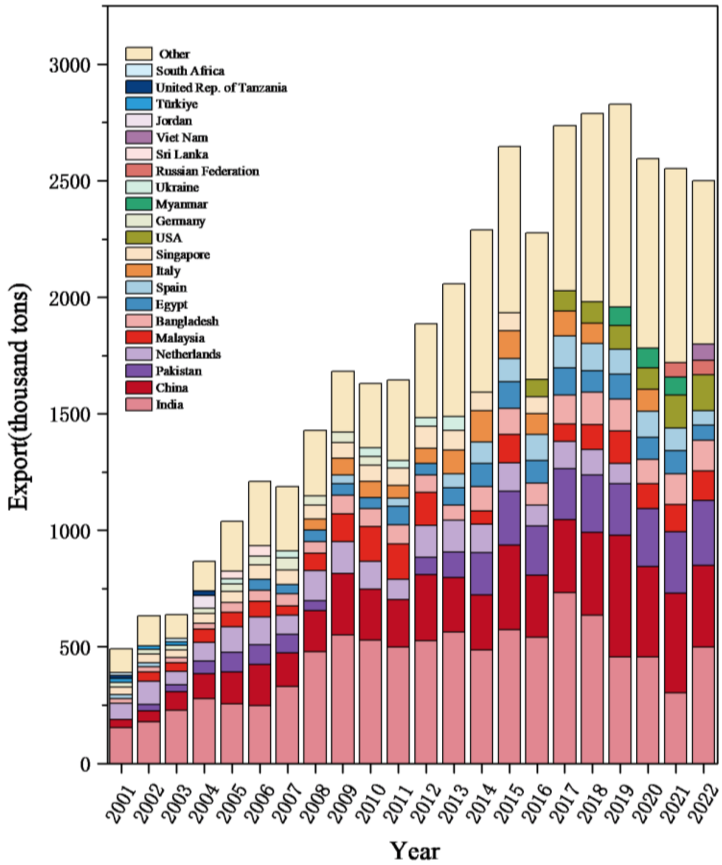


Fig. 3.3 History of export destinations of Indonesian Palm Oil (2001–2022)

Overall, global palm oil trade has exhibited sustained volume expansion, an eastward shift in regional focus, and a gradual move from concentrated to more diversified markets. Total trade volumes increased significantly between 2001 and 2022, peaking around 2019 and maintaining elevated levels thereafter, underscoring the enduring foundational role of palm oil in the global vegetable oil trade. Spatially, production and export remain concentrated in Southeast Asia, while consumption and imports are centered in Asia, with some activity extending to Europe, Africa, and selected emerging markets. India has long been a major market, with shares in China, Pakistan, and Bangladesh steadily rising, signaling that South and East Asia are primary drivers of global demand growth. Traditional re-export and distribution hubs, including the Netherlands and Singapore, continue to function as logistical nodes, though their relative dominance has declined.

3.2 Palm oil industry, land use, and biodiversity

Palm oil has become one of the most important vegetable oils in global agricultural production and trade, linking tropical land systems with international markets and consumption demand. As the industry has expanded, its environmental implications have increasingly been understood through the lens of land use: the establishment of oil palm plantations reshapes landscapes, alters ecological processes, and changes the relationship between production systems and natural habitats. These impacts are not determined by plantation area alone, but also by the ecological condition of the land brought into production and the management practices adopted after conversion. In this sense, palm oil production provides a clear example of how commodity-driven land-use change can translate into biodiversity loss, ecosystem degradation, and the weakening of ecological functions. The main land-conversion pathways and ecological consequences are summarized in Fig. 3.4.

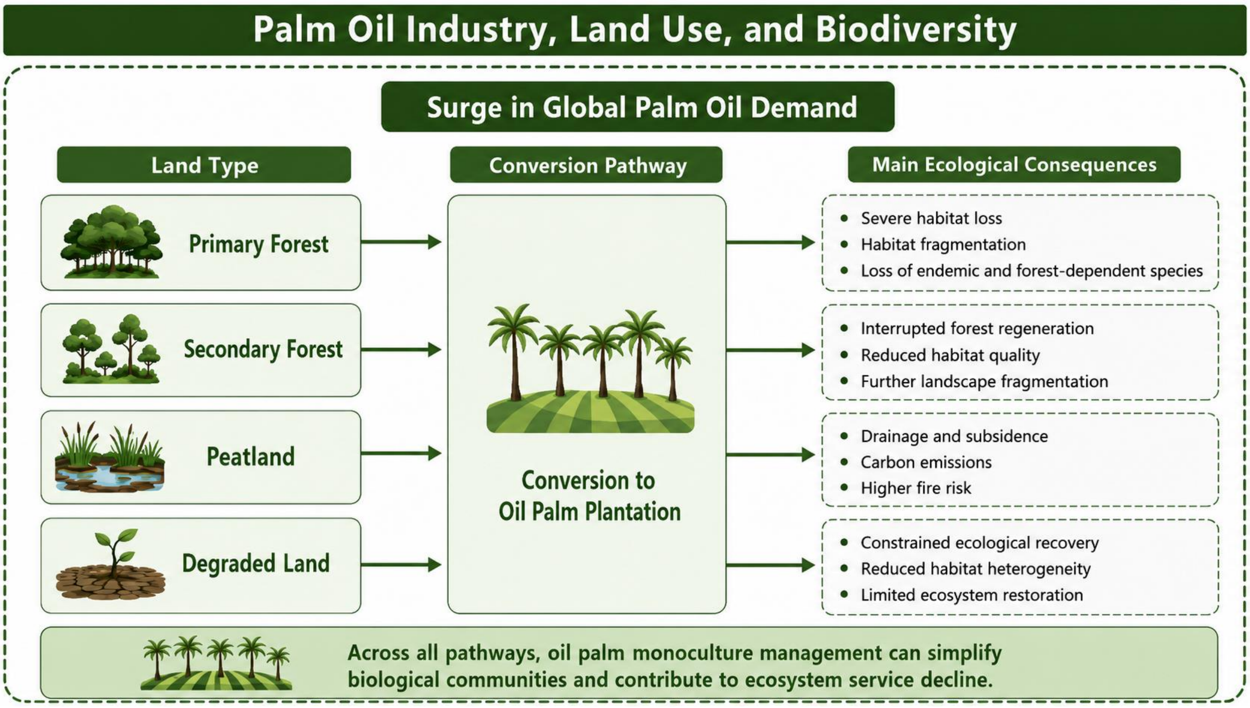


Fig. 3.4 Land Conversion Pathways and Ecological Consequences of Palm Oil Expansion

3.2.1 Habitat loss from forest-to-plantation conversion

Amid rising global demand for vegetable oils, palm oil expansion has historically been associated with forest-to-plantation conversion in tropical regions, making habitat loss an important concern in assessments of the sector's biodiversity impacts. In earlier phases of plantation expansion, this process was often associated with the replacement of primary forests, in which highly biodiverse natural forests are cleared and converted into structurally homogeneous industrial oil palm plantations—a phenomenon particularly pronounced in Indonesia and Malaysia (Tapia et al., 2021).This pathway represents the most ecologically severe form of forest conversion, because primary forests contain complex vertical structure, mature habitats, and species assemblages that are difficult to recover once removed. Forest conversion may also involve secondary forests, where previous disturbance has already altered ecosystem structure; nevertheless, their replacement by oil palm plantations can interrupt forest regeneration, reduce habitat quality, and further fragment landscape mosaics.

Such land-use change has made palm oil production an important historical contributor to tropical forest loss and habitat degradation. Forest-to-plantation conversion reduces overall habitat area and causes pronounced landscape fragmentation. Large-scale clearing directly eliminates and fragments habitats, severely constraining forest-dependent species and weakening ecological connectivity. Research indicates that species diversity declines across multiple biotic communities within oil palm plantations, with critically endangered species experiencing substantial reductions in population size and distribution, thereby increasing regional biodiversity loss and extinction risks. Habitat fragmentation also reduces gene flow among populations, potentially eroding genetic diversity and compromising species' adaptive capacity and long-term survival. Post-conversion plantation landscapes typically support simplified biological communities dominated by a smaller number of generalist and disturbance-tolerant species, limiting the ecological niches available to forest-dependent species and further exacerbating local extinction risks.

3.2.2 Ecosystem degradation and climate feedbacks from peatland conversion

The expansion of oil palm plantations affects ecosystems not only through direct deforestation but also through extensive peatland conversion, leading to marked ecosystem degradation. Tropical peatlands serve as globally significant carbon reservoirs and fragile wetland habitats, and their ecological functions depend critically on specific hydrological balances. In Southeast Asia, the conversion of peat swamp forests into oil palm plantations has often involved drainage and surface modification, disrupting the naturally waterlogged and anaerobic conditions that maintain peat formation and carbon storage. As peat soils dry and oxidize, their structural stability, chemical properties, and ecological functions can be progressively degraded.

Peatland conversion can amplify environmental risks through cumulative and long-lasting effects. On the one hand, peat oxidation releases large quantities of greenhouse gases, directly intensifying climate change pressures. On the other hand, local drainage practices interact with climate-driven drought extremes, accelerating peat decomposition and increasing vulnerability to fire. These compounded effects operate at both biotic and physical levels: peatland degradation generates substantial carbon emissions while fundamentally altering flora and fauna adapted to wetland environments, creating a resonance between local biodiversity loss and global climate risks. Consequently, peatland conversion associated with oil palm development links local ecosystem degradation with wider climate risks, underscoring the need for peatland protection, restoration, and improved land-use governance.

3.2.3 Systemic weakening of biodiversity and ecosystem services from monoculture practices

Oil palm plantations are commonly managed as intensive monoculture systems, which can increase yields but also place persistent pressure on ecosystem structure and function. Compared with natural tropical forests, monoculture plantations generally support lower species richness and a narrower range of ecological niches. Even where plantations provide limited alternative habitats for certain species, these cannot compensate for the comprehensive ecological losses associated with forest conversion (Darras et al., 2019). The intensive or inappropriate use of fertilizers and pesticides further increases the risk of soil and water contamination, posing potential threats to non-target species and human health. Such intensive production systems diminish the land's ecological carrying capacity and exacerbate the loss of ecosystem services. This is also relevant where oil palm expansion occurs on previously cleared or degraded land: although such pathways may involve lower additional biodiversity and carbon losses than the conversion of forests or peatlands, intensive monoculture management can still constrain ecological recovery, reduce habitat heterogeneity, and limit the restoration of ecosystem services. As diverse natural or semi-natural ecosystems are replaced by simplified plantation systems, critical functions such as climate regulation, water cycling, soil retention, and habitat provision may be progressively weakened, with implications for regional ecological security and human well-being.

3.3 Key environmental issue: palm oil mill effluent (POME)

As the palm oil industry expands rapidly, environmental pressures have become increasingly prominent, particularly in the management of palm oil mill effluent (POME). POME is an unavoidable by-product of palm oil processing, characterized by high concentrations of organic matter and nutrients. If inadequately treated, POME discharge can severely impair water quality and destabilize aquatic ecosystems. The environmental risks associated with palm oil mill effluent are summarized in Fig. 3.5.

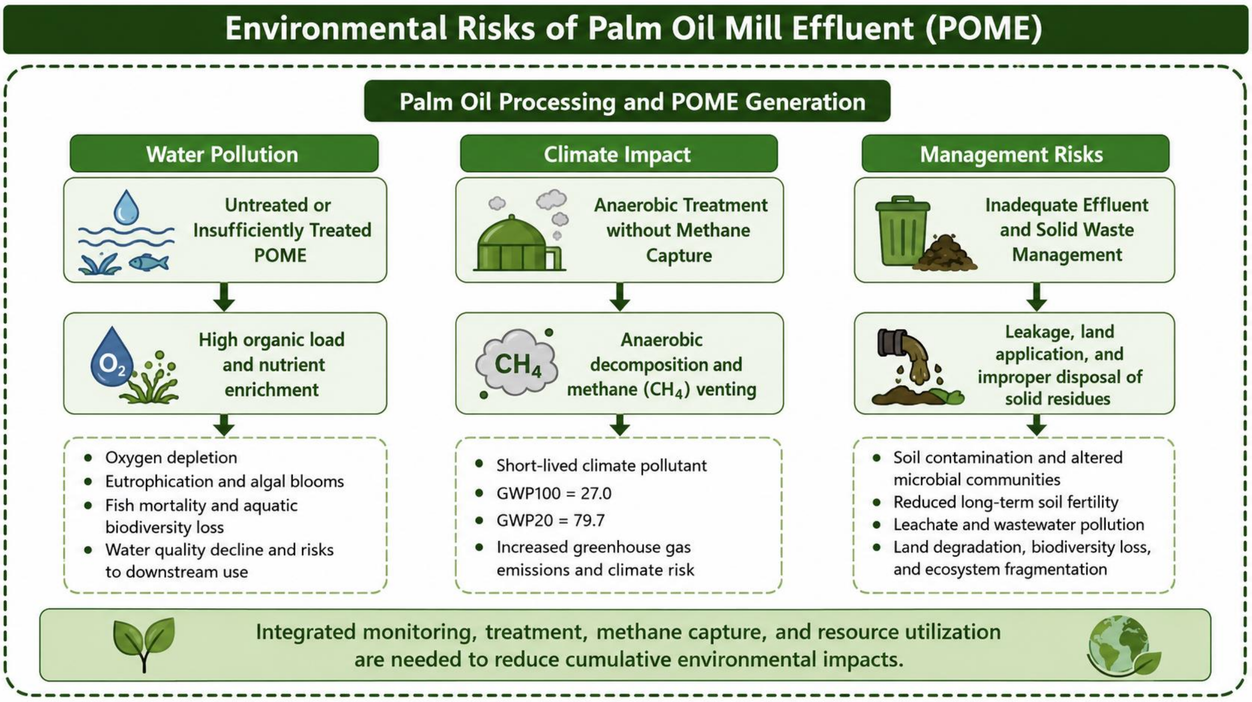


Fig. 3.5 Environmental Risks of Palm Oil Mill Effluent

3.3.1 Water pollution and ecological degradation from untreated effluent

POME is the largest-volume by-product of palm oil processing, with a high organic load and elevated nitrogen and phosphorus contents. Reported average concentrations of biochemical oxygen demand (BOD) and chemical oxygen demand (COD) in untreated POME are approximately 25,000 and 50,000 mg/L, respectively, although the actual values vary with mill operations and processing conditions (Yong et al., 2023). In primary-producing countries such as Indonesia and Malaysia, untreated or insufficiently treated POME discharged into rivers, lakes, and coastal waters causes significant water pollution (Asmara et al., 2024).

Decomposition of organic matter in POME consumes dissolved oxygen, leading to rapid oxygen depletion and mass mortality among fish and other aquatic organisms, thereby severely reducing underwater biodiversity. Nutrient enrichment can trigger eutrophication, algal blooms, and potentially toxic algal events, further degrading water quality, producing malodors, and introducing toxins into local food chains, which may pose health risks to surrounding communities. Water pollution also undermines the safety of downstream drinking water and fisheries and reduces regional water availability, particularly in water-scarce areas, exacerbating environmental and resource pressures. Establishing comprehensive POME monitoring and treatment systems is therefore essential not only for ecological protection but also for sustainable regional socioeconomic development.

3.3.2 Climate risks from methane emissions during anaerobic treatment

Anaerobic treatment is a common method for POME management, effectively reducing organic pollutant loads. Open anaerobic ponds use microbial metabolism to degrade organic matter, mitigating water pollution. However, this approach poses environmental risks, particularly when methane-capture facilities are absent. Long-term field monitoring of commercial anaerobic ponds in Malaysia recorded an average methane content of 54.4% in the emitted biogas and methane emissions of approximately 1,043.1 kg CH_4 per pond per day. This was equivalent to approximately 0.237 kg CH_4 for every kilogram of COD removed, demonstrating that pollution-load reduction through open anaerobic treatment can be accompanied by substantial greenhouse gas emissions (Yacob et al., 2006).Methane is a potent short-lived greenhouse gas; according to the IPCC Sixth Assessment Report, non-fossil methane has a 100-year global warming potential (GWP100) of 27.0 relative to carbon dioxide, while its 20-year global warming potential reaches 79.7, highlighting the near-term climate significance of uncontrolled methane release from POME treatment (Forster et al., 2021).

Conversely, methane capture can transform this emission source into a renewable-energy resource while improving wastewater treatment performance. An optimization study based on operating data from three commercial covered-lagoon biogas plants in Malaysia estimated a methane yield of 0.335 m3 CH_4 per kilogram of COD removed and a COD removal efficiency of 93.4% under optimized conditions (Yong et al., 2023).In major tropical palm oil regions, rapid industry expansion heightens the climate risk associated with methane emissions from POME treatment. In Malaysia, POME processing accounts for 23.7% of the industry's methane emissions. Focusing solely on water pollution mitigation while neglecting greenhouse gas control risks shifting the pollution burden across environmental media. Systematic technological measures are therefore urgently required to manage methane emissions and achieve comprehensive environmental benefits.

3.3.3 Integrated ecological risks from inadequate effluent and solid waste management

Effective management of POME and associated solid residues is central to sustainable palm oil production. Land application or uncontrolled leakage of POME introduces high organic loads and potential heavy metals into soils, altering microbial community structure and function and ultimately reducing long-term soil fertility and agricultural productivity(Dominic et al., 2022). These changes may extend beyond local plots, as toxic compounds bioaccumulate through the food chain, posing risks to human health and ecosystem integrity.

Solid wastes, including empty fruit bunches, palm fibers, and shells, if not systematically reused or managed, intensify ecological pressures. Improper disposal consumes land resources and, together with leachate and wastewater pollution, accelerates biodiversity loss and ecosystem fragmentation. Consequently, the environmental pressures from POME and associated solid wastes extend beyond single-medium pollution, constituting a comprehensive ecological risk that encompasses land degradation, water-soil imbalances, and biodiversity loss. This underscores the need for systemic governance approaches that integrate full-process monitoring and resource utilization to mitigate cumulative environmental impacts.

3.4 Interactions between climate change and the palm oil industry

3.4.1 Palm oil contributions to climate change

Land-use change is one of the most significant climate-related impacts of the palm oil industry and a primary driver of biodiversity loss in cultivation areas. To expand oil palm yields, primary and secondary forests are frequently converted into monoculture plantations, significantly altering local ecological conditions. Such anthropogenic land transformation affects temperature, atmospheric moisture (Hardwick et al., 2015), and soil hydrology, contributing to declines in biodiversity, peatland degradation, and, in some cases, complete peatland loss (Raven et al., 2021; Koh et al., 2011).

Beyond land conversion, the palm oil value chain contributes additional greenhouse gas emissions through methane generation during anaerobic wastewater decomposition and fossil fuel consumption in processing operations. Further processing of palm oil into biodiesel also generates emissions, as the esterification process requires additional fossil energy inputs and biodiesel typically increases fuel consumption per unit of work in engines (Reijnders et al., 2008; Searchinger et al., 2018; Meijaard et al., 2020).

Nonetheless, palm oil supplies approximately 40% of global vegetable oil demand while occupying less than 5-5.5% of global arable land dedicated to oil crops(Meijaard et al., 2020). Substituting palm oil with alternative oil crops such as soybean, rapeseed, or sunflower would likely necessitate clearing millions of hectares of forest, undermining global climate mitigation objectives (Chiriacò et al., 2024).

3.4.2 Climate change risks to the palm oil industry

Under climate change scenarios, environmental conditions—including precipitation and temperature—within oil palm cultivation zones are projected to shift, potentially reducing climate suitability for oil palm growth in some regions. Concurrently, these changes are likely to increase the frequency of pest outbreaks and diseases, as well as extreme weather events such as floods and droughts, thereby reducing arable land availability and constraining yields(Paterson et al., 2015; Okoro et al., 2017; Paterson, 2021, 2022).

Empirical studies indicate that climatic and hydrological factors strongly influence both oil palm yields and regional yield variability. Climate change can alter precipitation patterns and increase atmospheric evaporative demand, resulting in elevated water stress index (WSI) and vapor pressure deficit (VPD) in cultivation areas. These conditions exacerbate soil moisture limitations, reduce water-use efficiency, and inhibit photosynthesis, ultimately reducing the number of fruit bunches and single-bunch weight, leading to declines in fresh fruit and oil yields. Moreover, El Niño events in preceding winters can reduce spring rainfall and raise atmospheric temperatures, intensifying local water stress and diminishing total yields.

Indirect effects of climate change include heightened risks of pests and disease. Oil palms subjected to heat, drought, or flooding exhibit reduced disease resistance and increased vulnerability to pathogenic fungi, potentially leading to yield losses and the emergence (Paterson et al., 2013; Morand et al., 2021)of novel diseases. Flooding also has significant impacts: while oil palm seedlings can adapt morphologically, for example by forming aerial roots, prolonged waterlogging inhibits root growth. Studies from Malaysia and Indonesia indicate that some plantations experienced annual productivity losses of 20% to 50% due to flooding events (Lupascu et al., 2020; da Ponte et al., 2019).

However, not all effects of climate change are negative. Certain currently marginal regions—characterized by cooler temperatures, higher altitudes, or slightly higher latitudes—may benefit from warming through increased climate suitability for oil palm. Research in Southeast Asia suggests that highly suitable areas may expand in southern coastal Vietnam and selected highlands of Indonesia and Malaysia. Similarly, modeling in Nigeria's Niger Delta indicates that localized net benefits to oil palm productivity may occur under climate change, although these gains are spatially heterogeneous and typically contingent on adaptive management, such as altered planting schedules and irrigation (Okoro et al., 2017).

Despite these localized opportunities, climate change is expected to reduce climatic suitability, exacerbate water stress, and heighten disaster risk across many cultivation areas, thereby threatening yield stability and production growth globally.

3.5 Social impacts and livelihood implications of the palm oil industry

The social impacts of the palm oil industry exhibit a dual character. On one hand, the industry generates employment, increases cash income, and stimulates regional economic activity (Okoro et al., 2017). In producing countries, oil palm is often regarded as a development crop in areas with limited alternative agricultural opportunities. Among smallholder farm households, particularly those operating independently with access to land and markets, oil palm cultivation has been shown to generate significantly positive effects on education, nutrition, dietary quality, general living conditions, and asset ownership (Chrisendo et al., 2022). For scheme or contract smallholders, oil palm cultivation affects livelihoods primarily through their incorporation into company- or state-supported arrangements. Evidence from Indonesia shows that contracts between palm oil companies and local communities can contribute to village-level wealth accumulation and rural economic development, particularly when accompanied by public support, infrastructure investment, and clear institutional arrangements (Gatto et al., 2017). From a local economic perspective, benefits include increased income, expanded employment, and improved infrastructure.

On the other hand, these benefits are not evenly distributed. Multidimensional counterfactual assessments in Indonesia reveal significant heterogeneity in the effects of oil palm expansion on poverty reduction and socio-environmental well-being. Villages with strong market integration and market-oriented livelihoods typically see improvements in basic living conditions, infrastructure, and financial well-being. Conversely, remote villages with high forest cover and primarily subsistence-based livelihoods often show the opposite trend (Santika et al., 2019). Consequently, increased income from oil palm cannot be equated with comprehensive poverty alleviation or universal welfare improvement.

Smallholders face multiple challenges in adapting to new policies, regulations, and governance frameworks. In Sabah, Malaysia, smallholders participating in sustainable certification programs encounter land tenure insecurity, insufficient financial and technical capacity, food insecurity, and unstable certified palm oil prices (Hou et al., 2024). Broader studies indicate persistent challenges in Malaysia's crude palm oil supply chain, including inequitable inclusion of smallholders, limited local employment opportunities, low wages, and underutilization of biomass residues. These findings suggest that, while economic opportunities are generated, structural inequalities may be reinforced (Santika et al., 2019).

At the level of labor relations and social conflict, large-scale, company-driven oil palm expansion is often linked to land grabbing, local disputes, labor exploitation, and social inequities. Social life cycle assessment identifies working conditions, cultural heritage, and socio-economic consequences as critical social hotspots within the palm biodiesel value chain, underscoring that social impacts are central to industry sustainability rather than peripheral concerns.

Overall, while the palm oil industry creates employment and income and can support local economic development, the distribution of benefits is uneven. Smallholders, local communities, and low-skilled workers are more vulnerable to adverse outcomes, including price volatility, certification costs, insecure land tenure, and deteriorating labor conditions, than larger, better-resourced actors.

3.6 Summary

Overall, the palm oil industry has become a central component of the global vegetable oil system. Its development is closely linked not only to agricultural production and international trade but also to the energy transition, ecological conservation, climate governance, and social equity. From a historical perspective, policy frameworks and industry practices have evolved from a primary focus on production expansion toward sustainability-oriented governance and, more recently, toward approaches that emphasize circular bioeconomy principles and full value-chain resource utilization. Indonesia and Malaysia have long dominated the global supply, with production exhibiting strong regional concentration. At the same time, the industry structure has progressively shifted from reliance on crude palm oil exports toward downstream processing, energy applications, and higher-value use of by-products.

At the same time, the environmental and climate impacts of the palm oil sector remain substantial. Existing evidence indicates that oil palm expansion is closely associated with deforestation, peatland conversion, biodiversity loss, and increased greenhouse gas emissions. In addition, inadequate management of palm oil mill effluent and other by-products during processing can further intensify environmental pressures. From a climate perspective, the relationship between the palm oil industry and the climate system is characterized by clear bidirectional interactions. On the one hand, industrial activities influence the climate through land-use change and process-related emissions. On the other hand, climate change—manifested through extreme rainfall, droughts, and increased pest and disease risks—as well as tightening international regulatory frameworks related to zero-deforestation, due diligence, and supply chain transparency, are introducing growing uncertainties and external constraints on industry operations.

At the socio-economic level, the impacts of the palm oil industry on livelihoods are inherently dual. While the sector generates employment, increases cash income, and contributes to local economic development and infrastructure improvement, the distribution of benefits remains uneven. Factors such as land tenure insecurity, labor conditions, certification costs, and rising market entry barriers may exacerbate vulnerabilities among smallholders, local communities, and low-skilled workers. As sustainability certification and international compliance requirements become more stringent, disparities in access to resources, technical capacity, and market participation among actors are emerging as key challenges to inclusive development in the sector.

Looking ahead, the future of the palm oil industry will depend less on further expansion of production scale and more on a transition in development pathways. The literature consistently suggests that more sustainable trajectories should include increasing yields within existing plantations, limiting further encroachment on forests and peatlands through peatland protection and no-deforestation land-use planning, strengthening the resource utilization of POME and biomass by-products, including methane capture from POME and biogas recovery, and enhancing supply chain traceability and compliance capacity. At the same time, greater emphasis is needed in policy design on the inclusion of smallholders through certification support and compliance cost-sharing, equitable benefit-sharing, and accessible grievance mechanisms. Achieving a more effective balance among economic growth, circular resource use, environmental protection, climate governance, and social equity will be essential for ensuring the long-term resilience and sustainability of the palm oil industry.

4 Rubber Industry

The rubber industry is a globally important industrial sector underpinning transportation, healthcare, construction and manufacturing. It comprises natural rubber production together with downstream processing and manufacturing activities, while also interacting with synthetic rubber and other industrial inputs. As the demand for sustainable materials grows under the bioeconomy transition, the natural rubber component of the industry has attracted increasing attention because of its renewable origin and its links to land use, biodiversity, rural livelihoods and climate change. At the same time, the sector faces mounting challenges related to supply chain transparency, environmental performance and sustainable production. Against this background, this chapter reviews the historical evolution, environmental and social implications, and climate interactions of the natural rubber industry within the broader context of a sustainable bioeconomy.

4.1 Historical evolution of key policies and practices in rubber industry

Natural rubber is a significant plant-based biopolymer, primarily extracted from Hevea brasiliensis (Tang et al., 2022). Owing to its high carbon content and renewability, natural rubber is recognized as a critical alternative to petroleum-based synthetic rubbers, offering strategic potential to reduce dependence on fossil resources and support low-carbon transitions (He et al., 2019).

In terms of material properties, the strain-induced crystallization characteristic of natural rubber confers high tensile strength, elasticity, and fatigue resistance (Men et al., 2018), rendering it widely applicable in sectors such as transportation and healthcare (John et al., 2022). Approximately 70% of global natural rubber consumption is used in vehicle and aircraft tires (John et al., 2022; Zhao et al., 2024). The gradual incorporation of bio-based materials in the tire industry positions natural rubber as a key contributor to lowering fossil carbon inputs and facilitating the decarbonization of transport systems (Miedzianowska-Masłowska, 2025). Although the broader rubber industry also depends on synthetic rubber, carbon black, steel and various chemical additives for downstream product manufacturing, this chapter focuses primarily on natural rubber as the bio-based feedstock of the rubber value chain and its role in sustainable industrial development, rather than on downstream rubber products as a whole.

Against the backdrop of an advancing bioeconomy and increasingly complex global supply chain governance, the industrial role of natural rubber is evolving from an export-oriented agricultural commodity to a strategic bio-based material. This transition entails adjustments to industrial policies, production geographies, and international trade patterns.

4.1.1 Policy evolution and governance shift in the bio-based economy

Within the traditional global industrial framework, natural rubber has long been classified as a tropical cash crop, with policy frameworks primarily focused on smallholder livelihoods, cultivation expansion, and primary trade management (Fig. 4.1). The development of the bioeconomy paradigm has prompted a shift in the policy positioning of natural rubber, recognizing it as a renewable biological resource and a critical industrial feedstock. The Food and Agriculture Organization of the United Nations (FAO), in its 2022-2031 Strategic Framework, identified the bioeconomy as a priority development area and emphasized the role of agricultural biological resources in the circular economy. In this context, natural rubber has gradually been integrated into governance systems for bio-based materials and renewable resources, with policy attention shifting from agricultural production management to value chain development and supply chain governance.

In recent years, global environmental priorities, including climate change mitigation and biodiversity conservation, have heightened international attention to the risks of deforestation and ecological degradation linked to the expansion of rubber cultivation. This has catalyzed the development of sustainable natural rubber governance frameworks. Early governance efforts were primarily based on voluntary commitments, such as the Sustainable Natural Rubber Initiative (SNR-i) launched by the International Rubber Study Group (IRSG) in 2013, which established a set of voluntary principles for more sustainable production and trade. In 2018, the Global Platform for Sustainable Natural Rubber (GPSNR) was established as a multi-stakeholder platform, bringing together producers, companies, civil society organizations, and other stakeholders to promote sustainable procurement principles and responsible supply chain practices. In parallel, third-party certification schemes and corporate sustainability reporting have further contributed to improving sustainability assurance, transparency, and accountability across supply chains, although their implementation and coverage vary among regions and market actors. More recently, the European Union Deforestation Regulation (EUDR), adopted in 2023, has introduced legally binding due diligence and traceability requirements for market access, marking a shift from predominantly voluntary governance towards mandatory supply chain compliance. While these governance mechanisms play complementary roles in promoting sustainable natural rubber production, continued efforts are needed to strengthen implementation capacity, enhance inclusiveness, and support the effective participation of smallholder producers in sustainable supply chains.

In response to these international policy developments, major Southeast Asian producing countries have shifted national policies from traditional agricultural support to a dual focus on industrial upgrading and sustainable governance. Thailand enacted the Rubber Authority of Thailand Act (B.E. 2558) in 2015, establishing the Rubber Authority of Thailand (RAOT) to consolidate management from cultivation through processing. The 'Rubber City' initiative and the BCG Economy Model were also implemented to promote industrial upgrading. Malaysia designated natural rubber as a strategic bio-based material under the National Agro-Food Policy 2.0 and launched the Malaysia Sustainable Natural Rubber (MSNR) certification system in 2022 to integrate environmental compliance into industrial management. Meanwhile, Indonesia has advanced smallholder land tenure through social forestry policies, incorporated rubber cultivation into the FoLU Net Sink 2030 Operational Plan and promoted agroforestry-based production models.

Driven by the parallel forces of bioeconomy development and global sustainable supply chain governance, natural rubber policy is shifting from a traditional agriculture-centered management model to a governance framework that emphasizes value chain integration and compliance with sustainability standards. This policy reorientation has, in turn, influenced the spatial distribution of natural rubber production and the structure of the industry.

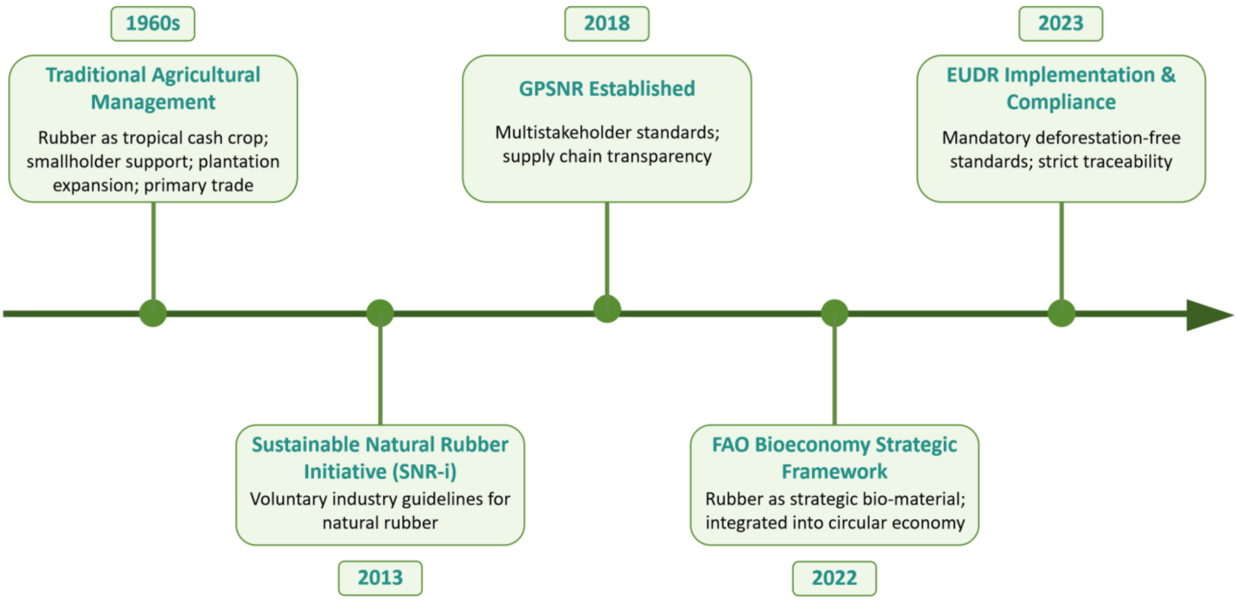


Fig. 4.1 The evolutionary pathway of natural rubber policy: From agricultural production to sustainable bioeconomy governance

4.1.2 Production expansion and spatial restructuring

Global natural rubber production is undergoing structural shifts, marked by a gradual diffusion from traditional core regions to emerging producing areas. Historically, global supply has been heavily concentrated in Southeast Asia; however, in recent years, expansion in traditional producing countries has moderated due to multiple constraints, including land scarcity, rising labor costs, and competition from alternative crops. While Thailand remains the world's leading natural rubber producer, its production growth has stabilized. In parallel, Indonesia and Malaysia are grappling with shrinking cultivation areas, as rubber plantations are progressively converted to more lucrative alternatives such as oil palm.

In contrast, emerging producing regions have experienced sustained growth. According to FAO data for 2024 (Fig. 4.2), Côte d'Ivoire has risen to become the third-largest global natural rubber producer, reflecting Africa's increasing prominence within the global supply system. Vietnam and Cambodia have achieved sustained increases in production through large-scale plantation development and industrial upgrading. Overall, while traditional producers like Thailand and Indonesia continue to dominate the market, the production landscape is progressively extending into the Greater Mekong Subregion and selected areas in West Africa. This diversification of production reflects distinct regional resource endowments and development pathways, while concurrently enhancing the resilience and stability of the global natural rubber supply chain. Furthermore, this reconfiguration of production patterns is fundamentally reshaping global trade flows and the sector's value chain structure.

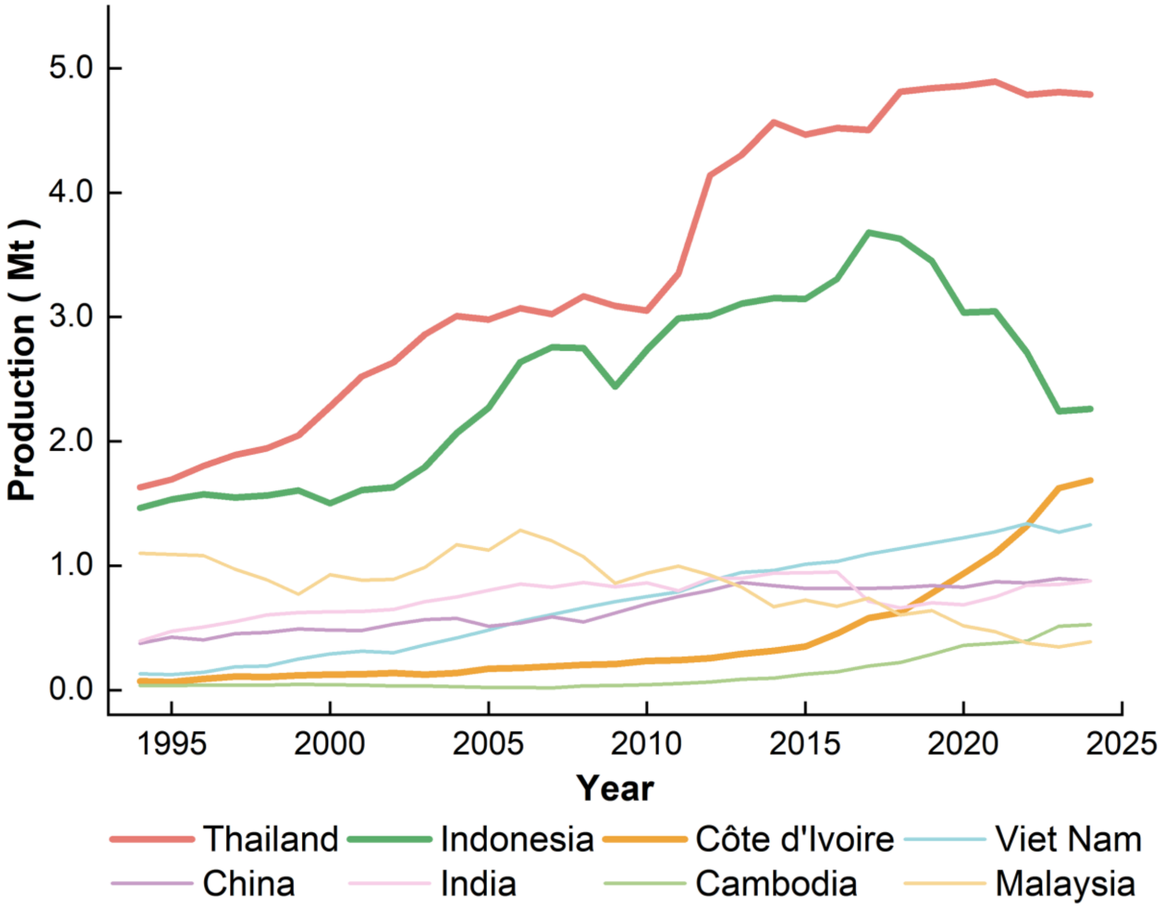


Fig. 4.2 Annual natural rubber production by major countries, 1994-2024 (Mt). Thick lines represent the top three producing countries in 2024. Source: FAOSTAT

4.1.3 Global trade patterns and value chain reconfiguration

Global natural rubber production is primarily concentrated in Southeast Asia and West Africa, while consumption and processing are predominantly centered in Asia and North America. This spatial separation (Fig. 4.3) makes international trade the principal mechanism for connecting supply and demand, and the natural rubber value chain is heavily reliant on cross-border transactions to allocate resources efficiently.

On the supply side, the top three exporters in 2024-Thailand, Côte d'Ivoire, and Indonesia-demonstrate distinct functional roles within the global manufacturing system. Thailand and Côte d'Ivoire have become deeply integrated into large-scale industrial manufacturing clusters, primarily serving the substantial processing demands of China and Malaysia. In contrast, Indonesia's export flows are strategically oriented toward advanced manufacturing sectors and high-value-added supply chains in Japan and the United States, which together account for approximately 46% of Indonesia's total exports. While Indonesia has experienced a significant contraction in overall export volume since 2017, the concurrent surge in Côte d'Ivoire's exports provides a crucial structural offset, thereby helping stabilize the global supply architecture.

On the demand side, Asia and North America remain the principal consumption regions. China, supported by its massive tire and rubber products industry, has emerged as the world's largest importer and occupies a central position as the dominant demand-side player. Concurrently, certain traditional producing countries are experiencing fundamental shifts in their industrial functions. For instance, Malaysia, as the world's second-largest importer, is transitioning toward serving as a regional processing and trade hub, indicating that some producing countries are extending their involvement from upstream cultivation to midstream processing. Furthermore, Viet Nam's simultaneous ranking among the top five exporters and importers (Fig. 4.3) reflects the complexity of intra-industry trade in the global rubber market.

Within this supply-demand configuration, the global natural rubber value chain is undergoing a profound reconfiguration. Traditional hubs are increasingly moving toward higher value-added processing and trade, while the emergence of new production nodes diversifies sourcing, thereby enhancing the resilience and stability of the global supply system against localized disruptions. Overall, the global trade structure of natural rubber is gradually adjusting in response to evolving production patterns and deepening industrial specialization.

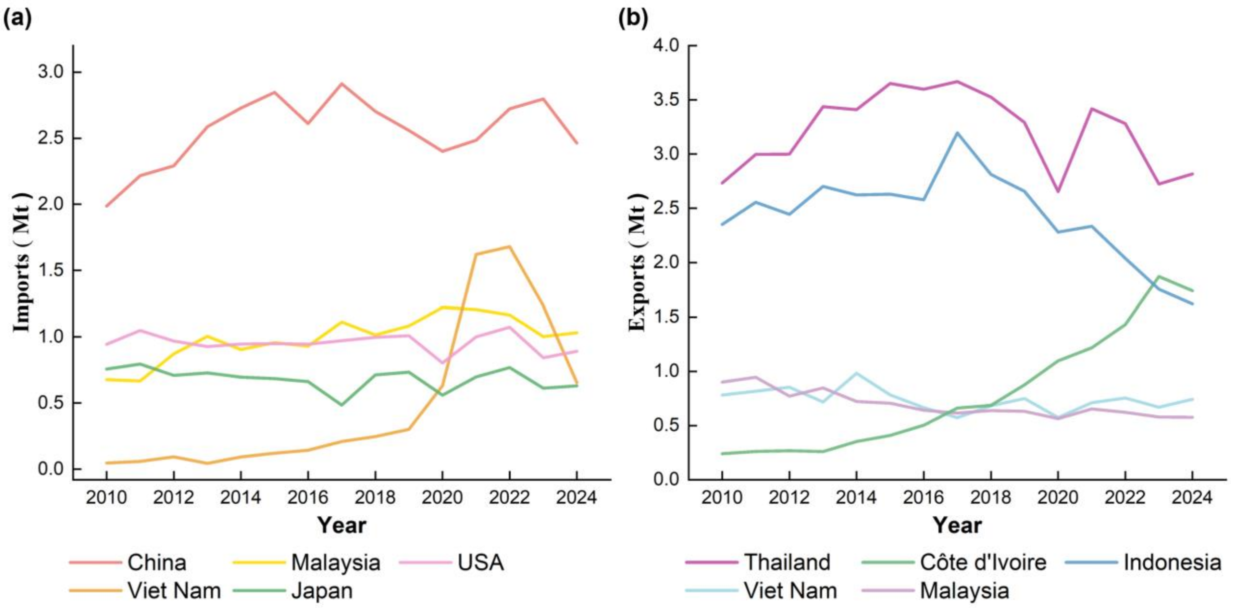


Fig. 4.3 Trends in natural rubber trade volumes for key importing and exporting countries, 2010-2024. (a) Imports by major importing countries; (b) Exports by major exporting countries. Source: FAOSTAT.

4.2 Rubber industry, land use and biodiversity

The development of the natural rubber sector is closely linked to land-use change (Fig. 4.4). As a land-intensive bio-based production system, the expansion of rubber production is typically associated with changes in agricultural land-use patterns and the conversion of natural ecosystems. In tropical regions, where rubber cultivation is concentrated, rising global demand and price incentives have made plantation expansion a key driver of land-use change.

This expansion often involves converting forests and other natural habitats into monoculture systems, resulting in substantial changes to ecosystem structure and function and placing continued pressure on biodiversity (Fig. 4.4). Understanding the spatial drivers of rubber expansion, the pathways of land-use change, and their ecological consequences is therefore important for assessing the sector's sustainability and informing policy decisions.

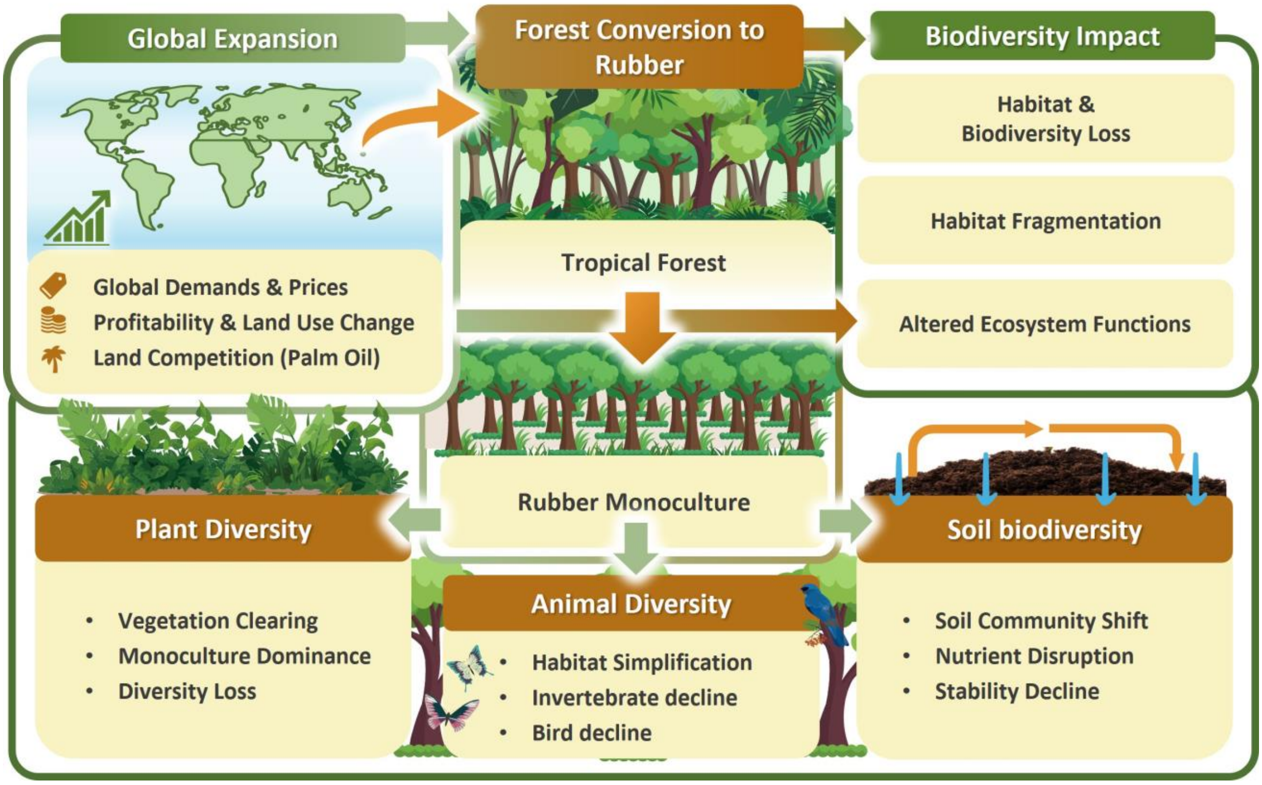


Fig. 4.4 Land-use transitions and biodiversity responses in rubber plantation systems.

4.2.1 Global distribution and expansion of rubber plantations

Natural rubber plantations are highly concentrated globally, primarily in tropical and subtropical regions, with a particular concentration in Southeast Asia, South Asia, and parts of Africa and Latin America (Warren-Thomas et al., 2015). Among these regions, Southeast Asia has long been the core area of global natural rubber production and plays a dominant role in the global supply system (Wang et al., 2023). The region provides suitable climatic conditions for rubber cultivation, including high mean annual temperatures, long frost-free periods, and monsoon-driven rainfall patterns, which support large-scale plantation development (Carr, 2012). As a result, countries such as Thailand, Indonesia, and Malaysia have become the world's leading producers of natural rubber.

Against the backdrop of sustained growth in global demand, natural rubber production has largely followed an area-expansion-driven path. Unlike some crops where yields can be significantly improved through technological progress, increases in rubber production rely primarily on the expansion of planted area (Warren-Thomas et al., 2023; Warren-Thomas et al., 2015), reinforcing the close link between the rubber sector and land-use change. In addition to market demand, rubber expansion is also shaped by competition for land with oil palm (Fox & Castella, 2013; Jayathilake et al., 2023). Oil palm typically occupies more favorable lowland areas in humid tropical regions, whereas rubber, supported by varietal improvement and technological advances, shows greater adaptability to a wider range of terrain and soil conditions. As oil palm continues to expand, rubber cultivation in some regions has increasingly shifted towards upland, sloping, and other marginal lands, which are often more ecologically sensitive.

The spatial patterns of rubber expansion and associated forest loss vary considerably across producing regions. In Southeast Asia, the largest absolute areas of rubber-related deforestation have been concentrated in major producing countries, particularly Indonesia and Thailand, while Cambodia has experienced a particularly high proportion of rubber plantations associated with forest conversion (Wang et al., 2023). Beyond these established production centers, rubber cultivation has expanded across the Greater Mekong region, including Viet Nam, Cambodia, Laos, Myanmar, and southern China, where plantations have increasingly extended into non-traditional growing areas and mountainous landscapes (Fox and Castella, 2013). These contrasting patterns indicate that rubber-related land-use change is not confined to established production centers but also extends across emerging cultivation frontiers. Outside Southeast Asia, rapidly growing production in West Africa, particularly in Côte d'Ivoire, further indicates a geographical diversification of global rubber production and highlights the need to closely monitor land-use change in emerging production regions.

Such spatial expansion and relocation not only extend the potential distribution of rubber plantations but also increase their overlap with natural habitats. In many tropical regions, the expansion of rubber plantations has been associated with the conversion of forests to agricultural land, making it a major driver of land-use change and deforestation and exerting sustained pressure on regional biodiversity.

4.2.2 Land-use change and ecosystem transformation

Rubber expansion is closely linked to tropical deforestation. As global demand continues to rise, large tracts of forest have been converted into plantations (Warren-Thomas et al., 2023; Warren-Thomas et al., 2015). Evidence from high-resolution rubber distribution and land-cover change datasets indicates that, between 1993 and 2016, approximately 4.1 million hectares of forest were cleared in Southeast Asia alone (Wang et al., 2023).

In many cases, this conversion has occurred in high-value forests, making rubber production an increasingly important driver of forest loss in tropical regions (Normile, 2015). By 2021, more than 1 million hectares of plantations in Southeast Asia were located within Key Biodiversity Areas (Wang et al., 2023), highlighting the growing overlap between rubber cultivation and priority areas for biodiversity conservation.

The shift from forest to rubber plantations represents not only a change in land cover, but also a substantial reorganization of ecosystem structure and functioning. Tropical forests, among the most biodiverse ecosystems globally, provide a range of ecological niches through their complex, multi-layered vegetation structure (Lewis et al., 2015). They also support stable biological communities through processes such as nutrient cycling, water regulation, and microclimate stabilization. When replaced by monoculture systems, these key ecological functions are often reduced (Singh et al., 2021).

Compared with natural forests, rubber plantations are typically characterized by single-species composition, even-aged stands, and regular planting patterns. Their vertical structure is markedly simplified, lacking the multi-layered vegetation typical of natural systems. In addition, the highly synchronized phenological cycles of rubber trees reduce temporal variation in food resources and habitat conditions, limiting their capacity to support diverse species assemblages. Under conventional management practices, herbicide use and periodic removal of understory vegetation further reduce habitat complexity (Singh et al., 2021).

Together, these structural and functional changes lead to declines in habitat quality, contraction of ecological niches, and continued losses of species diversity, making forest conversion to rubber plantations a major pathway of biodiversity loss in tropical regions.

4.2.3 Biodiversity impacts and ecological responses

The impacts of rubber plantation expansion on biodiversity operate across multiple ecological levels, affecting both above- and below-ground systems. Following land-use conversion, natural forest ecosystems are replaced by monoculture plantations, altering habitat structure, resource availability, and key ecological processes, thereby reducing the suitability of these systems for many species.

Regarding plant diversity, rubber cultivation typically involves clearing existing vegetation, replacing diverse forest plant communities with single-species plantations (Singh et al., 2021). Management practices such as fertilization, understory clearing, and frequent human disturbance further constrain the natural regeneration of native plant communities. As a result of simplified vegetation structure and species composition, plant diversity in rubber plantations is generally much lower than in natural forests.

Regarding animal biodiversity, a substantial body of field evidence shows that rubber plantations cannot support species richness and community structure comparable to those of natural forests. Insects and other invertebrates generally exhibit reduced diversity in rubber-dominated systems (Liu et al., 2019). Species that depend on forest resources, such as birds that rely on fruits and insects, are particularly affected by declines in food availability and suitable habitat (Normile, 2015).

Rubber cultivation also has significant implications for belowground ecosystems. Converting forests to plantations often alters the composition and functioning of soil biotic communities, with subsequent effects on soil structure, nutrient cycling, and ecosystem stability. Studies from regions such as Xishuangbanna in China and southern Thailand have consistently reported declines in soil biodiversity under rubber cultivation, with cumulative negative effects observed under long-term monoculture management (Panklang et al., 2022; Singh et al., 2019).

Although rubber cultivation generally exerts significant pressure on biodiversity, its impacts are not entirely irreversible. Under conditions where production levels are maintained, there is potential to mitigate biodiversity loss through improved plantation design and management. For example, rubber agroforestry systems, which increase tree species diversity and understory complexity, can enhance habitat conditions to some extent (Zou et al., 2024), and have been shown to support higher diversity of birds and certain insect groups (Warren-Thomas et al., 2020). However, these benefits are not consistent across taxa. Some studies suggest that agroforestry systems may negatively affect the abundance and richness of ground-dwelling arthropods (Liu et al., 2021), indicating that responses to land-use change vary among biological groups.

In a bio-based economy, more ecologically informed land-use practices may help alleviate biodiversity pressures while maintaining economic outputs. However, their effectiveness remains context-dependent, varying across ecosystems and taxonomic groups.

4.3 Impact on livelihoods

Natural rubber production is one of the most smallholder-dominated bio-based sectors globally. In Thailand, Indonesia, Malaysia, and other tropical countries, rubber cultivation is a major source of livelihood for millions of rural households and has played an important role in poverty reduction and rural economic transformation. Beyond providing employment and relatively stable cash income, rubber production has also contributed to the development of rural infrastructure and market systems, facilitating the integration of rural areas into national and global economies (Fig. 4.5).

However, these livelihood systems are closely embedded in global market structures, and income stability remains highly sensitive to fluctuations in international demand and prices (Fig. 4.5). During periods of market expansion, rubber cultivation can substantially improve household welfare and support greater investment in public services. In contrast, periods of price declines or demand uncertainty can rapidly pressure incomes and employment in producing regions. Smallholders are also exposed to production and environmental shocks, including disease outbreaks, droughts, excessive rainfall, and extreme weather events, which can interact with market downturns and further destabilize production and household income. Their capacity to absorb these shocks is often constrained by limited financial resources, weak access to information and services, and limited bargaining power within fragmented value chains. At the same time, the expansion of rubber cultivation often reshapes local production systems and reinforces dependence on a single commodity, increasing exposure to market and environmental risks.

From a sustainable development perspective, the rubber sector is both a critical pillar of rural livelihoods and a system facing multiple challenges, including the need to enhance income stability, strengthen social protection mechanisms, and improve overall resilience.

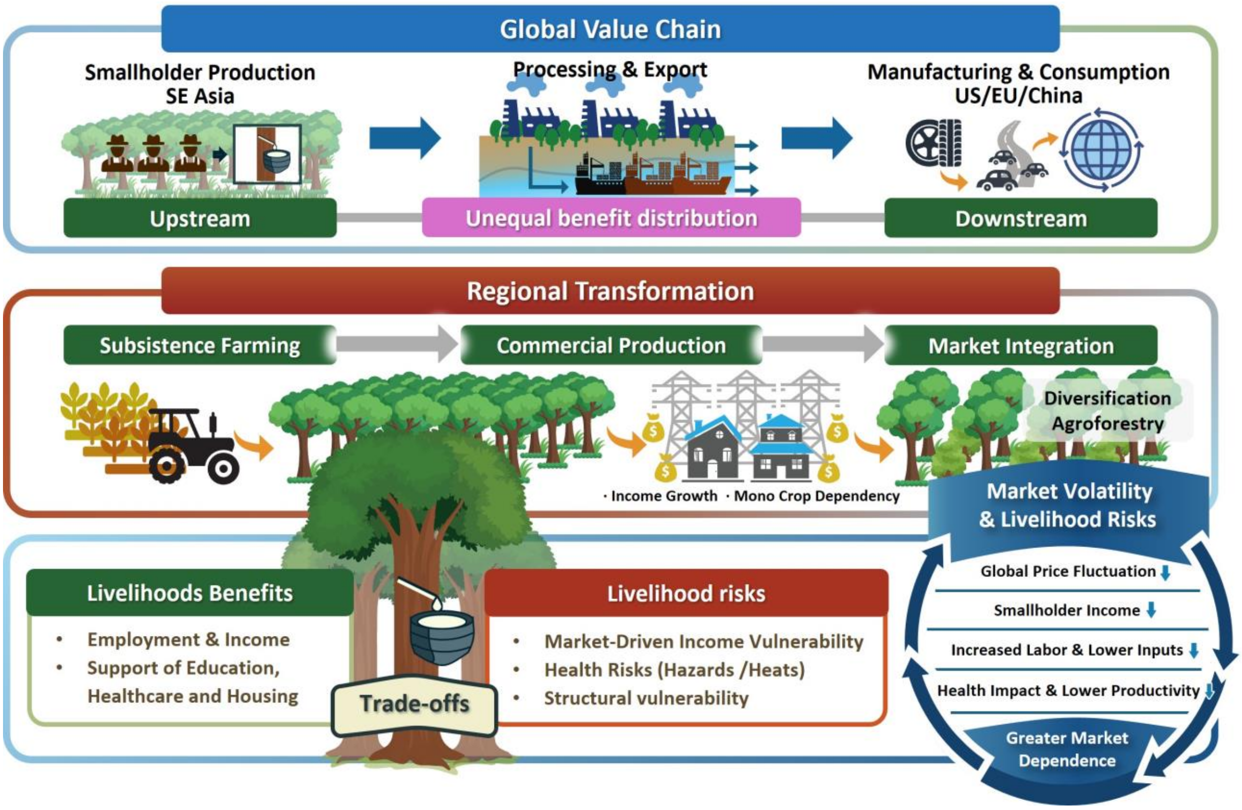


Fig. 4.5 Market integration and smallholder livelihood vulnerability in the rubber industry.

4.3.1 Smallholder livelihoods and health dimensions

Natural rubber production, particularly in major producing countries, is predominantly organized around smallholder systems and is highly labor-intensive (Carr, 2012). Cultivation and tapping activities are typically carried out by household labor, with production extending throughout the year and forming a relatively stable source of employment in rural areas. As perennial crops, rubber trees can produce latex for more than a decade once they reach maturity, making them an important, sustained source of household cash income. In some regions, rubber accounts for a substantial share of total household income and provides critical support for expenditures on education, healthcare, and housing, thereby contributing to improvements in rural living standards.

However, smallholder rubber economies are also associated with considerable labor demands and health risks. Tapping is often conducted in the early morning hours and relies on repetitive, physically demanding work. Prolonged bending and the use of tapping knives can lead to musculoskeletal strain and occupational injuries (Pramchoo et al., 2020; Stankevitz et al., 2016; Varghese & Panicker, 2025; Varghese & Panicker, 2022). To increase yields, farmers may apply stimulants, pesticides, and fertilizers, which, in the absence of adequate protective measures, can pose risks to skin and respiratory health, as well as long-term well-being (Abdul Rashid et al., 2026; Chaiyasarn et al., 2026). In addition, rubber production is sensitive to climatic conditions, and working in hot and humid environments further increases the risk of heat stress and dehydration.

These health risks are often borne at the household level, as smallholder systems generally lack adequate occupational safety protections and access to healthcare support, which translates into hidden livelihood costs. With the expansion of global value chains, smallholders have become increasingly integrated into transnational supply systems. While their incomes remain highly dependent on international market prices, their bargaining power within these chains is limited. Small production volumes, fragmented marketing channels, and unequal access to price and market information can further weaken the position of individual farmers in transactions with traders and processors, increasing their exposure to downstream buyer power and unfavorable market conditions. During periods of low prices, farmers may respond by extending working hours, reducing production costs, or cutting back on health and safety investments, thereby intensifying labor burdens and associated health risks.

Overall, rubber production is not only an agricultural activity but also a livelihood system embedded in global supply chains and exposed to both economic and health-related pressures. This underscores the need to improve social protection, strengthen occupational health safeguards, and enhance equity within supply chains, alongside efforts to increase production efficiency.

4.3.2 Regional livelihood transformation and structural changes

The expansion of rubber cultivation has reshaped local economic structures and transformed the organization of rural livelihoods. As a major cash crop, rubber has contributed to the development of rural infrastructure, including roads, primary processing facilities, and market networks, thereby strengthening linkages between rural areas and urban economies. In many regions previously dominated by subsistence agriculture, rubber production has driven a shift from diversified food cropping toward market-oriented commodity production, increasing the share of cash income and accelerating the monetization of rural livelihood systems (Carr, 2012).

This transition is often associated with short-term income gains. Rubber provides relatively stable cash flows, supporting improvements in housing conditions, increased investment in education, and higher consumption levels (Nath et al., 2013). In some remote areas, it has also played an important role in regional poverty reduction (Qiu, 2009). However, this development pathway, centered on a single cash crop, also introduces structural vulnerability. Where local economies become highly dependent on rubber production, household livelihoods are increasingly exposed to fluctuations in international market prices (Goh et al., 2016). During periods of high prices, incomes tend to rise, whereas price declines can lead to rapid income contraction, particularly for households lacking alternative income sources (Nicod et al., 2020). In addition, the expansion of rubber cultivation may crowd out other crops and non-farm activities, reducing livelihood diversification and weakening overall system resilience (Jessy et al., 2017).

In most major producing countries, limited access to rural financial services and incomplete social protection systems mean that price fluctuations are often directly passed through to household-level risks. Smallholders may also face multiple overlapping risks associated with unfavorable weather conditions, rubber diseases, and price declines, all of which can reduce productivity, farm income, and livelihood stability (Imelda et al., 2023). These pressures can reinforce one another, as production losses reduce household income, while low prices and financial constraints limit farmers' capacity to invest in plantation management, disease control, and recovery from production shocks. When market shocks or production-related risks occur, household incomes can decline sharply, prompting farmers to rely on borrowing, asset sales, or off-farm activities to sustain basic livelihoods and production (Min et al., 2026; Nicod et al., 2020). While such coping strategies may buffer short-term shocks, they can undermine long-term asset accumulation. At the same time, smallholder livelihoods are constrained by limited access to improved technologies and management practices. Under low-price conditions, financial constraints further restrict investment in productivity-enhancing inputs, reinforcing a cycle of low income and underinvestment (Asywadi & Syarifa, 2025).

As the income instability of monoculture rubber systems becomes more apparent, smallholders have increasingly explored diversified livelihood strategies (Nath et al., 2013). In recent years, policies and development initiatives have promoted integrating additional crops and tree species into rubber-based systems, supporting the development of agroforestry practices. For example, intercropping with fruits, spices, or timber species can improve land-use efficiency and broaden income sources (Qi et al., 2024; Zhou et al., 2025; Zou et al., 2024). Evidence from rubber-producing regions suggests that diversified agroforestry systems can reduce smallholder vulnerability to volatile rubber markets when secondary crops, trees, or livestock provide meaningful complementary income streams (Huang et al., 2023). Evidence from rubber-producing regions suggests that diversified agroforestry systems can reduce smallholder vulnerability to volatile rubber markets when secondary crops, trees, or livestock provide meaningful complementary income streams (Huang et al., 2023). In some regions, such as Indonesia and Ghana, rubber production is combined with traditional food crops in complementary ways. Farmers may reduce food-crop cultivation during periods of high rubber prices and resume it during market downturns, thereby buffering against income fluctuations and enhancing livelihood stability (Ashiagbor et al., 2024; Fox & Castella, 2013).

Beyond farm-level diversification, off-farm employment and other non-rubber income sources can provide additional buffers against periods of low rubber prices and production shocks. Collective organization through cooperatives and producer groups may further complement these strategies by improving access to market information, technical support, and collective marketing channels. Taken together, agroforestry, income diversification, and stronger producer organization provide complementary pathways for reducing dependence on a single commodity and strengthening the capacity of smallholder households to respond to market, production, and climate-related risks.

4.3.3 Global market integration and value chain implications

At the global level, natural rubber is a key raw material in transportation, industrial manufacturing, and consumer goods production, with the tire industry as its dominant end-use sector (Cucci et al., 2025). It is widely used in automotive tires, industrial seals, conveyor belts, and a range of consumer products, including footwear and medical supplies. With the continued expansion of the global automotive industry and transport infrastructure, demand for natural rubber has shown an overall upward trend, reinforcing its role as an important bio-based material underpinning modern industrial systems and as a foundational input in global consumer goods supply chains (Laroche et al., 2022).

This broad industrial demand has led to the deep integration of the natural rubber sector into global supply chains. Within the international division of labor, Southeast Asian countries, including Thailand, Indonesia, and Malaysia, serve as major production centers, while economies such as China, the European Union, and the United States constitute key consumption markets (Wang et al., 2023; Warren-Thomas et al., 2015). For producing countries, natural rubber is not only an important export-oriented agricultural commodity but also a significant source of foreign exchange earnings and rural employment (Agustina et al., 2025). In many producing regions, smallholder cultivation, primary processing, and related trade and transport activities are central components of local economies.

However, this export-oriented structure is marked by clear asymmetries across the value chain. Smallholders and producing countries typically occupy upstream segments of the rubber value chain, whereas higher-value-added activities, including advanced processing, manufacturing, and branding, are concentrated in more industrialized economies. As a result, producing countries bear most of the land and labor inputs yet capture only a limited share of economic value. In addition, shifts in global industrial structures, the development of alternative materials, and changes in trade patterns may reshape demand for natural rubber, with implications for employment and income stability in producing regions.

In recent years, rising international expectations for sustainable production and supply chain transparency have introduced new environmental and trade-related standards that are increasingly prerequisites for market access (Traldi et al., 2023). While these developments can promote more sustainable practices, they may also create additional barriers for lower-income producing regions. The integration of the natural rubber sector into global markets thus generates both development opportunities and structural constraints, highlighting the need for more equitable and sustainable outcomes within global supply chains.

4.4 Prime environmental issues: waste and chemical use

The rubber industry, a critical global supplier of bio-based raw materials, has an environmental footprint that spans its entire life cycle, from upstream cultivation to downstream end-of-life management (Fig. 4.6). Because rubber production integrates both agricultural cultivation and industrial processing, environmental pressures vary significantly across stages in terms of spatial scale, impact pathways, and governance complexity, necessitating stage-specific environmental management and integrated regulatory frameworks. Accordingly, environmental management priorities and policy responses also differ across the cultivation, processing, and end-of-life stages, ranging from sustainable land-use and agrochemical management, to pollution prevention and cleaner production, and finally to resource recovery and circular economy approaches.

During the cultivation phase, rubber trees are typically grown in large-scale plantations, where land-use change, the intensive use of fertilizers and pesticides, and field-level runoff can degrade soil quality and harm aquatic ecosystems. Subsequent industrial stages, including primary processing and product manufacturing, involve substantial consumption of water, energy, and chemicals, resulting in the release of pollutants, including wastewater, air emissions, and solid waste.

As consumption of tires and other rubber products continues to grow, the end-of-life management of waste rubber is becoming a significant issue in global solid waste management. The inherent stability and durability of rubber materials pose additional environmental risks during disposal and recycling processes. Therefore, it is essential to identify key environmental issues at each stage of the rubber value chain from a life-cycle perspective to support more sustainable industrial pathways.

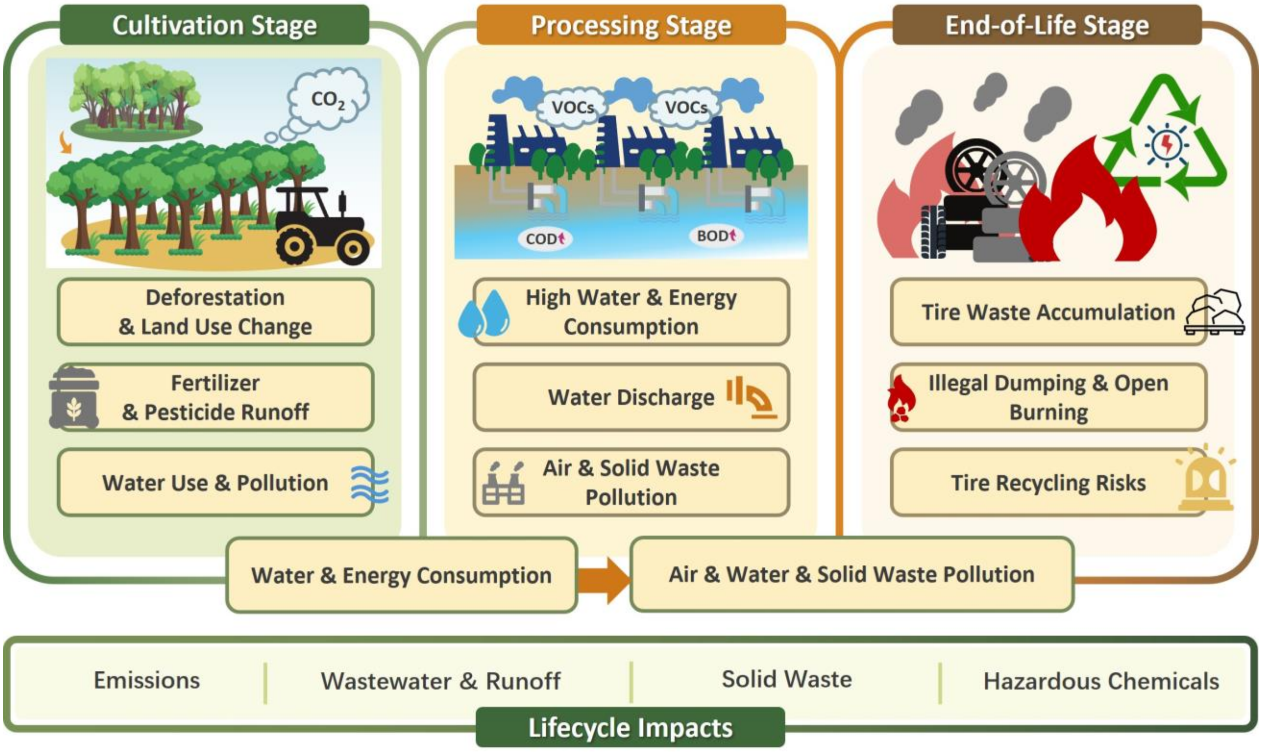


Fig. 4.6 Life-cycle environmental impacts of the rubber industry

4.4.1 Cultivation stage: land-use change and agrochemical inputs

Environmental impacts during the cultivation phase primarily arise from land-use change, the production and application of agricultural inputs, and field-level emissions. The expansion of rubber plantations often involves converting forests into cultivated land, which reduces ecosystem carbon stocks and significantly increases greenhouse gas emissions (Nunes et al., 2025). Studies indicate that in recently established rubber plantations converted from forests, carbon emissions per ton of fresh latex can reach 6.4 t CO_2-eq, significantly higher than the 0.2 t CO_2-eq observed in plantations established on long-term agricultural land, reflecting the significant carbon footprint associated with land-use change (Jawjit et al., 2010).

Monoculture rubber plantations are prone to soil nutrient depletion, necessitating a heavy reliance on fertilizers and pesticides (Panda & Sarkar, 2020). The production and application of inorganic fertilizers contribute significantly to multiple environmental impact categories, including global warming, acidification, eutrophication, human toxicity, and photochemical oxidant formation (Jawjit et al., 2021), with nitrogen-based fertilizers exerting the most pronounced effects (Panda & Sarkar, 2020). During field management, nitrogen and phosphorus runoff can trigger water eutrophication and algal blooms, which, through oxygen-consuming decomposition, disrupt the balance of the aquatic ecosystem (Panda & Sarkar, 2020; Pyay et al., 2019). Pesticide residues entering water bodies may exert toxic effects on non-target aquatic organisms and bioaccumulate through the food chain, posing potential risks to both ecosystems and human health (Sitepu et al., 2019).

Rubber cultivation can also affect regional hydrological processes. Compared with certain native vegetation, rubber trees have higher water requirements. Large-scale plantations can increase evapotranspiration and may reduce surface runoff and water yield. In some areas, this process is even considered to be linked to declining groundwater levels and the drying of local water bodies, thereby affecting the regional water resource balance (Vijayan et al., 2024).

In addition to the aforementioned impacts, the burning of biomass residues during the rubber plantation renewal, as well as the energy consumed by agricultural operations such as tillage, planting, and latex harvesting, contribute to atmospheric pollution and ecotoxicity, although the overall impact is relatively limited (Cucci et al., 2025).

4.4.2 Processing stage: wastewater, air emissions, and solid waste

Rubber processing after harvesting primarily encompasses two operational stages: first, primary processing, in which fresh latex is converted into crude rubber products such as block rubber and smoked sheets; second, product manufacturing, in which crude rubber is used as a raw material to fabricate tires and other rubber products through processes such as compounding and vulcanization. Pollutant types and emission characteristics vary accordingly between these two stages.

During the primary processing stage, wastewater constitutes a major environmental concern. Water consumption during this stage is substantial, with approximately 20-35 m3 of wastewater generated per ton of natural rubber processed (Ho et al., 2023). This wastewater exhibits a high organic load and strong acidity, with pollutants primarily originating from natural organic components in the latex, such as rubber hydrocarbons, proteins, and sugars, as well as chemical agents added to stabilize or coagulate the latex (Panda & Sarkar, 2020). Specifically, the application of sulfuric acid and ammonia increases the concentrations of nitrogen compounds and sulfates in wastewater (Diana, 2007). Specifically, sulfuric acid and ammonia increase nitrogen and sulfate levels in wastewater. Residual uncoagulated latex, lipids, and inorganic compounds further contribute to high chemical oxygen demand (COD) and biochemical oxygen demand (BOD) (Gouyon et al., 1993; Rosman et al., 2013). If discharged directly without effective treatment, such wastewater can induce hypoxia and eutrophication, imposing severe stress on the aquatic ecosystem (Ho et al., 2023).

Air emissions occur throughout the rubber processing stages. In primary processing, ammonia volatilization is the principal gaseous pollutant and may exert irritant effects on the surrounding environment and human health (Dunuwila et al., 2023; Komarudin et al., 2022). The use of sulfuric acid during coagulation can additionally generate sulfur dioxide (SO2) emissions (Putri et al., 2022). In the product manufacturing stage, emissions are more complex, dominated by volatile organic compounds (VOCs) (Huang et al., 2022). Aromatic hydrocarbons and halogenated organics released during compounding and vulcanization not only have high ozone-forming potential but may also pose carcinogenic and neurotoxic risks, threatening worker health and regional air quality (Bolden et al., 2015; Huang et al., 2022; Komarudin et al., 2022).

4.4.3 End-of-life stage: waste rubber management and recycling

Expanding natural rubber production has led to a surge in solid waste as products reach the end of their service life. End-of-life tires (ELTs) are the primary component of this waste stream, originating mainly from the automotive and transport sectors (Nunes et al., 2025). Global estimates indicate that approximately 800 million ELTs are generated annually (Mayer et al., 2024). Because rubber resists biodegradation, the prolonged accumulation of ELTs not only occupies land resources but also poses a major environmental challenge for solid waste management (Kazemi et al., 2023). In regions with underdeveloped recycling systems, illegal dumping and open-air stockpiling persist, further intensifying environmental and public health risks.

Globally, ELT management can generally be categorized into four approaches: uncontrolled disposal (including open dumping and landfilling), retreading for product reuse, material recycling, and energy recovery. Improper disposal poses the greatest environmental risks. Tire stockpiles are highly susceptible to fire, releasing toxic pollutants such as dioxins and polycyclic aromatic hydrocarbons (PAHs) (Goevert, 2024), while contaminated runoff generated during such incidents may pollute surface water and groundwater. In addition, accumulated water in discarded tires provides breeding habitats for disease vectors (Kordoghli et al., 2014). In recent years, many countries and regions have strengthened regulations governing landfill disposal and open stockpiling of ELTs while promoting more sustainable recycling practices. Nevertheless, uncontrolled disposal remains a challenge in regions where waste management capacity is limited.

Among resource management options, retreading extends tire service life by replacing worn tread while retaining the original tire casing. Compared with manufacturing new tires, retreading generally requires substantially lower energy and material inputs and is widely recognized as one of the most environmentally preferable strategies for ELT management, particularly for truck and aircraft tires (Wang et al., 2021).

When retreading is no longer feasible, material recycling becomes an important management option. Mechanical recycling produces ground tire rubber (GTR), which is widely used in road construction, sports surfaces, artificial turf, and rubber-modified asphalt (Liu et al., 2020). However, these applications are generally classified as downcycling and may release PAHs, volatile organic compounds (VOCs) (Formela, 2022; Hsieh et al., 2024), and trace metals such as zinc and lead during use (Milan & Jurowski, 2024). Long-term weathering and fragmentation of rubber particles may also generate microplastics, posing potential risks to terrestrial and aquatic ecosystems.

Pyrolysis has attracted increasing attention as a chemical recycling technology capable of recovering pyrolysis oil, gas, recovered carbon black, and steel from ELTs (Maganinho et al., 2025). Compared with landfill disposal or uncontrolled burning, pyrolysis has the potential to improve resource recovery and reduce dependence on virgin fossil resources. However, its environmental and economic performance depends on product quality, energy efficiency, and process optimization (Hossain et al., 2023).

Energy recovery utilizes ELTs as an alternative fuel in cement kilns or dedicated combustion facilities. Although this approach can reduce waste volume and partially substitute fossil fuels, inadequate emission control may release heavy metals such as zinc and cadmium, as well as black carbon particles, resulting in secondary environmental pollution (Kazemi et al., 2023). Within the framework of the circular economy, energy recovery is generally regarded as a complementary option when higher-value recovery pathways are not feasible.

Tire wear particles (TWPs) have recently emerged as an important environmental concern associated with rubber products. Generated through tire-road friction, TWPs range from the micrometer to nanometer scale and are now recognized as one of the largest sources of primary microplastics released into the environment (Mayer et al., 2024). These particles may adsorb persistent organic pollutants and heavy metals because of their large specific surface area. They also contain tire additives such as 6PPD, whose transformation product, 6PPD-quinone, has been shown to be highly toxic to aquatic organisms. TWPs can be transported through the atmosphere and surface runoff into soil and aquatic environments, where they have been widely detected in urban dust, river sediments, and marine ecosystems (Järlskog et al., 2020; Luo et al., 2021). Their persistence and widespread occurrence have made TWPs an emerging environmental concern associated with the rubber value chain.

Overall, retreading, material recycling, and energy recovery each contribute to reducing the environmental impacts associated with end-of-life tires, although their environmental performance depends on the technologies employed and the effectiveness of pollution control. Meanwhile, the growing recognition of tire wear particles highlights additional environmental pressures associated with rubber products and underscores the importance of continued technological innovation and integrated environmental management across the rubber value chain.

4.5 The interaction between climate change and the rubber industry

The relationship between the natural rubber sector and climate change is complex and bidirectional (Fig. 4.7). On the one hand, the production and processing of natural rubber, along with associated land-use change, can generate greenhouse gas emissions and contribute to climate change. On the other hand, rubber plantations, as perennial woody systems, can provide carbon storage and certain ecosystem-regulation functions under appropriate management, thereby contributing to climate change mitigation to some extent.

At the same time, rubber production systems are highly sensitive to climatic conditions. Changes in temperature, shifts in precipitation patterns, and the increasing frequency of extreme weather events can affect tree growth, latex yield cycles, and the overall stability of production systems.

Understanding this interaction from three key dimensions, namely greenhouse gas emissions, carbon sequestration and mitigation potential, and the impacts of climate change on production systems, is essential for assessing the rubber sector's role in the transition toward a bio-based economy.

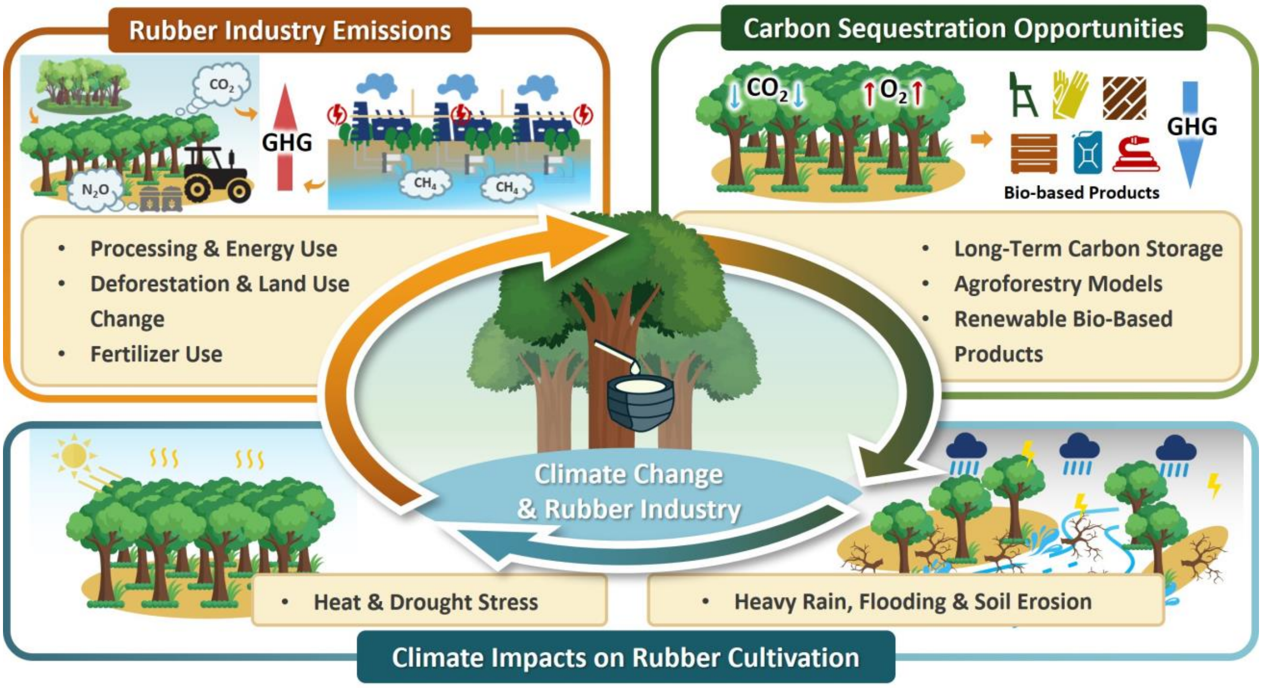


Fig. 4.7 Interactions between the rubber industry and climate change

4.5.1 Greenhouse gas emissions across the rubber value chain

From a value chain perspective, greenhouse gas (GHG) emissions in the rubber sector arise primarily from the processing and cultivation stages, with processing typically the dominant source. The transformation of natural rubber from latex into commercial products involves multiple steps, including coagulation, drying, smoking, pressing, and further processing, all of which are generally energy-intensive. As a result, electricity and fuel use (e.g., diesel and liquefied petroleum gas) constitute the main sources of GHG emissions during processing (Jawjit et al., 2010; Vidanagama & Lokupitiya, 2018). Emission intensities vary across product types due to differences in processing technologies. For example, the production of standard block rubber (STR20) is largely mechanized and electricity-intensive, whereas emissions from concentrated latex production are primarily associated with electricity consumption during centrifugation.

In addition to direct energy use, organic wastewater from rubber processing can emit methane (CH_4) under anaerobic conditions, representing an additional source of GHG emissions (Vidanagama & Lokupitiya, 2018). The choice of wastewater treatment technology is critical in determining emission levels. Open anaerobic treatment systems are typically associated with higher methane emissions, whereas closed systems can substantially reduce them (Tanikawa et al., 2019). In some major producing countries, relatively low technological levels at processing facilities and limited energy efficiency further increase the carbon intensity per unit of output. With continued growth in global demand for natural rubber, a lack of improvements in processing technologies and energy structures may lead to further increases in the sector's overall carbon footprint.

By comparison, emissions from the cultivation stage are driven not only by agricultural inputs but also by land-use change. During the expansion of rubber cultivation, the conversion of forests to plantations is often one of the largest sources of carbon emissions. This process entails substantial losses of aboveground biomass carbon and disturbances to soil organic carbon (SOC) pools, resulting in significant GHG emissions during land clearing and ecosystem conversion. These emissions are typically concentrated in the initial phase of land-use change and can generate high emission intensities over a short period, making them a major contributor to the life-cycle carbon footprint of rubber production (Cucci et al., 2025).

In addition, agricultural inputs used during the cultivation stage contribute to emissions. The production of synthetic fertilizers is energy-intensive and associated with considerable CO_2 emissions (Jawjit et al., 2010). Furthermore, nitrogen fertilizers applied to soils can lead to emissions of nitrous oxide (N_2O) through soil biogeochemical processes (Zhou et al., 2016), further increasing the GHG burden of rubber cultivation.

4.5.2 Carbon sequestration and mitigation potential

Assessing the role of the rubber sector in climate change solely from an emissions perspective provides an incomplete picture. During the cultivation stage, rubber plantations, as perennial woody systems, exhibit ecological characteristics distinct from those of annual crops. Over their lifespan, rubber trees accumulate biomass through photosynthesis, sequestering atmospheric carbon dioxide and contributing to carbon storage (Li et al., 2015; Qi et al., 2023; Yang et al., 2023). As stands mature, both above- and belowground biomass increase, resulting in progressive carbon accumulation within plantation biomass and soils (Guo et al., 2024; Saha et al., 2025). This carbon storage capacity represents an important ecological function of established rubber plantations, but does not, by itself, imply a net climate benefit from plantation expansion. In addition, under certain management conditions, rubber plantations can contribute to ecosystem regulation by influencing soil structure, water cycling, and local microclimates, thereby providing ecosystem services such as oxygen release, soil protection, and environmental regulation (Ling et al., 2025).

From a broader bio-based economy perspective, natural rubber, as a renewable biological material, has the potential to substitute for certain petroleum-based products. Its widespread use in tire manufacturing, industrial applications, and consumer goods suggests a potential for emissions reduction across material life cycles. When natural rubber replaces synthetic rubber, its biogenic carbon cycle may, in principle, reduce dependence on fossil carbon. Moreover, rubber production systems can generate additional by-products, such as rubber seeds for biodiesel production and rubberwood for timber and wood-based products at the end of plantation cycles (Gitz, 2020; Wagner et al., 2018), thereby improving overall resource-use efficiency.

However, the magnitude of these mitigation benefits is highly sensitive to land-use practices and production systems. When rubber expansion occurs at the expense of natural forests, large amounts of previously stored carbon may be released during land clearing and conversion, potentially offsetting or even exceeding the subsequent carbon sequestration by rubber plantations (Jawjit et al., 2010). In addition, the ecological limitations of monoculture rubber systems, particularly their limited structural complexity and biodiversity, may constrain their long-term environmental performance.

4.5.3 Climate change impacts on rubber cultivation systems

Climate change is increasingly imposing external pressures on rubber production systems. The growth and latex production of rubber trees are highly sensitive to climatic conditions, and changes in temperature, shifts in precipitation patterns, and the increasing frequency of extreme weather events directly affect growth cycles and production stability (Pinizzotto, 2021). Prolonged or recurrent drought can suppress tree growth, delay the onset of stable latex production, and reduce yields by inhibiting the expression of key enzymes involved in rubber biosynthesis, such as HMGR (Mohammadi Nodehi et al., 2025). Conversely, excessive rainfall may cause flooding or soil saturation, increasing the risk of landslides and soil erosion in certain regions (Pradeep et al., 2022). At the same time, warm and humid conditions favor the emergence and spread of pests and diseases, adding further uncertainty to production systems. Evidence also suggests that climate warming may alter phenological processes and facilitate the emergence of new disease dynamics, with potential implications for yield (Azizan et al., 2023).

The increasing frequency and intensity of extreme weather events further amplify the climate vulnerability of rubber production. Storms and strong convective weather can cause tree breakage, uprooting, and even large-scale stand damage. As a perennial crop, rubber requires a relatively long recovery period, and structural damage to plantations often results in prolonged reductions in production capacity, with persistent, path-dependent effects (Pradeep et al., 2022). This characteristic makes rubber production systems more sensitive to climatic shocks than many annual cropping systems.

Overall, the impacts of climate change on rubber production manifest as production disruptions, yield variability, and structural risks associated with extreme events. These effects tend to accumulate over time and exhibit clear regional heterogeneity, thereby constituting a major external constraint on the sustainability of the rubber sector under changing climatic conditions.

4.6 Summary

In the context of the bio-based economy, the natural rubber sector is transitioning from conventional agricultural production toward greater integration of value chains and supply chain governance. Global production patterns are gradually expanding beyond traditional Southeast Asian centers toward West Africa and the Greater Mekong Subregion, accompanied by shifts in industrial organization and trade structures. At the socio-economic level, the sector remains largely based on smallholder systems, which support rural livelihoods but are highly sensitive to market fluctuations and labor conditions. Natural rubber production spans multiple stages across its life cycle, including land-use change, agricultural inputs, industrial processing, and waste management, and generates combined impacts on ecosystems and environmental quality while interacting closely with climate change.

Within this transformation, the development of the natural rubber sector is characterized by both opportunities and constraints. As a renewable biological material and a perennial crop, natural rubber offers potential benefits for material substitution, resource efficiency, and carbon sequestration. However, its production is highly dependent on land resources and is associated with multiple environmental pressures, including biodiversity loss, ecological degradation, and climate-related risks. These factors jointly shape the sector's development pathways.

The role of the natural rubber sector in the bio-based economy can therefore be understood as a dynamic interaction between resource utilization and environmental constraints. This reflects the broader systemic complexity inherent in bio-based transitions and highlights the need to balance production, resource efficiency, and ecological sustainability in the sector's development.

5

Duckweed Industry

5.1 Introduction to duckweed

Duckweeds are tiny, free-floating aquatic plants that often form dense mats on still or slow-moving freshwater and are frequently mistaken for algae but are in fact the world's smallest flowering plants (Bog et al., 2019). They usually consist of small, oval- to lens-shaped fronds and, depending on the genus, may bear none, one, or several roots. Rather than relying primarily on seed production, duckweeds reproduce at exponential rates, mainly through vegetative budding from specialized reproductive pouches. Hence, they are also among the fastest-growing vascular plant groups, capable of doubling within 24-48 hours. (Acosta et al., 2021; Bog et al., 2020).

Duckweeds are increasingly recognized as an unusually versatile plant group as their biological traits make them relevant far beyond basic aquatic ecology. Its dry biomass typically contains 20–35% protein, can reach around 45% under favorable cultivation conditions, and has reached 50.89% in Wolffia arrhiza under artificial conditions (Xu et al., 2021; Hu et al., 2022; Appenroth et al., 2018). Under optimal conditions, duckweed has been reported to yield 10–18 t protein ha^{-1} yr^{-1}, compared with 0.6–1.2 t protein ha^{-1} yr^{-1} for soybean in Europe, representing roughly 8–30 times higher protein productivity per unit land area (Nieuwland et al., 2021). Its starch content can reach up to 75.9% of dry weight, with estimated production of about 28 t starch ha^{-1} yr^{-1} on average and up to 30.8 t ha^{-1} yr^{-1} under highly optimized laboratory conditions, far exceeding the roughly 6 t ha^{-1} yr^{-1} often cited for corn starch production (Yang et al., 2022; Guo et al., 2023). At the same time, duckweed absorbs large amounts of nitrogen and phosphorus from the water, helping reduce eutrophication, while also taking up hazardous heavy metals, organic pollutants, and microplastics in contaminated waters (Thingujam et al., 2024). Duckweed is also emerging as a molecular-farming platform for recombinant proteins and other applications (Kang et al., 2025). An edible vaccine against avian infectious bronchitis virus (IBV) produced in duckweed induced strong immunity and achieved 100% survival against lethal viral challenge, matching or exceeding a commercial live-attenuated vaccine against the same virus (Tan et al., 2025; Tan et al., 2022).

Duckweed development has shifted from scattered research into a more organized research and industrial field. In 2011, the first International Conference on Duckweed Research and Applications was held in Chengdu, China, and established a recurring international forum every two years for duckweed research and applications (Zhao et al., 2012; Oláh et al., 2023). China also became an important center for duckweed resource preservation, with the Chengdu Institute of Biology establishing one of the world's largest living duckweed germplasm collections and databases from more than 800 collected materials . In 2024, the Duckweed Research and Development Innovation Alliance was established at Jiangnan University in Wuxi, bringing together 26 universities, research institutes, and companies to coordinate duckweed-related research and development . Since the late 2010s, commercial activity has also expanded, with more than 20 companies worldwide working on duckweed-based products (Acosta et al., 2021).

In a world facing intertwined pressures from food security, land-use efficiency, pollution control, renewable energy production, and ecosystem restoration, duckweed offers a rare example of a biological system that can address multiple problems through simple pathways. As Academician Xu Zhihong argued in his written address to the Third Seminar on Duckweed Resource Development and Utilization, the industrial significance of duckweed lies not simply in replacing imported agricultural products or supplementing conventional crops, but in opening an additional pathway for plant production. Because duckweed can be cultivated without conventional arable land, its successful scaling could partially loosen plant production from land dependence and challenge the land-based agricultural model that has shaped human society since the rise of farming 12,000–13,000 years ago .

Unlike more established biobased industries with decades of accumulated commercial infrastructure, duckweed cultivation and processing is still in the early stages of industrialization. This chapter is therefore intended less as an account of mature, settled practice and more as an introduction to this emerging industry for readers unfamiliar with it, mapping where current research, pilot projects, and early commercial ventures are actively pushing the field.

5.1.1 Classification and morphology

Traditionally treated as the family Lemnaceae, duckweeds are a highly reduced lineage of aquatic angiosperms adapted to life at or just below the water surface (Acosta et al., 2021). Under current taxonomy, they are placed in Kingdom Plantae, phylum Angiosperms, class Monocots, order Alismatales, family Araceae, subfamily Lemnoideae, and comprise five genera and 37 species (Sree et al., 2017). These five genera — Spirodela, Landoltia, Lemna, Wolffiella, and Wolffia — differ in morphology and degree of structural reduction (Bog et al., 2019). Spirodela is generally the largest, with broader fronds and roughly 7 roots; Landoltia is smaller and less robust, with broad fronds and 2-7 roots; Lemna is smaller and simpler, typically with a single root per frond; Wolffiella is rootless and more elongated or strap-like; and Wolffia is the most reduced, rootless, and often nearly globose to oval, and includes the smallest flowering plants known (Smith et al., 2024; Acosta et al., 2021; Romano et al., 2021; Edelman et al., 2020). Spirodela, Landoltia, and Lemna produce daughter fronds from two lateral vegetative pouches, whereas Wolffiella and Wolffia develop from a single basal pouch (Acosta et al., 2021). Because duckweeds are so morphologically reduced, modern classification combines visible morphology with developmental structure and molecular phylogeny, even though practical keys still use traits such as frond shape, size, and root number for identification (Fig. 5.1; Bog et al., 2019; Bog et al., 2020; Acosta et al., 2021).

Current molecular-taxonomic work supports treating the five duckweed genera as distinct monophyletic lineages rather than loose descriptive groupings (Bog et al., 2019). Recent evolutionary analyses place these genera in the sequence Spirodela -> Landoltia -> Lemna -> Wolffiella -> Wolffia, with Spirodela representing the oldest extant genus and Wolffia being the most derived (Fang et al., 2025). This sequence is associated with an overall trend toward decreasing body size and progressive root loss, so the visible differences among genera can also be read as an evolutionary gradient of structural reduction (Fang et al., 2025). This broader phylogenetic pattern is reinforced by recent work showing that duckweeds evolved back into water after an earlier transition onto land, contrary to the common understanding of most evolutionary pathways. This was accompanied by progressive reduction of terrestrial traits, including body size, roots, stomatal responses, and lignocellulosic structure, while some pathways, such as flavonoid biosynthesis, expanded under floating aquatic conditions, placing genus-level differences within a directional evolutionary pathway of reduction and specialization (Fang et al., 2025).

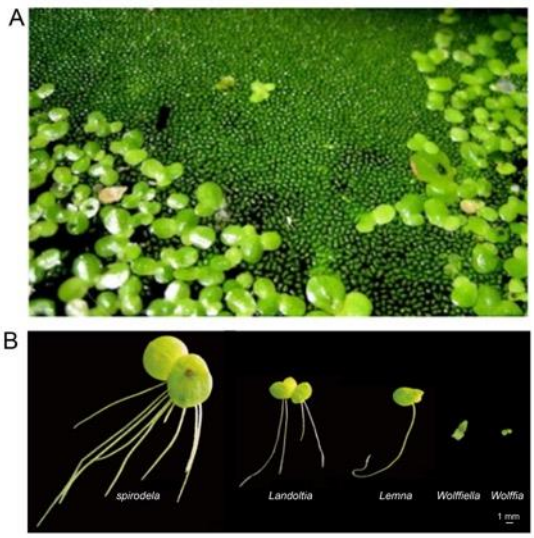


Fig. 5.1 Morphology of duckweed. (A) A dense duckweed mat on the water surface, showing the characteristic free-floating growth habit. (B) Morphological comparison of the five duckweed genera: Spirodela, Landoltia, Lemna, Wolffiella, and Wolffia, illustrating the progressive reduction in frond size and root number across genera. (B) Scale bar = 1 mm.

5.1.2 Environmental adaptability

A major reason duckweed is of interest in environmental and bioeconomy contexts is its combination of rapid growth and broad environmental adaptability. Its strong physiological plasticity and rapid population growth make it highly adaptable to a wide range of environments (Ziegler et al., 2023). Duckweed exhibits substantial thermotolerance across climatic zones, including temperate, cold-temperate, and subarctic habitats (Hitsman et al., 2020). Although optimal growth for many species generally falls between 19 and 30 °C, this varies by species, and temperature strongly influences biomass accumulation, protein synthesis, and photosynthetic efficiency (Ujong et al., 2025). Duckweed also shows broad tolerance to water chemistry, with the capacity to acclimate across a wide pH range from acidic to alkaline conditions, although optimum growth generally occurs between pH 5 and 8 (Ziegler et al., 2023). Additionally, light availability further shapes performance. Increased light intensity generally promotes growth, but duckweed can also maintain growth under low-light conditions below 25 μmol m^{-2} s^{-1} (Yin et al., 2015; Femeena et al., 2023). Its nutrient tolerance is similarly broad. Duckweed can grow well in highly enriched water, including environments with high nitrogen (N) and phosphorus (P) concentrations (Cheng et al., 2002), while also maintaining growth and accumulating high biomass under nutrient-deficient conditions (Huang et al., 2014; Appenroth et al., 2021; Guo et al., 2025).

5.1.3 Ecological distribution

Duckweeds are primarily associated with freshwater habitats such as ponds, lakes, ditches, and other still or slow-moving waters (Mateo-Elizalde et al., 2023). Rather than occupying the rooted-sediment niche used by many emergent or submerged aquatic plants, they float on or just below the water's surface (Ziegler et al., 2023). This allows them to spread quickly across calm aquatic surfaces and makes them especially well adapted to shallow, nutrient-rich freshwater systems. At the family level, duckweeds are nearly cosmopolitan in distribution (Müller et al., 2025). They occur in warm tropical and subtropical waters (Chen et al., 2021) as well as in cold temperate and subarctic freshwater systems (Ziegler, 2024), although they are generally absent from polar regions and deserts (Tippery & Les, 2020). Nevertheless, individual taxa differ markedly in their geographic distributions. For example, Spirodela polyrhiza is widely recorded in cold temperate North America, whereas Landoltia punctata and Wolffia globosa are more strongly associated with tropical and subtropical regions in Asia and Africa (NatureServe, n.d.; Plants of the World Online, n.d.-a, n.d.-b; Yosef et al., 2022). However, these patterns may not reflect climate alone, because dispersal by migratory birds and other vectors can also shape observed distributions.

Duckweed distribution is not static, and recent evidence suggests that some taxa are already shifting in response to climate change. On a global biogeographic scale, duckweed exhibits a broad but highly heterogeneous spatial distribution, and warming is expected to reorganize suitable habitats for different species. Mesothermic taxa appear to be expanding northward into higher latitudes and elevations. For example, Lemna turionifera, historically associated with more southern latitudes, has shifted more than 200 km northward within northern Eurasia's permafrost zone, likely due to increased extreme summer heat events within its original range (Bobrov et al., 2025). Climate change may also affect competitive dynamics among duckweed species. In Europe and the UK, the spread of the invasive Lemna minuta has been linked to rising winter temperatures and eutrophication, with its high resource-use efficiency enabling it to occupy niches previously held by native Lemna minor under warming conditions (Paolacci et al., 2018). Because duckweed species occupy distinct climatic niches and differ in their thermal tolerances and geographic distributions, projected responses to future climate change are expected to remain species-specific rather than uniform across the family (Rodríguez-Merino et al., 2018; Volkova et al., 2024).

5.2 Duckweed primary application scenarios

5.2.1 The global challenge

Our food systems begin with plants. Most of the calories in human diets, and a large share of the proteins, edible oils, vitamins, minerals, and fiber that sustain human life, originate in plant biomass, whether consumed directly or first routed through animals and processed foods (Martin et al., 2018; Huang et al., 2020). Over the past century, agriculture has been transformed at a scale that would once have seemed impossible. Global primary crop production reached 9.6 billion tons in 2022, and total food supply available for human consumption reached 2,985 kilocalories per person per day that year, for a world population that surpassed 8 billion on 15 November 2022 (FAO, 2024; GOV.UK, 2024; United Nations, 2022). Yet in 2023, around 733 million people still faced hunger, and more than 2 billion people remained deficient in essential vitamins and minerals (FAO et al., 2024; Stevens et al., 2022). This mismatch is not only nutritional. Agrifood systems account for about one-third of anthropogenic greenhouse gas emissions (FAO, 2024), and agriculture accounts for about 70% of global freshwater withdrawals (UNESCO, 2024).

The dominant structure of the modern food system remains far older than the world it is expected to feed. Human societies still rely primarily on terrestrial seed crops whose domestication began about 12,000-11,000 years ago, and the system built around them is still organized around the storage and consumption of grain (Larson et al., 2014; Bevan, 2020). Grain stores well, but that same logic confines food production within a narrow biological frame. Cultivation depends on arable land, seasonal cycles, suitable temperature and water conditions, and the successful completion of reproductive growth (Porker et al., 2020). In cereal systems, only the grain is finally harvested as food, and that grain commonly represents roughly one-third to one-half of the aboveground biomass (Porker et al., 2020; Saito et al., 2021).

Over the past century, breeding and agronomy have already pushed these crops hard toward traits that improve harvest and yield, especially shorter stature, greater lodging resistance, and higher harvest index. Much of the yield gain of the Green Revolution came from directing a larger share of biomass into grain rather than from fundamentally changing the biological structure of the crop itself (Cheng et al., 2024; Spielmeyer et al., 2002; Porker et al., 2020). That pathway delivered very large gains, but it also means the ceiling is now much harder to lift. Around 84% of the rice-growing area and 56% of the wheat-growing area are now under ceiling pressure, and across 24-39% of the world's maize-, rice-, wheat-, and soybean-growing areas, yields either never improved, stagnated, or collapsed (Gerber et al., 2024; Ray et al., 2012). Climate change makes this dependence on fixed environmental windows even more dangerous. Rising temperatures, shifting rainfall, drought, and extreme heat disrupt flowering, grain filling, and final harvest. On average, each 1°C increase in global mean temperature reduces yields by about 6.0% for wheat, 7.4% for maize, 3.2% for rice, and 3.1% for soybean (Zhao et al., 2017). Droughts and extreme heat already reduce national cereal production by about 9-10% globally, and drought reduces both yield and harvested area (Lesk et al., 2016). Additionally, the current crop system depends heavily on fertilizers. More than half of the nitrogen added to cropland is not recovered in harvested crops, and phosphorus use efficiency remains below 50% across the major staple crops, leaving large nutrient surpluses that are readily lost through runoff and leaching. (Lassaletta et al., 2014; Liu et al., 2025)

These constraints become sharper once crops are routed through livestock. Feed protein becomes the bottleneck because large-scale animal production depends on concentrated protein inputs like soybean meal (Pexas et al., 2023; Holtshausen et al., 2021). Most global livestock systems rely heavily on soybean meal and long-distance soy flows. For example, imports from South America support European livestock production, thereby exposing feed systems to trade volatility and environmental spillovers (Pexas et al., 2023; de Visser et al., 2014). In China, this has become especially inseparable from food security itself. Feed grain demand has risen with meat production, domestic soybean supply remains far below demand, and soybean self-sufficiency was only 14.2% in 2021, leaving the livestock system exposed to external shocks (Liu et al., 2026). At the same time, the waste stream from livestock has become one of the most serious pressures on water quality worldwide (Sampat et al., 2021; Wurtsbaugh et al., 2019). When manure and fertilizer release excess nitrogen and phosphorus into rivers, lakes, and coastal waters, they drive eutrophication and broader ecological decline (Wurtsbaugh et al., 2019; Sampat et al., 2021). Agriculture, human sewage, and aquaculture are becoming increasingly dominant sources of nutrient delivery to surface waters and coastal seas worldwide, and under future scenarios can account for up to 80% of nutrient delivery; coastal eutrophication and hypoxia are still spreading, including across Asia and with growing emergence in South America and Africa (Beusen et al., 2022; Dai et al., 2023).

Water pollution extends far beyond nutrient runoff. Rivers, lakes, groundwater, and even drinking-water sources now carry a widening mixture of hazardous substances, like persistent organic pollutants, PFAS, pharmaceuticals, pesticides, trace metals, and microplastics (Li et al., 2024). These contaminants need to be intercepted and removed because many persist in the environment and remain difficult to eliminate once they enter aquatic systems and drinking-water pathways (Hale et al., 2022). Some of the most concerning pollutants combine persistence, mobility, and toxicity. PFAS, for example, are highly persistent, harmful to aquatic organisms at very low concentrations, and can accumulate in organisms through food webs, while persistent organic pollutants more broadly resist degradation and remain bioaccumulative across water systems and biota (Brunn et al., 2023; Aravind kumar et al., 2022). On top of that, global energy demand continues to rise, yet almost 75% of it is still expected to be met by fossil fuels in 2030 (IEA, 2024). Alternative sustainable energy sources are therefore essential, and renewable bioenergy is especially important as it is already the largest source of renewable energy use globally, accounting for more than half of global renewable energy use in 2023 (IEA, n.d.).

Duckweed stands out as a plant that can engage with all these issues at once. Rather than waiting for seasonal seed set, it propagates clonally, can double biomass in 48-72 hours under favorable conditions, and allows repeated harvest of whole vegetative biomass rather than grain alone (Mateo-Elizalde et al., 2023; Jurga et al., 2026). Its biomass can contain up to 45% protein, with a well-balanced amino acid profile, along with starch, minerals, and other bioactive compounds, making it nutritionally competitive with conventional crops (Ujong et al., 2025; Habeeb et al., 2025). At the same time, duckweed absorbs dissolved nutrients and other pollutants that can be used as phytoremediation systems where its biomass can be used for downstream products as food, feed, fertilizer, or bioenergy feedstock (Jurga et al., 2026; Zhou et al., 2023). This gives duckweed unusual potential in circular agronomy systems. In the following section of 5.2, we will examine its four primary application scenarios in greater detail: as animal feed, as a wastewater treatment tool, as a biofuel feedstock, and as a human food source (Fig. 5.2).

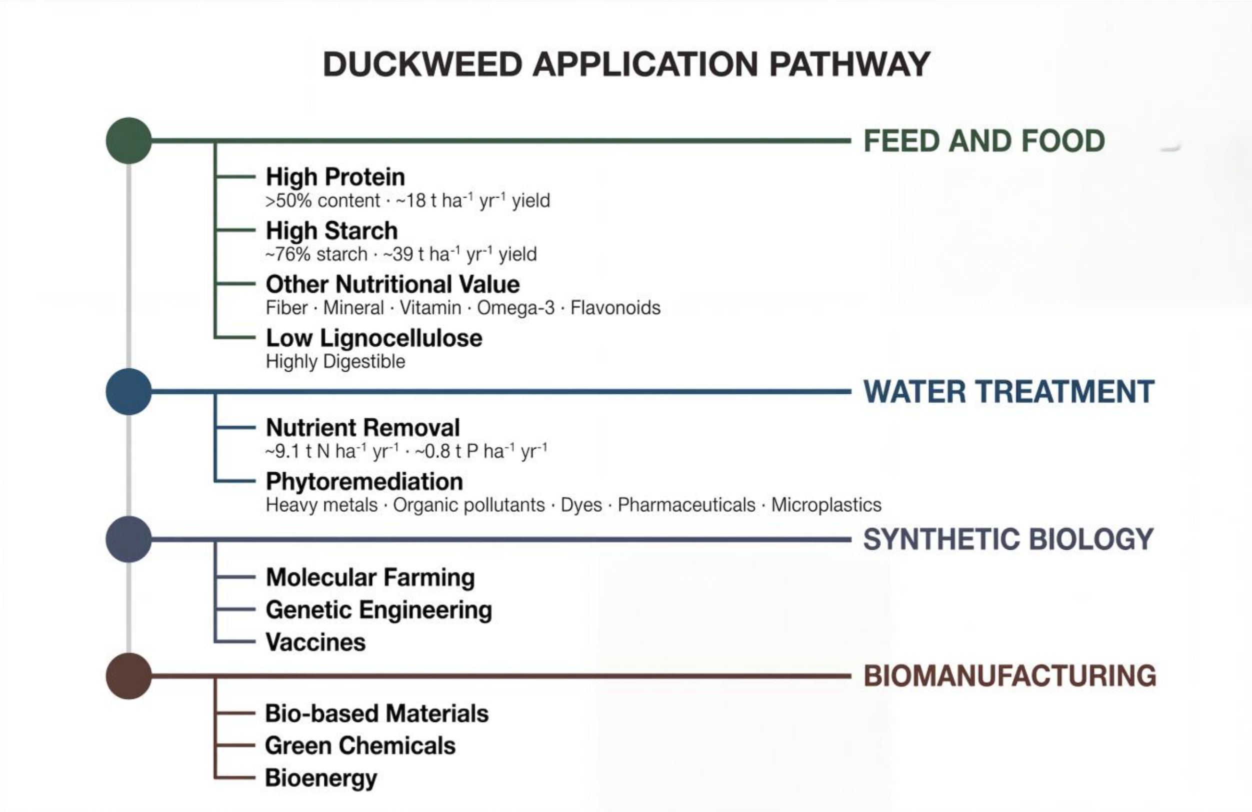


Fig. 5.2 Duckweed application pathway

5.2.2 Feed and food crop

Plant protein underpins almost all food-protein systems, and soybean is the clearest benchmark because it remains the dominant commercial source of concentrated plant protein in both food processing and animal feed (Qin et al., 2022; Guo et al., 2022). However, soybean is still produced through a conventional terrestrial seed-crop model whose concentration and annual output remain constrained by arable land, fertilizer dependence, seasonality, and climatic instability. Its seeds typically contain about 36-40% protein, and the world average soybean protein yield is roughly 1.00-1.11 t ha^{-1} yr^{-1} (Qin et al., 2022; Toyoda et al., 2026). Duckweed enters this comparison through a different production logic. Instead of waiting for seed formation, it produces fast-renewing vegetative biomass that grows and renews on much shorter cycles and can be harvested repeatedly, so annual output is not tied to a single reproductive harvest (Ujong et al., 2025; Appenroth et al., 2018). Its dry biomass commonly contains about 20-35% protein, reaches around 45% under favorable cultivation, and in Wolffia arrhiza has reached 50.89% under artificial conditions (Xu et al., 2021; Hu et al., 2022; Appenroth et al., 2018). In addition to protein content, W. arrhiza on average yields about 2.08 t protein ha^{-1} yr^{-1}, which is roughly twice the global soybean protein yield per unit of land (Xu et al., 2021; Toyoda et al., 2026; Qin et al., 2022). Under optimal conditions, duckweed has been estimated to yield 10–18 t protein ha^{-1} yr^{-1}, compared with 0.6–1.2 t protein ha^{-1} yr^{-1} for soy in Europe, equivalent to roughly 8–30 times higher protein productivity per unit of land area (Nieuwland et al., 2021). Duckweed protein is also comparable to soybean protein in quality because it contains all essential amino acids in a broadly balanced pattern, with lysine levels close to those of soybean. Additionally, a measured digestible indispensable amino acid score of 0.75 in Wolffia arrhiza further shows that duckweed protein is digestible and nutritionally valuable (Appenroth et al., 2018; Hu et al., 2022).

With strong metabolic plasticity, duckweed can also function as a starch crop, the primary source of energy in both food and feed systems (Guo et al., 2025). Under nutrient-limited cultivation, duckweed can rapidly redirect carbon allocation toward starch accumulation, thereby turning the frond itself into a starch-rich, harvestable biomass (Guo et al., 2025; Yang et al., 2022). In an automated duckweed plant factory developed for high-starch production, starch content in Landoltia punctata exceeded 45% after 3 days of cultivation, and starch productivity exceeded 9.4 g m^{-2} d^{-1}, equivalent to about 30.8 t ha^{-1} yr^{-1}. The starch content also increased from about 6.5% to 75.9% of dry weight within only 10 days (Guo et al., 2023). On the same land basis, 30.8 t ha^{-1} yr^{-1} is more than 7 times the global maize starch benchmark of roughly 4.2 t ha^{-1} yr^{-1}, calculated from average global maize yield and kernel starch content (USDA FAS, 2026; FAO, n.d.-a). Traditional starch crops accumulate starch mainly in grain, while much of the rest of the plant remains as stem, leaf, husk, and cob residues after harvest. Duckweed leaves little comparable waste behind, as starch accumulates throughout the plant, which can all be harvested and used (Guo et al., 2025).

The ability to produce high levels of protein and starch makes duckweed especially attractive as animal feed. Feed value depends on composition, but it also depends on how much of the biomass remains nutritionally accessible instead of being locked into structural fiber. Even though duckweed is among the plants that produce the most biomass, the combined fraction of cellulose, hemicellulose, pectin, and lignin in its biomass is much lower than in other high-biomass crops, and under certain cultivation conditions, it declines even further. In Landoltia punctata, this combined structural fraction fell from 27.2% to 7.3% of dry biomass within 10 days, whereas in crops such as maize, the comparable structural fraction is around 70%. This means that a much larger share of duckweed biomass remains nutritionally accessible rather than being locked into hard structural tissue. The plant therefore offers denser, more digestible feed biomass than many conventional high-biomass crops (Guo et al., 2025; Ge et al., 2012).

Duckweed also offers a distinct feed production pathway because it can be cultivated directly from runoff and wastewater. Nitrogen and phosphorus are exactly the nutrients duckweed requires for rapid growth and protein formation, which are abundant in agricultural runoff, livestock wastewater, and other eutrophic waters. They can be used directly as growth media to produce usable biomass. A cultivation system was explicitly designed around wastewater containing total nitrogen of 4-40 ppm and total phosphorus of 1-6 ppm, with duckweed harvested repeatedly while it grows on the water surface. The system used 0.5 m-deep pools with a 6-day hydraulic retention time, CO_2-enriched to 500-3,000 ppm (avg. 1,560 ppm), at 13-32°C (avg. 24.41°C), in Kunming, Yunnan (25.04°N, 102.72°E). Under that system, starch and crude protein yields can each reach 12.75 t ha^{-1} yr^{-1}, and the highest crude-protein yield reaches 15.9 t ha^{-1} yr^{-1} while starch yield at 4.65 t ha^{-1} yr^{-1} (Zhao et al., 2014). A related patent on micro-polluted surface water shows that duckweed can still take up nutrients when nitrogen and phosphorus are present only at relatively low concentrations. It can still accumulate starch and can be harvested and further processed into food or feed (Zhao et al., 2018). Recent work also shows that duckweed can support indirect feed production through insects. In a circular aquaculture experiment, duckweed was used to rear black soldier fly larvae, and 33% of the African catfish feed was replaced with the resulting larval meal, with no significant differences in survival, biomass, feed conversion ratio, or specific growth rate. This suggests that duckweed can help convert aquaculture nutrients into insect protein and return them back into fish production (Bartucz et al., 2026)

Beyond its role in animal feed, duckweed also has real potential as a human food. In fact, species of Wolffia have been cultivated and eaten for more than 25 years in Laos, Myanmar, and Thailand, where they are sold and cooked as vegetables under local names such as khai nam, kai-pum, and kai nhae (EFSA, 2021; Xu et al., 2021). As a part of established food culture, duckweed has immense nutritional value for humans. In addition to protein and starch, duckweed is also rich in dietary fiber, unsaturated fats, minerals, vitamins, and beneficial plant compounds (Xu et al., 2021; Appenroth et al., 2018). In Wolffia, dietary fiber is about 25% of dry weight and mineral-rich ash averages about 18%, while edible W. globosa also reports polyphenols, iron, zinc, and vitamin B12 in abundance (Appenroth et al., 2018; Kaplan et al., 2019). Among these compounds, α-linolenic acid, an essential omega-3 fatty acid that the body must obtain from food, is the main fatty acid in Wolffia (Appenroth et al., 2018; NIH ODS, 2022). Bioactive vitamin B12 that is needed for healthy blood cells, nerve function, and DNA synthesis has also been reported in W. globosa. This is particularly notable since vitamin B12 is usually associated mainly with animal-derived foods rather than plants (NIH ODS, 2023; Sela et al., 2020). Duckweed also provides important pigments and vitamins, such as lutein and zeaxanthin, which are associated with eye health; β-carotene, which can be converted into vitamin A; and α-tocopherol, the main form of vitamin E. In Wolffia, lutein is the dominant carotenoid, and β-carotene, zeaxanthin, and α-tocopherol have also been reported (Appenroth et al., 2018; Xu et al., 2021; NIH ODS, 2025; NIH ODS, 2021). Duckweed also provides a broad mineral profile, including calcium, potassium, magnesium, phosphorus, iron, zinc, iodine, manganese, and selenium (Appenroth et al., 2018; Golob et al., 2021). Among these, selenium is especially important because it supports thyroid function and antioxidant defense, and duckweed converts accumulated selenium largely into organic forms, which is generally easier for the body to use than inorganic selenium (Kieliszek & Serrano Sandoval, 2023).

Regulatory acceptance has already moved beyond experimental discussion. In the European Union, fresh plants of Wolffia arrhiza and/or Wolffia globosa were authorized as a traditional food from a third country in 2021, protein concentrate from Lemna gibba and Lemna minor was authorized as a novel food in 2024, and whole plants of Lemna gibba and Lemna minor were authorized as a novel food in 2025 (European Commission, 2021; European Commission, 2024; European Commission, 2025). Beyond Europe, the FDA also issued a "no questions" GRAS response for Lemna minor leaf protein in 2026 for use across a wide range of foods (FDA, 2026). Commercialization is still in its early stages, but it is no longer hypothetical. A conservative scan already shows at least ten identifiable duckweed food offerings or ingredient lines worldwide spanning both Wolffia and Lemna, with products now appearing as fresh biomass, dried biomass, powders, drink mixes, and extracted protein ingredients for use in a broad range of processed foods (Government of Japan, 2025; FDA, 2026).

5.2.3 Water treatment

Nutrient-rich runoff and wastewater are among the main drivers of eutrophication because excess nitrogen and phosphorus stimulate algal overgrowth and oxygen depletion in receiving waters (US EPA, 2023; USGS, 2019). Duckweed is exceptional at removing dissolved nutrients directly from the water column (Zhou et al., 2023; Chen et al., 2018). In pilot-scale eutrophic wastewater, total nitrogen fell from 6.0 mg L^{-1} to below 0.5 mg L^{-1} and total phosphorus fell from 0.56 mg L^{-1} to below 0.1 mg L^{-1}, with maximum removal efficiencies of 99.1% for TN and 90.8% for TP in polyculture (Chen et al., 2018). At the annual scale, duckweed biomass can accumulate up to 9.1 t N ha^{-1} yr^{-1} and 0.8 t P ha^{-1} yr^{-1} (Zhou et al., 2023). This removal capacity extends across a wide concentration range. In high-concentration diluted livestock wastewater, duckweed removed 83.7% of total nitrogen and 89.4% of total phosphorus over eight weeks (Xu et al., 2011). At low concentrations, duckweed also performs well in micro-polluted water. With $NH4^+$-N at 1.65–2.01 mg L^{-1} and TP at 0.32–0.47 mg L^{-1}, Landoltia punctata still achieved 99.4% nitrogen removal and 93.5% phosphorus removal (Li et al., 2022).

Water hyacinth, Eichhornia crassipes, is a large free-floating aquatic plant and is often treated as a benchmark in wastewater treatment, as it has the strongest wastewater-treatment performance among common floating macrophytes and produces more than 140 t ha^{-1} yr^{-1} of biomass. Against that benchmark, duckweed remained highly competitive. In a year-long pilot comparison, duckweed had the same total nitrogen recovery rate as water hyacinth, 0.4 g m^{-2} d^{-1}, and only a slightly lower total phosphorus recovery rate of about 0.1 g m^{-2} d^{-1}. In the same system, even though duckweed produced only about half as much biomass the quality of the duckweed biomass is much higher than that of water hyacinth. It contained 33.34% crude protein, 25.80% amino acids, 40.19% starch, 1.24% phosphorus, and 2.91% flavonoids, and had lower fiber content than water hyacinth. The biomass of duckweed produced had higher nutritional quality than the bulky and fibrous biomass of water hyacinth (Zhao et al., 2014). In eutrophic wastewater, starch content still reached 24.8% in Spirodela polyrhiza, 32.3% in Lemna minor, 39.3% in Landoltia punctata, and 36.3% in polyculture (Chen et al., 2018). In wastewater-grown Lemna minor, biomass also contained 32.3% protein and 10–36% starch (Ge et al., 2012).

This difference in biomass quality gives duckweed an advantage in systems primarily to clean water as it can also produce materially useful biomass. In a field-scale case treating typical village wastewater, the effluent transitioned from initially non-compliant to meeting China's first-grade discharge standard within six days. That includes parameters such as TN, TP, COD and turbidity. Duckweed was grown on sewage containing 4–40 mg L^{-1} TN and 1–6 mg L^{-1} total phosphorus and reduced to under 15 mg L^{-1} of TN and 0.5 mg L^{-1} of TP. Nitrogen and phosphorus are removed during conversion into starch- and protein-rich biomass, with annual starch and crude protein yields each reaching 12.75 t ha^{-1} yr^{-1} (Zhao et al., 2014). In this way, nutrients that would otherwise remain in wastewater and drive eutrophication are captured in harvested biomass and can be cycled back into productive use through feed, food, or fertilizer. However, duckweed grown for nutrient recovery from wastewater must be distinguished from duckweed intended for human food. Wastewater-grown biomass can accumulate heavy metals, pathogens, pharmaceuticals, pesticides, and persistent organic pollutants, so food-grade cultivation requires clean water sources and does not interchange with nutrient-recovery biomass without contaminant testing.

In addition to recovering excess nitrogen and phosphorus from eutrophic water, duckweed can also be used to treat water contaminated with hazardous pollutants. Unlike the nutrients discussed above, these substances are not meant to be present in natural water bodies in the first place, and many remain toxic even at low concentrations after entering aquatic systems through industrial effluents, mining drainage, textile and dye wastewater, hospital wastewater, domestic sewage, and mixed municipal flows. These pollutants commonly include heavy metals and metalloids, organic pollutants, dyes, pesticides, pharmaceuticals, personal care products, and microplastics (Ekperusi et al., 2019; Zhou et al., 2023). For duckweed to grow on these waterbodies, contaminant exposure can suppress frond growth, chlorophyll content, and photosynthetic performance; therefore, removal efficiency depends strongly on species or strain, pollutant identity, concentration, pH, and exposure time. Even under that stress, many duckweed systems remain active enough to keep intercepting and accumulating pollutants from the water column (Zhou et al., 2023; Yang et al., 2024). This also extends to resource recovery. Rare earth elements and yttrium are widely used in high-technology products, and their release into aquatic environments is becoming a growing concern. Naturally grown duckweed can strongly concentrate these elements from surrounding water, which can convert them into biomass that can be processed for downstream use instead of dispersed in water systems (Zocher et al., 2022)

The reported removal range is already broad across very different contaminant classes. Pb removal reached up to 98.1% and Cd up to 84.8% in Lemna gibba, while Lemna minor continued removing Cr(VI) in continuous flow across 0.25–5.0 mg L^{-1} (Verma and Suthar, 2015; Uysal, 2013). Arsenic removal by Lemna minor exceeded 70% at 0.5 mg L^{-1}, and duckweed-based systems removed more than 90% of paracetamol, caffeine, and triclosan (Goswami et al., 2014; Li et al., 2017). Methylene blue removal reached 80.56% within 24 hours (Imron et al., 2019). Microplastics, such as polyethylene particles, adhere to Lemna minor surfaces at up to 7 particles mm^{-2}, allowing floating duckweed to capture pollutants that are otherwise difficult to intercept once dispersed on the water surface (Mateos-Cárdenas et al., 2019; Rozman and Kalčíková, 2022).

However, biomass grown in these waterbodies should not be recycled into food, feed, or routine fertilizer use once it contains heavy metals or persistent organic contaminants (Liu et al., 2021; Mukherjee et al., 2025). In some cases, it can still be directed into carefully managed industrial energy pathways, including anaerobic digestion or thermochemical conversion, but only with controlled handling of contaminated residues (Kotamraju et al., 2023; Mukherjee et al., 2025). The broader implication is that duckweed converts dispersed contaminants in water into harvestable biomass and concentrated residues that can then be removed from the system and handled in a controlled manner downstream (Liu et al., 2021; Mukherjee et al., 2025).

5.2.4 Synthetic biology

Synthetic biology applications of duckweed span two related dimensions: its utility as a model plant system, and its development as an engineered chassis for the expression of recombinant biological products. Its tiny body plan, rapid clonal propagation, simple cultivation, and direct contact with the surrounding medium make it highly tractable for controlled experiments on growth, development, physiology, nutrient responses, toxicology, and plant-environment interaction. Its small size and fast multiplication make it easy to maintain large numbers of genetically similar plants under uniform conditions, which is especially useful in high-throughput or screening-based work where terrestrial plants are slower, bulkier, or harder to standardize. At the same time, expanding genome and transcriptome resources have strengthened duckweed's role in systems-level plant biology, pushing it beyond the status of a convenient aquatic test plant into a more mature experimental system (Acosta et al., 2021; Thingujam et al., 2024).

As a platform organism, duckweed is valuable because it can be engineered as a bioproduction chassis (Yin et al., 2026). Reviews describe it as a promising plant bioreactor due to its rapid growth, high biomass productivity in small areas, simple processing, and compatibility with contained water-based cultivation, which avoids many of the land-use constraints associated with field-grown plants (Yang et al., 2021). Genetic access is also improving in practical ways. A frond transformation system in Lemna minor established a simpler Agrobacterium-mediated route for stable genetic engineering and showed that duckweed could be used for targeted metabolite engineering by increasing stigmasterol production through CYP710A11 overexpression (Yang et al., 2018). Later work improved the speed of transformation in Lemna minor and showed that duckweed-expressed chicken IL-17B remained biologically activating better transformation efficiency to a concrete biotechnological use (Tan et al., 2022). The endogenous duckweed promoter LpSUT2 also performed more strongly than 35S under antibiotic stress, with eGFP expression 1.76 times higher at 100 mg L^{-1} G418 and 6.18 times higher at 500 mg L^{-1}, while avoiding the stress-associated methylation that weakened 35S activity (Wei et al., 2024).

Duckweed's platform value is evident in what has already been produced. In poultry, IL-17B-expressing duckweed engineered as an oral mucosal vaccine adjuvant significantly increased IBV-specific antibody levels and mucosal sIgA when used with the commercial H120 vaccine, while also reducing viral loads in multiple tissues (Tan et al., 2022). Moreover, a duckweed-based edible vaccine targeting avian infectious bronchitis virus induced robust humoral and mucosal immunity and achieved 100% survival after challenge, with lower viral loads and reduced tissue damage than controls (Tan et al., 2025). This shows that duckweed can act simultaneously as a plant production system and as an oral delivery matrix for biologically active products (Tan et al., 2025; Yang et al., 2021).

5.2.5 Biomanufacturing

Where the preceding section addressed genetic modification as a production mechanism, biomanufacturing here addresses the downstream conversion of harvested duckweed biomass. This can be done through fermentation, anaerobic digestion, and biorefinery processes, and does not require genetic engineering, instead exploiting duckweed's favorable biomass composition. Once duckweed biomass is harvested, it can enter downstream conversion pathways that recover additional value from the same biological material. Because duckweed combines rapid biomass accumulation with high starch and protein content and relatively low lignin, its carbohydrates are generally easier to hydrolyze and ferment than those of more lignified terrestrial biomass feedstocks. For systems designed for fast turnover, minimal pretreatment, and efficient conversion, duckweed is an ideal candidate (Chen et al., 2022).

Reported conversion results are already strong across multiple routes. In high-starch Spirodela polyrrhiza, enzymatic hydrolysis and yeast fermentation achieved 94.7% of the theoretical starch-to-ethanol conversion (Xu et al., 2011). In Wolffia globosa, ethanol yield reached 170 g kg^{-1} dry mass after simultaneous saccharification and fermentation, while the same biomass also produced succinate at 200 g kg^{-1} dry mass, thereby broadening the discussion from fuel alone to industrial precursor production (Soda et al., 2015). Duckweed is also suitable for anaerobic digestion. In sequential processing of wastewater-derived duckweed, methane yield reached about 390 mL CH_4 g^{-1} volatile solids, with residual biomass still carrying substantial energy value after earlier processing steps or under direct digestion routes (Calicioglu et al., 2018). In the same sequential ethanol fermentation and anaerobic digestion study, fermenting duckweed first and then digesting the residue produced 70.4% more total bioenergy than anaerobic digestion alone, a strong illustration of duckweed's suitability for biorefinery design rather than producing only a single output (Calicioglu et al., 2018). This makes duckweed a more flexible biomass resource. The same point extends beyond energy. Duckweed can also feed fermentation-based production of succinate and other industrial precursors, placing it within a broader bio-based manufacturing framework (Soda et al., 2015; Chen et al., 2022).

5.3 Duckweed in tackling the triple planetary crisis

5.3.1 Climate change

Climate change is the long-term alteration of Earth's climate system driven by the buildup of heat-trapping gases in the atmosphere. The synthetic nitrogen fertilizer supply chain accounts for about 1.1 billion tons of carbon dioxide (CO_2)-equivalent emissions per year globally, or roughly 2.1% of total greenhouse gas emissions (Menegat et al., 2022). By partially replacing fertilizer-intensive crops such as corn and soy, duckweed can reduce dependence on synthetic fertilizers. Field and greenhouse trials show that duckweed can serve as a biofertilizer, supporting crop yields comparable to those of inorganic fertilizers while improving mineral nitrogen retention and, in some cases, residual soil nutrient status (Kreider et al., 2019; Fernandez Pulido et al., 2024). In rice fields, duckweed mats covering paddy water surfaces can reduce ammonia volatilization by slowing water temperature rise and enhancing CO_2 dissolution (Liu et al., 2024) and by acting as a physical barrier that effectively impedes ammonia volatilization (Ahmed et al., 2026). Yao et al. (2017) showed that combining urea with duckweed reduces ammonia volatilization by 36% to 52%, compared to urea alone. However, shifts in ammonium metabolism in aquatic systems directly alter nitrous oxide (N_2O) emissions. Sun et al. (2019) demonstrated via field experiments in paddy fields in East China that duckweed addition reduced nitrogen loss and ammonia volatilization while simultaneously increasing N_2O emission fluxes (Sun et al., 2019). Consistent findings were reported by Wang et al. (2014), who showed that duckweed addition reduced paddy methane emissions while increasing N_2O emission fluxes, resulting in an overall 17% reduction in global warming potential (GWP) (Wang et al., 2014). This demonstrates that while duckweed can influence multiple greenhouse gases (GHG) in complex ways, its overall impact on reducing GHG emissions in agricultural systems remains positive.

Beyond its role in mitigating GHG emissions from agricultural systems, duckweed can further modulate GHG emissions in sewage treatment ponds. Studies have demonstrated that duckweed- modified wastewater stabilization ponds not only enable the sustainable production of high-quality duckweed biomass but also mitigate N_2O emissions. Methane emissions are higher than those in the control group without duckweed addition, while the overall increase in GWP is comparable (Zhao et al., 2022).

Additionally, in polishing ponds with lower organic waste loads, duckweed ponds fixed almost three times as much CO_2 as they released, suggesting that duckweed is the most promising for downstream low-load polishing or nutrient recovery (Mohedano et al., 2019). This ability is partly due to duckweed's high photosynthetic efficiency and unique biological features, including non-functional stomata that remain open, allowing continuous gas exchange (Fig. 5.3; Takács et al., 2025).

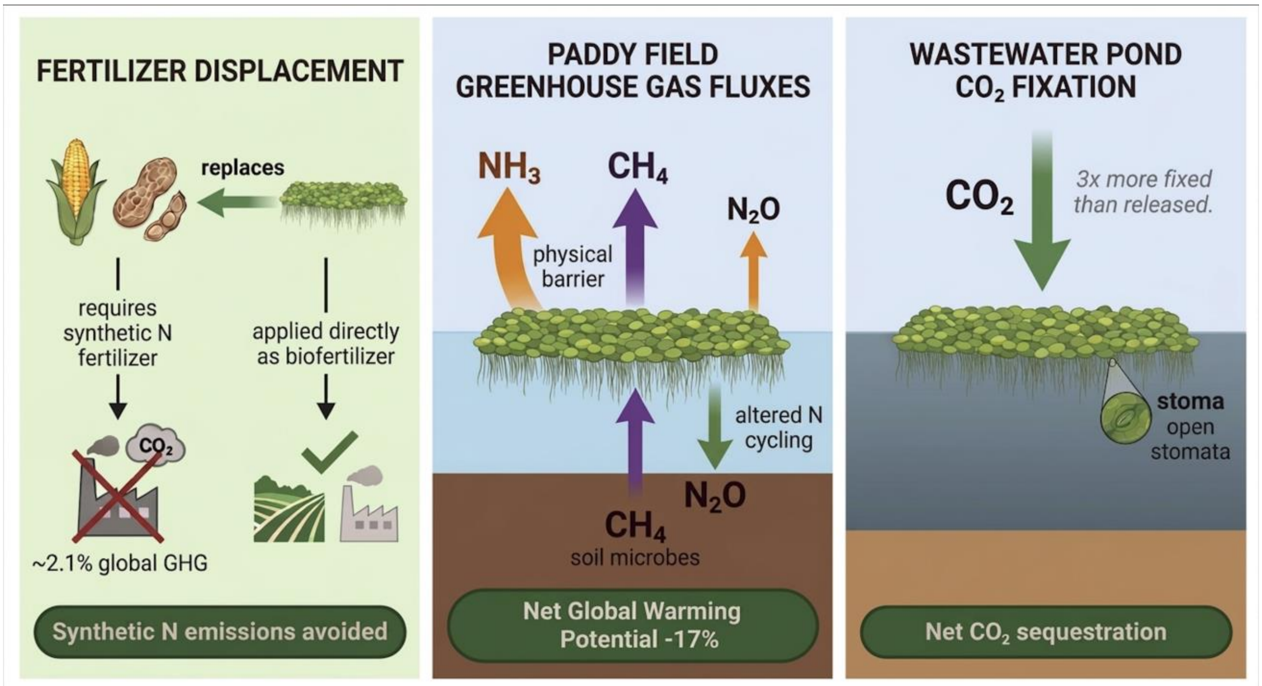


Fig. 5.3 Duckweed's role in pollution mitigation and greenhouse gas reduction. (Left) Duckweed as biofertilizer displaces synthetic nitrogen fertilizer, avoiding ~2.1% of global GHG emissions. (Center) Duckweed mats in paddy fields reduce ammonia volatilization and alter nitrogen cycling, achieving a net 17% reduction in global warming potential. (Right) In wastewater ponds, continuously open stomata enable net CO_2 sequestration at 3× the release rate.

5.3.2 Pollution

Nutrient overload from agricultural runoff and wastewater leads to eutrophication, causing algal blooms that deplete oxygen and harm aquatic life (Smith et al., 2006). Under future scenarios, agriculture, sewage, and aquaculture can account for up to 80% of nutrient delivery to surface waters globally, and coastal eutrophication and hypoxia continue to spread across Asia, South America, and Africa (Beusen et al., 2022; Dai et al., 2023). The accumulation of hazardous pollutants, including heavy metals, pesticides, and pharmaceuticals, further disrupts ecosystems and poses health risks through contaminated water and aquatic organisms (Li et al., 2024). Much of this pollution enters water systems across dispersed agricultural and peri-urban sources that are difficult to intercept through conventional treatment.

Duckweed can be grown directly on the ponds, paddies, and lagoons where this pollution originates. At annual scale, duckweed biomass can accumulate up to 9.1 t N ha^{-1} yr^{-1} and 0.8 t P ha^{-1} yr^{-1}, and field-scale systems have brought effluent from non-compliant levels to China's first-grade discharge standard within six days (Zhou et al., 2023; Zhao et al., 2014). It is also effective against hazardous pollutants, removing significant fractions of heavy metals, organic contaminants, and pharmaceuticals across a wide range of concentrations (Ekperusi et al., 2019)

After harvest, the biomass enriched with nitrogen and phosphorus can be returned to agricultural land as biofertilizer, reducing dependence on synthetic fertilizers by up to 50% in certain systems (Kreider et al., 2019). This closes the nutrient cycle, returning to productive use what would otherwise reach coastal waters. Biomass that has taken up heavy metals or persistent organic contaminants must be directed to managed disposal or industrial energy conversion and cannot re-enter food, feed, or fertilizer streams (Liu et al., 2021; Mukherjee et al., 2025). In both cases, pollutants are concentrated into harvestable biomass that can be physically removed from the water system and managed downstream (Fig. 5.4).

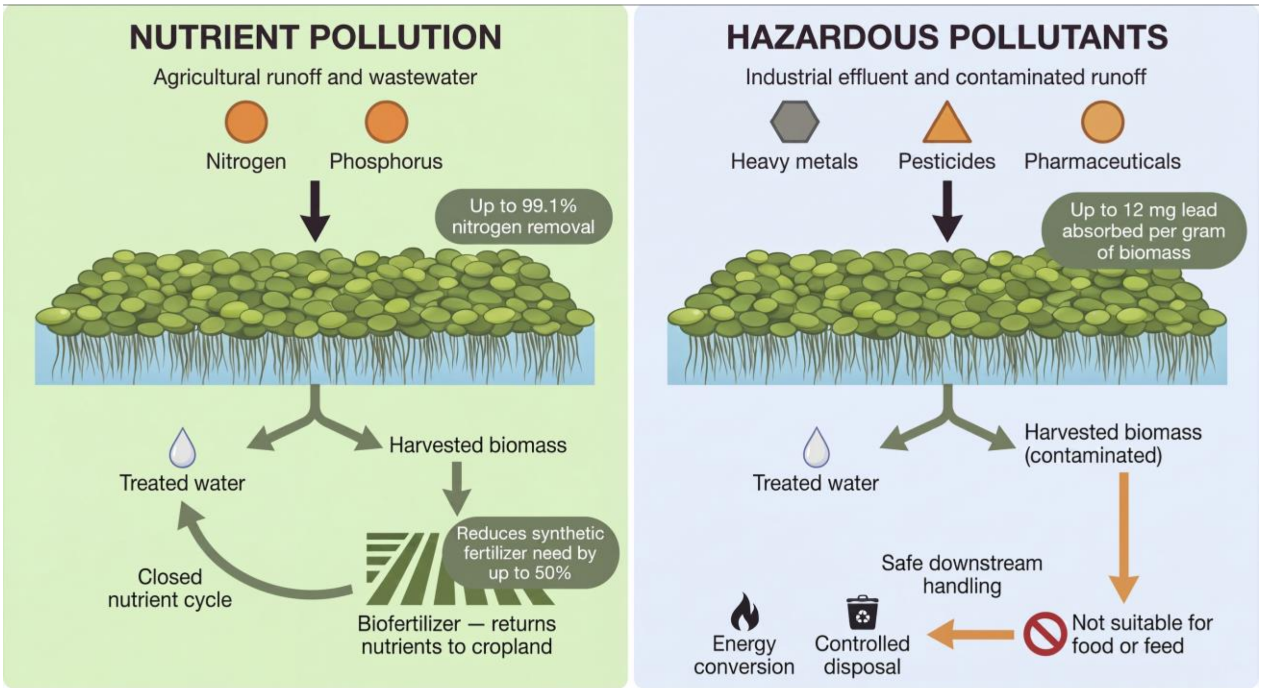


Fig. 5.4 Duckweed's role in mitigating water pollution. Nutrient-loaded water (left) yields harvestable biomass recycled as biofertilizer, closing the nutrient cycle. Water contaminated with hazardous pollutants (right) produces biomass directed to controlled disposal or energy conversion rather than food or feed.

5.3.3 Biodiversity loss

As natural habitats are converted to farmland and pollution enters the remaining habitats, the space available to wildlife diminishes, disrupting ecosystems and reducing species diversity. Duckweed offers a solution by supporting biodiversity conservation through multiple pathways. One of the key contributions of duckweed to biodiversity conservation is its role in land sparing. With vertical farming systems, it is possible to produce crops with much higher yields per square meter than traditional farming methods, with some estimates suggesting vertical farms can yield up to 20 times more per square meter (Benke & Tomkins, 2017). This controlled aquatic production system allows for agricultural yields without contributing to land conversion or deforestation. Duckweed cultivation can replace a portion of traditional crop production, preserve valuable natural habitats and support biodiversity (Takács et al., 2025).

In addition to land preservation, duckweed plays a critical role in water purification within managed aquatic ecosystems. Duckweed helps clean water by removing excess nutrients such as N and P, as well as hazardous contaminants that degrade aquatic ecosystems. Its role in purifying water directly supports aquatic biodiversity by maintaining stable, habitable water conditions, which are essential for the survival of many aquatic species (Chen et al., 2018).

Duckweed's climatic adaptability and stable growth in lentic systems support floating mats that serve as refugia, escape routes, and cover for vulnerable taxa, including dragonfly/damselfly eggs, fish eggs, and fry, thereby reducing predation risk and buffering environmental stressors. They also provide critical camouflage for amphibians and reptiles (Pagliuso et al., 2022). Duckweed mats reduce light penetration via shading, creating thermally stable microhabitats that favor the survival of thermoregulating and shade-tolerant taxa while promoting microhabitat diversity (Ahmed et al., 2026). Furthermore, duckweed grows in interconnected patches, which benefit taxa requiring oxygen-rich environments for respiration, including fish, amphibians, and invertebrates. By promoting the growth and survival of micro aquatic organisms, duckweed further sustains trophic relationships and biodiversity (Ahmed et al., 2026). However, field cultivation carries its own ecological risks, such as obstructing waterways or other potential changes to the ecosystem environment. When overgrown, duckweed can block sunlight and deplete oxygen, which highlights the importance of managing its growth to prevent ecosystem disruption (Fig. 5.5; Janes et al., 2002).

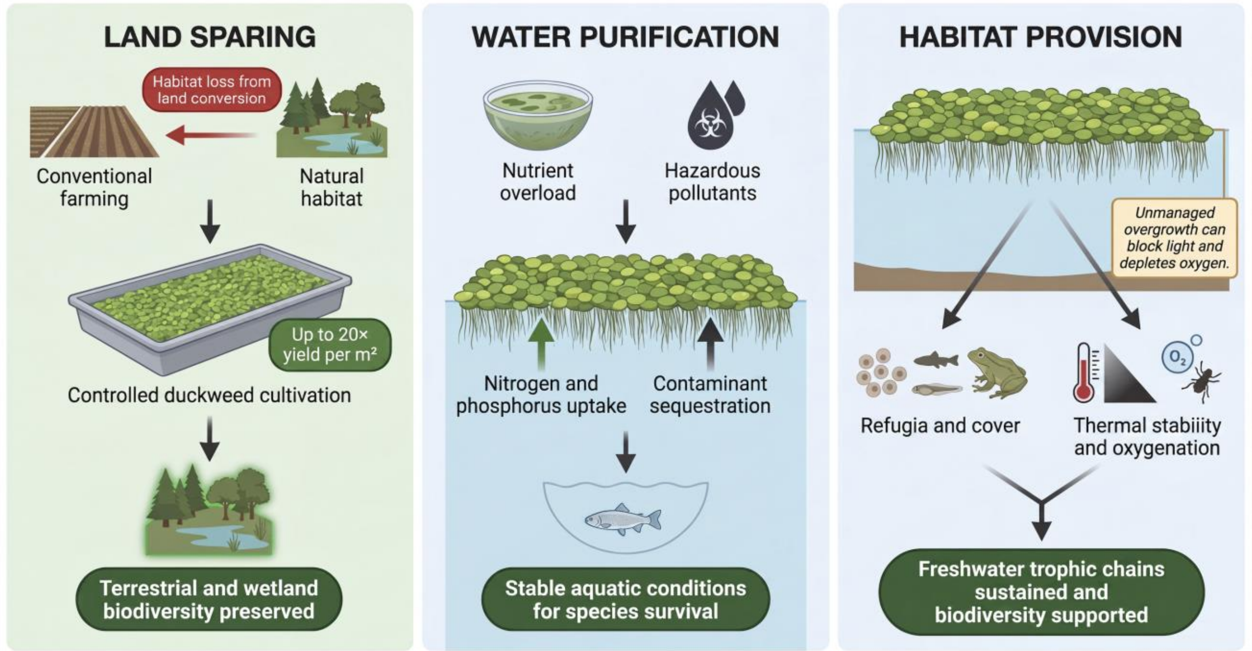


Fig. 5.5 Duckweed-mediated pathways for freshwater biodiversity conservation. High-yield controlled cultivation spares natural habitats from land conversion (left), nutrient and pollutant removal stabilizes aquatic conditions for species survival (center), and floating mats provide refugia and microhabitats that sustain freshwater trophic chains (right).

5.4 Socio-economic implications

5.4.1 Overview of the industry

Since the mid-2010s, duckweed has shifted from a mostly research-focused crop to a small but emerging commercial sector, especially in food ingredients, feed, and water-linked production systems (Takács et al., 2025; Ofoedu et al., 2025). The industry is still young, so market-size estimates should be treated as indicative rather than definitive. Even so, recent reports point to clear growth: the broader global duckweed market has been estimated at about USD 89.4 million in 2025 and is projected to reach USD 256.7 million by 2035, while duckweed protein alone has been estimated between USD 104 million and USD 179.57 million in 2025, with projections rising to USD 246.2–344.88 million by the mid-2030s (Future Market Insights, 2025; DataM Intelligence, 2026).

Regulatory approval is also providing the sector with clearer market pathways. The European Commission authorized fresh Wolffia arrhiza and Wolffia globosa as traditional foods in 2021; Lemna gibba and Lemna minor protein concentrate in 2024; and Lemna minor and Lemna gibba plants in 2025 (European Commission, 2021; European Commission, 2024; European Commission, 2025). EFSA described the Lemna protein concentrate as safe under the proposed use conditions and protein-rich, with a mean protein content of about 64% (EFSA, 2023). In the United States, the FDA issued a "no questions" response in 2026 for Plantible Foods' Lemna leaf protein for use as a conventional food ingredient, emulsifier, gelation agent, thickener, and protein source (FDA, 2026).

Geographically, the industry is developing across North America, Asia-Pacific, and Europe. North America has become a commercialization hub because of alternative-protein investment, ingredient-scale development, and wastewater-linked agricultural applications (Market.us, 2025; FDA, 2026; MIT News, 2025). Asia-Pacific is also a major growth region, supported by demand for sustainable protein from China and India and by Southeast Asia's longer history of edible Wolffia use (DataM Intelligence, 2026; European Commission, 2021). Europe currently stands out for its more formal regulatory pathway for duckweed as human food (European Commission, 2021; European Commission, 2024; European Commission, 2025).

Commercialization is taking three main forms: animal feed, human food ingredients, and wastewater- or nutrient-recovery-linked production systems (Takács et al., 2025; Müller et al., 2025). As feed, duckweed is being explored as a supplement or partial replacement for conventional protein crops such as soy and corn because of its protein, starch, and amino acid content (Sulaiman et al., 2025; Takács et al., 2025). In human nutrition, it is being developed as fresh whole-plant food, protein concentrate, isolate, and functional ingredient, with companies such as Parabel, Plantible, Hinoman, GreenOnyx, Rubisco Foods, and Fyto active across these routes. The sector is expanding, but large-scale supply, consumer acceptance, regulation, contaminant control, and end-use development remain major constraints (Ofoedu et al., 2025; EFSA, 2023).

5.4.2 Case studies

In this section, we ground the discussion in real-world settings to provide more concrete evidence of duckweed's practical applications. The cases below are intended to move beyond general claims about duckweed's potential and show how it performs under real production conditions. The first case is a quantitatively measured feeding trial on pig farms, proving that a small inclusion of duckweed can produce substantial improvements in pig growth and feed-use efficiency under practical farm conditions. The second case is a circular cultivation system in which duckweed helps connect waste treatment, biomass production, water management, and animal feeding within the same farm. The two cases show distinct yet related dimensions of real-world impact.

Case 1: Feed Efficiency

A feeding trial in Nyingchi, Tibet, China, tested duckweed as a partial substitute in pig diets under practical farm conditions. The experiment used 40 post-nursery Tibetan pigs of similar origin and body weight, weighing about 19 kg each, and compared a control diet with one containing 3% duckweed. The basal ration was formulated in accordance with GB/T 39235-2020 for 30–50 kg fattening pigs, and the diet structure was adjusted to ensure that major nutritional targets remained broadly comparable across treatments. This allows the trial to assess duckweed as a realistic feed ingredient rather than as a simple additive. In composition, crude protein content reached 23.79% in duckweed, much higher than corn at 8.04%, though still below soybean meal, while its calcium and iron contents were especially high, at 38,858.36 mg kg^{-1} and 2,853 mg kg^{-1}, respectively.

The results show that even a small amount of duckweed can yield striking improvements in pig production performance. Initial body weight was similar across groups, and feed intake remained broadly comparable throughout the trial. The main differences appeared in growth performance and feed-use efficiency. Compared with the control group, adding just 3% duckweed increased average daily gain by 46.15%, raised final market weight by 19.7%, and reduced the feed conversion ratio by 43.71%. The feed conversion ratio is the amount of feed required to produce a unit of body-weight gain, with a lower value indicating that animals convert feed into meat more efficiently. Since feed consumption did not increase markedly, these gains were driven mainly by improved feed conversion to body mass rather than by greater intake. This suggests that duckweed can improve production efficiency without requiring major reformulation or heavy substitution of conventional feed ingredients.

Case 2: Circular Farming

Guangxi Zhunong Animal Husbandry Technology Co., Ltd. is an ecological livestock and technical-service company based in Nanning, Guangxi, China. The farm covers approximately ~6.7 ha of land, located near Nanning, Guangxi (22.82°N, 108.32°E). Its business combines animal husbandry and environmental treatment. Over the past two years, they have been experimenting with duckweed as a broader ecological farming model.

Duckweed is built into a closed nutrient loop (Fig. 5.6). Duckweed biomass is used as feed for pigs, chickens, ducks, and fish as part of, or in place of, their diet. The manure, wastewater, and solid residues produced by these animals then enter a three-stage microbial fermentation process that removes much of the carbon-rich waste load, leaving a wastewater stream that still contains nutrients such as nitrogen and phosphorus. That water is then used for duckweed cultivation, where the nutrients are taken up again by new plant biomass and returned to the feed system. The duckweed grown from these waters is then minimally processed and fed back to the livestock. Duckweed is therefore the biological medium through which livestock waste is converted back into usable feed while easing the burden of waste discharge.

This circular logic is tied to concrete production outcomes across several animal systems. In tilapia culture, adding 20% duckweed to the feed reportedly increased weight gain by 57.5%. In chicken production, replacing part of the concentrate feed with duckweed reduced feeding costs by 35% while also increasing egg laying rate. In ducks, duckweed replaced up to 50% of the feed and was associated with higher meat quality and firmer meat texture. In grass carp culture, replacing forage grass with duckweed on the farm more than doubled feed efficiency. In pig production, duckweed is also being used to replace the green-feed component, which previously accounted for around 15% of the ration. Research on koi carp further shows that duckweed acts as a functional ingredient beyond protein supply. At 20% inclusion, Lemna minor and Wolffia globosa improved weight gain, enhanced skin pigmentation through greater carotenoid deposition, elevated antioxidant defenses, and enriched beneficial gut microbiota (Song et al., 2026). These results suggest that duckweed can be used as a productive feed resource across multiple species, with effects on growth, feed efficiency, product quality, and farm economics.

The system also changes how livestock waste is handled. Waste is easier to manage within the farm cycle; the treated wastewater can be discharged within regulated limits, and turbidity drops sharply after treatment (Fig. 5.7). At the same time, duckweed grows well on the nutrient stream generated by this system, with reported harvests of about 25 kg of fresh biomass per 500 m2 of cultivation area. Waste treatment, feed production, and animal husbandry are linked closely enough that value can be recovered more than once from the same nutrient flow.

This model also appears to extend beyond a single demonstration farm. The case was promoted by the local government to about 210 demonstration sites across Guangxi province within the last year, reached more than 200 farming households, and received about RMB 3 million in government support for technical promotion, or roughly USD 410,000 at a rounded exchange rate. Duckweed can support farm systems in shifting away from the traditional model that relies heavily on external feed inputs and waste outputs, and toward a more internally circulating production structure.

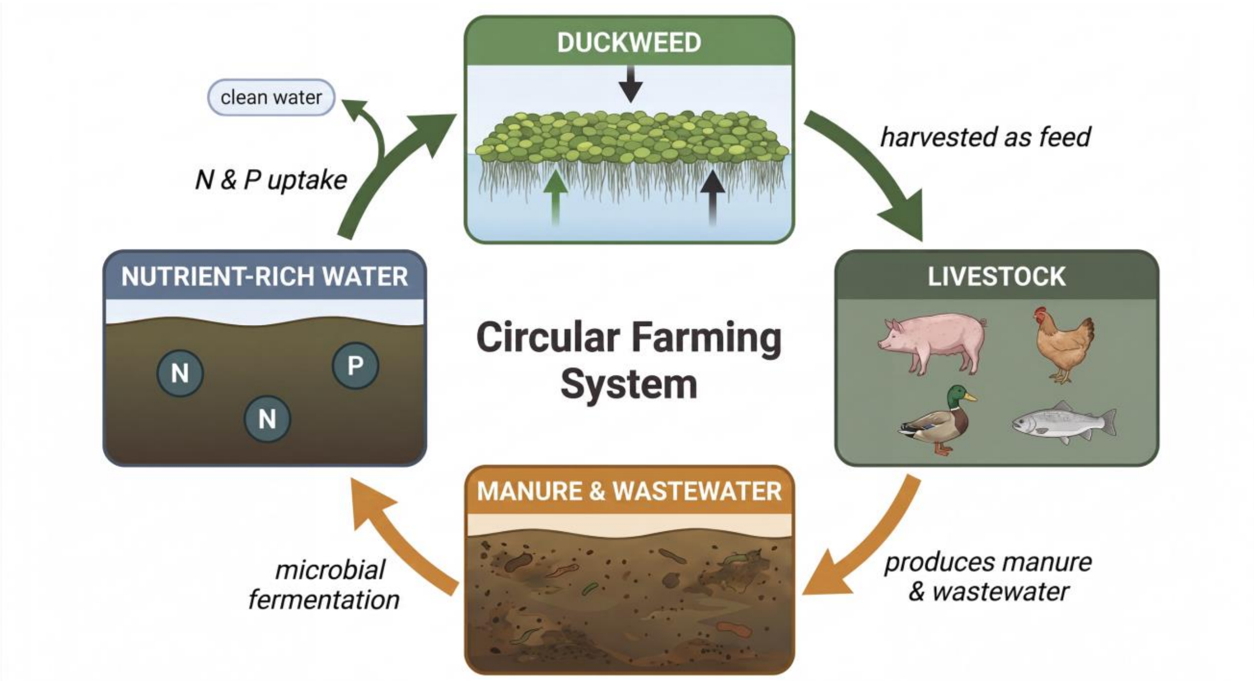


Fig. 5.6 Circular farming system integrating duckweed cultivation with livestock production. Duckweed is harvested as feed for pigs, chickens, ducks, and fish. Animal manure and wastewater undergo microbial fermentation to produce nutrient-rich water, which is then used to cultivate duckweed, closing the nutrient loop and yielding clean water as a byproduct.

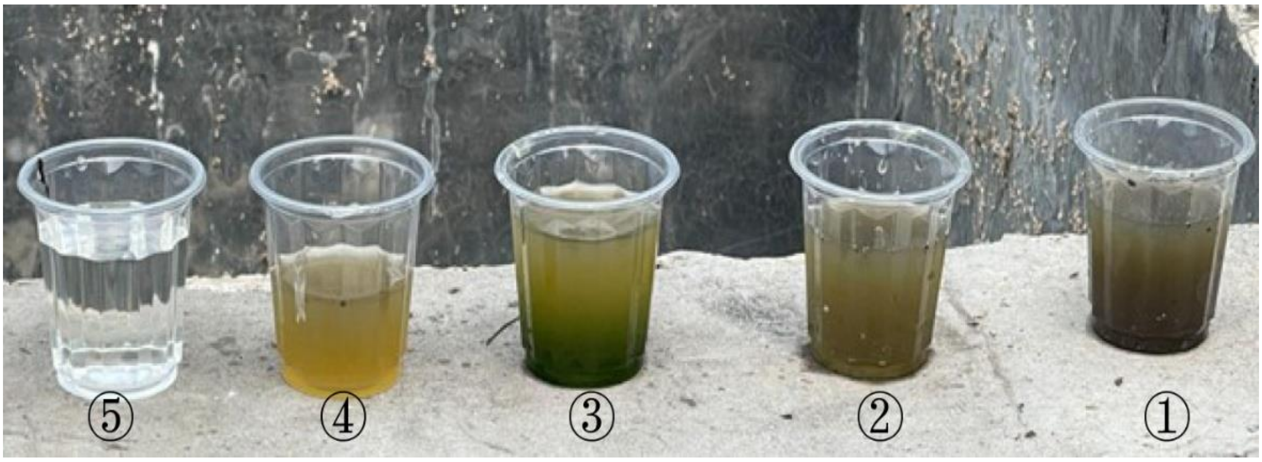


Fig. 5.7 Progressive clarification of aquaculture wastewater through microbial treatment and duckweed polishing. The photograph displays samples (5)–(1) from left to right, whereas treatment proceeds from (1) to (5). Sample (1) is untreated aquaculture wastewater; samples (2)–(4) are the effluents after the first, second, and third microbial reactors, respectively; and sample (5) is the final effluent after the additional duckweed-polishing stage.

5.4.3 Broader socioeconomic impact

Many vulnerable regions face multiple agricultural constraints simultaneously. Food insecurity often develops alongside land and water stress, rising input costs, and heavy dependence on imported staples or production inputs. These pressures become harder to manage where demand is rising quickly and imports are unstable, creating food systems that are ecologically constrained at home and economically exposed from outside. Globally, hunger has continued to worsen in Africa and Western Asia; the Near East and North Africa remain the world's most land- and water-scarce region, and many small island developing states remain highly dependent on imported food (FAO et al., 2025; FAO, n.d.-b; UNCTAD, 2022). Duckweed may expand what communities can produce under these constraints.

Duckweed may reduce the usual dependence of agricultural production on land and suitable weather conditions. It can be cultivated in any still-water system and increasingly in controlled indoor or vertical farming setups. Even as an aquatic crop, it requires less water than many conventional crops, particularly in contained or recirculating systems, which have a lower overall water footprint (Song et al., 2026; Ujong et al., 2025). This widens the range of places where productive biomass can be grown, including peri-urban areas, regions with scarce or degraded cropland, and climates where open-field farming is becoming less reliable. It also reduces pressure on fertilizer use and freshwater withdrawals when grown in nutrient-rich water or in recirculating systems. This is especially relevant in the Near East and North Africa, where agriculture already consumes about 85% of available freshwater and water scarcity has become a defining constraint on food security and rural livelihoods (FAO, n.d.-b).

At the farm level, the value proposition becomes more immediate. Livestock farms and aquaculture systems already generate nutrient-rich wastewater and manure and treating them before disposal is often a persistent burden. Duckweed can convert part of that burden into usable biomass that can be redirected into feed, fertilizer, or other bio-based products (Femeena et al., 2023). This allows wastewater treatment and feed production to no longer be separate problems. Nutrient-rich water becomes a growth medium; the water is partially cleaned, and the harvested biomass can re-enter production as a protein-rich resource. Studies and pilot-scale systems have repeatedly shown the effectiveness of this circular approach (Ujong et al., 2025). For small livestock or fish farms, even partial feed replacement can reduce reliance on commercial feed and its price fluctuations.

On a broader scale, duckweed may support greater local food autonomy and more self-sustaining rural economies. When communities can produce a portion of their own crops, they will have more control over parts of the food, feed, and nutrient systems they depend on. Many vulnerable communities are constrained by local ecological limits, but they are also constrained by distant markets. In 2018–2020, 95% of small island developing states were net importers of cereals and cereal preparations, showing a near-total dependence on international trade for a core food category (UNCTAD, 2022). Due to its flexibility in its cultivating environment, duckweed can localize part of feed and biomass production in community-based systems where conventional crop expansion is difficult.

Duckweed may also lower some barriers that typically exclude smaller producers from agricultural innovation. Its short growth cycle allows farmers to observe and adjust cultivation conditions within days or weeks, rather than waiting for a full field-crop season. Its vegetative reproduction also means that a small starter culture can expand without purchasing seed each season. These traits do not remove corporate power from the food system, and duckweed could still be patented and commercialized in ways that monopolizes the market and marginalizes individual farmers and producers. However, useful duckweed species already exist widely in nature, and their basic productivity does not depend on the same seed, machinery, and input structures that shape many conventional crops. If developed through open knowledge and structural support, duckweed could help communities retain more value within local systems. This would not replace the global food system, but it could create meaningful openings toward more circular and locally controlled food economies.

5.5 Summary

This chapter has shown that duckweed's productivity numbers represent a different production logic from conventional crops. Its protein yields reaching up to 18 t ha^{-1} yr^{-1} against soy's roughly 1 t and starch productivity exceeding 30.8 t ha^{-1} yr^{-1} in optimized systems against maize's 4–6 t, point to a plant operating under a fundamentally different framework. It does not require arable land, does not depend on a handful of annual harvests, and can grow directly on the nutrient-rich wastewater that conventional agriculture generates as a disposal problem. The same biological system that treats water also produces harvestable biomass, and that biomass can re-enter production as feed, fertilizer, or fermentation feedstock. These capabilities make duckweed unusually promising among candidate crops for the challenges described in this chapter.

The regulatory and scientific case has already moved considerably ahead of public awareness. The European Union authorized fresh Wolffia plants as a traditional food, protein concentrate from Lemna as a novel food ingredient, and whole Lemna plants as novel food across three separate decisions between 2021 and 2025 (European Commission, 2021; European Commission, 2024; European Commission, 2025). The FDA issued a no-questions GRAS response for Lemna leaf protein in 2026 (FDA, 2026). Species of Wolffia have been cultivated and eaten in Laos, Myanmar, and Thailand for more than 25 years. Yet outside specialist circles, duckweed is still routinely dismissed as pond scum, confused with algae, or simply unrecognized. The perception gap is no longer a scientific problem; the challenge has shifted to public communication and familiarity, now one of the more concrete obstacles to commercial uptake and broader policy engagement.

Regulatory progress in some regions demonstrates what becomes possible when formal frameworks catch up with the science. The EU authorizations are meaningful not just as approvals but as signals that edible duckweed products can move through established food safety processes and emerge with defined legal status and market access. The more significant constraint is the unevenness of this progress. Scientific evidence alone cannot build a functioning sector if regulatory systems in other regions have not yet developed the frameworks to evaluate and approve duckweed products, across feed, food, water treatment, or the circular systems that combine several of these at once. Extending the kind of regulatory clarity that Europe and the United States have begun to establish across other major markets would do more to accelerate duckweed's development than almost any further research publication.

Nonetheless, there is technical work still to be done. Duckweed is far from a uniform material. The performance differences between species, strains, water sources, and cultivation conditions documented are large enough to point towards completely different industries. A system optimized for starch accumulation in Landoltia punctata on dilute swine wastewater will behave very differently from one targeting protein yield in Wolffia arrhiza under controlled indoor conditions. Most published work has focused on optimizing individual steps including growth conditions, nutrient removal, biomass conversion. The weaker links are the ones connecting these steps into a reliable chain like harvesting protocols, post-harvest drying and storage, quality control across variable water sources, and the logistics of moving biomass from production into processing at sufficient scale and consistency. These tend to be the questions that determine whether a crop stays at pilot scale or moves into commercial viability.

The trajectory of duckweed development will also depend on how effectively it is integrated with emerging production technologies. Duckweed's short growth cycle, with biomass doubling within 24 to 48 hours, demands harvesting at a frequency that automated equipment handles far better than manual systems. Its water-based cultivation is directly amenable to real-time sensor monitoring of nutrient concentrations, pH, and biomass density, which AI-driven management systems can use to optimize yields continuously. Renewable energy reduces the carbon cost of the controlled environments and artificial lighting that indoor systems require. These technologies address some of the practical limitations that have kept high-productivity systems at demonstration scale, and their convergence with duckweed's biological characteristics is one of the more concrete reasons to expect that scale-up is a near-term possibility.

The science behind duckweed is no longer the limiting factor. This chapter shows that the constraints have shifted from demonstrating that duckweed can perform, to building the conditions under which it consistently does. Duckweed is already present in regulated food markets, already integrated into working circular farm systems, already producing validated results in poultry vaccine trials. Whether it develops into a significant part of future food and biomass systems depends largely on whether the investment needed to build that role is treated with the urgency the underlying problems demand.

6 Conclusions and Future Perspectives

6.1 Restating the imperativeness of a circular bioeconomy

The transition from a linear, resource-substitution model to a fully integrated circular bioeconomy is one of the most critical structural shifts in contemporary industrial and environmental governance. Early iterations of the bioeconomy, roughly from the early 2000s to 2010, were primarily growth-oriented strategies aimed at replacing fossil fuels with biological resources, often based on the assumption that biomass renewability automatically equated to environmental sustainability. This volume has traced the evolution of this paradigm, showing how the second phase (2010–2018) introduced necessary but reactive sustainability safeguards, such as certification schemes, in response to escalating ecological risks. We are now in a third phase (2018–present), which defines the circular bioeconomy as a multi-objective governance framework. This modern framework demands systemic efficiency, cascading use of biomass, and strict adherence to planetary boundaries, recognizing that expanding bio-based production without restructuring material flows will exacerbate land-use change and biodiversity loss.

The preceding report systematically mapped this transition through the lens of four representative agro-industrial sectors: bamboo, palm oil, natural rubber, and duckweed. These specific bioresources were selected not only for their global economic footprint but also for their ability to capture the profound tensions inherent in the modern bioeconomy. They reveal the friction between achieving the United Nations Sustainable Development Goals (SDGs)—particularly poverty alleviation (SDG 1), clean energy (SDG 7), and decent work (SDG 8)—and the severe environmental trade-offs threatening life on land (SDG 15) and climate action (SDG 13).

6.2 The tension between potential and practice

The core findings of this report underscore that the sustainability of a bio-based economy is never just inherent to the plant itself; rather, it is entirely dictated by its cultivation, industrial processing, use and integration into global trade networks.

The transformation of the bamboo sector, heavily led by China over the past three decades, illustrates a successful transition from a marginalized subsistence forestry product to a strategic, highly engineered material capable of disrupting heavy industries. Propelled by pivotal policy shifts such as the 1998 National Natural Forest Protection Program and the recent "Substitute for Plastic" initiative (2023–2025), bamboo is now widely processed into laminated lumber, high-density scrimber, and bioplastics. These engineered materials offer tensile strengths comparable to those of mild steel and serve as highly effective, long-term carbon sinks in the construction sector, helping delay the emission of biogenic carbon. However, to meet soaring processing demands, diverse natural forests might have been aggressively converted into intense bamboo monocultures. The aggressive expansion and dense canopy shading of bamboo effectively eliminate understory vegetation and native tree seedlings. Empirical studies from China demonstrate that such monoculture practices trigger declines in soil bacterial and fungal diversity, fundamentally undermining the soil microbiome and local nutrient cycling. Furthermore, intensive irrigation required to maximize yields during dry seasons places acute stress on regional hydrological systems, creating a direct conflict with human and agricultural water needs.

Palm oil remains the most consumed vegetable oil globally, supplying 40% of the world's demand while occupying less than 6% of the arable land dedicated to oil crops. The analysis of the palm oil sector highlights a mature industry caught in intense international political friction. Historically driven by expansive schemes such as Indonesia's NES/PIR and, later, mandated biofuel blending policies, the sector's growth has lifted millions out of poverty and spurred rural monetization in Southeast Asia. Yet the ecological footprint of this expansion should not be overlooked. The conversion of highly biodiverse tropical rainforests and fragile peatlands into structurally homogeneous oil palm estates has triggered massive landscape fragmentation and species decline. Peatland drainage has led to severe ecosystem degradation and massive GHG emissions. During the midstream processing stage, POME emerges as a critical hazard. Untreated POME causes severe water hypoxia and eutrophication, while conventional open-air anaerobic treatment releases massive quantities of methane. The sector is now facing stringent downstream regulatory pressures, most notably the EU Deforestation Regulation, which is forcing a painful transition toward traceability and zero-deforestation compliance.

Natural rubber, known for its strain-induced crystallization and fatigue resistance, is an indispensable biopolymer for the global transportation and medical sectors. The industry's spatial restructuring reflects a shift from traditional Southeast Asian strongholds toward the Greater Mekong Subregion and West Africa. Like palm oil, rubber expansion has driven forest clearance in Southeast Asia, leading to severe declines in above- and belowground biodiversity. A defining feature of the rubber industry is its overwhelming reliance on smallholder labor. While providing critical cash income that supports rural education and healthcare, smallholders are trapped at the bottom of an asymmetric global value chain. They endure severe occupational health hazards while absorbing the brutal financial shocks of volatile international market prices. Furthermore, the industry is plagued by opacity; most processors and tire manufacturers lack the traceability needed to link their supply chains to specific harvest areas, allowing deforestation risks to remain hidden within the system.

In stark contrast to the terrestrial constraints of bamboo, rubber, and palm oil, duckweed represents a frontier application of aquatic biomass. Comprising the world's smallest flowering plants, duckweed achieves phenomenal growth rates, capable of doubling its biomass in 48 hours, highlighting its extraordinary nutritional profile under controlled conditions. Duckweed embodies the core principles of the circular bioeconomy. It thrives on nutrient-rich agricultural runoff and wastewater, effectively removing up to 99% of total nitrogen and phosphorus, thereby mitigating the primary drivers of coastal and freshwater eutrophication. Practical case studies demonstrate that duckweed can partially replace conventional feed, improve feed conversion ratios, and simultaneously clean livestock wastewater. However, its potential massive aquatic cultivation may create ecological risks if non-native species escape, block waterways or alter oxygen dynamics.

6.3 Existing problems and systemic bottlenecks

Despite the distinct characteristics of these four sectors, a cross-sector analysis reveals several systemic problems that threaten the viability of the global bioeconomy.

A profound spatial inequity defines modern bio-based trade. Developing nations in the Global South disproportionately bear the ecological burdens of biomass cultivation—including deforestation, water depletion, and agrochemical pollution—while capturing only a fraction of the economic value. Furthermore, the global trade in biomaterials often results in carbon leakage. For example, the vast export of short-lived, single-use bamboo products from East Asia to Western markets results in immediate carbon release upon disposal, failing to offset the fossil energy consumed during their manufacture. Conversely, high-value, carbon-locking engineered materials are disproportionately absorbed by affluent nations, leaving producing nations with the ecological deficit.

The current paradigm relies heavily on land-intensive monocultures. Whether it is the conversion of intact tropical rainforests to oil palm and rubber, or the replacement of mixed broadleaf forests with Moso bamboo, resulting simplification of habitats. This monoculture model inherently degrades soil organic carbon, diminishes ecological niches for avifauna and arthropods, and increases vulnerability to pests and diseases. The fundamental problem is that current market mechanisms incentivize maximizing short-term biomass volume at the expense of long-term landscape resilience.

While international environmental regulations and certification schemes are necessary for ecological protection, they inadvertently create severe structural barriers for smallholders. The financial costs, complex land-tenure documentation, and rigorous geolocation auditing required for compliance are largely prohibitive for independent rural farmers cultivating palm oil and natural rubber. Without robust financial and public support, these top-down sustainability mandates risk excluding the most vulnerable populations from global supply chains, thereby exacerbating rural poverty rather than alleviating it.

The bioeconomy currently struggles with the downstream fate of its products. The rubber industry faces a monumental solid waste crisis, generating approximately 800 million end-of-life tires (ELTs) annually. Because of their crosslinked structure, ELTs resist biodegradation; illegal dumping poses severe fire hazards and toxic leachate, while energy recovery via combustion can release heavy metals and volatile organic compounds if improperly managed. Similarly, while the palm oil and bamboo sectors produce massive amounts of residues, the capital expenditure required for advanced biorefineries to convert these wastes into biochar, syngas, or advanced composites remains out of reach for many mid-sized processors in the Global South.

6.4 Future trends and strategic imperatives

To overcome these structural bottlenecks and ensure the bioeconomy operates safely within planetary boundaries, several development trends and strategic imperatives must shape the next decade of agro-industrial policy and practice.

Transitioning from Monoculture Yield Maximization to Regenerative mix-planting. The future of terrestrial biomass production must pivot away from ecologically sterile monocultures toward mixed-species, regenerative agroforestry models. Integrating fruit, spice, or timber species into rubber and bamboo plantations has been proven to improve land-use efficiency, broaden farmers' income streams, and restore habitat complexity for local fauna. Future agricultural policies must incentivize these diverse systems, recognizing that while the absolute per-hectare volume of a single commodity may slightly decrease, the overall economic and ecological stability of the system improves, significantly buffering farmers against international price shocks and climate-induced extreme weather.

Next-Generation Traceability and Inclusive Global Governance. The future trend points toward mandatory, legally binding supply chain traceability, tracking biomass from the individual plot level to the final consumer good. However, for this to be sustainable, global governance must shift from a punitive, exclusionary model to a supportive, inclusive one. Downstream multinational corporations and affluent consuming nations must share the financial burden of certification and traceability. Providing smallholders with the technological tools, financial premiums, and tenure security required to meet zero-deforestation standards is essential to prevent trade diversion—in which non-compliant products simply shift to less-regulated markets, resulting in risk leakage rather than actual environmental improvement.

Deep Valorization of Waste and Closed-Loop Biomanufacturing. True circularity will be achieved only when processing residues are viewed as primary feedstocks rather than disposal liabilities. The integration of advanced biomanufacturing will define future processing hubs. In the palm oil sector, this means the mandatory capture of methane from POME during anaerobic digestion to produce biogas, thereby eliminating a major climate threat while generating localized energy. In the bamboo industry, scaling thermo-mechanical extrusion is required to turn sawdust and processing dust into durable bioplastics, and utilizing closed-loop solvent systems to eliminate chemical water pollution. Across all sectors, bio-refineries must be developed to fractionate biomass into high-value biochemicals, antioxidants, and biochar, ensuring high-rate resource utilization.

Decoupling Biomass from Arable Land. One of the most disruptive future trends is the spatial decoupling of biomass production from the constraints of traditional arable land. As competition for terrestrial land among food, fuel, and fiber intensifies, aquatic and controlled-environment systems will become vital. Rapid advances in duckweed cultivation exemplify this trajectory. Future agricultural frameworks will increasingly integrate aquatic macrophytes into vertical farms and into municipal or agricultural wastewater treatment systems. By using solar power and automated digital management, these systems can produce large yields of food-grade protein and industrial starch independent of seasonal rainfall, soil quality, or land availability. This shift not only preserves intact terrestrial ecosystems but also closes the loop on nutrient pollution in coastal and freshwater systems.

The evolution toward a circular bioeconomy is not a mere technological upgrade; it is a fundamental renegotiation of humanity's relationship with nature. Analyses of bamboo, palm oil, natural rubber, and duckweed reveal that biological resources have immense power to decarbonize industries, replace persistent petrochemicals, and elevate rural livelihoods. Yet this power is perilous if left to the devices of linear, extractive economic models. Going forward, the success of the bioeconomy will be measured not by the sheer volume of biomass extracted from the earth, but by the efficiency, equity, and ecological intelligence with which that biomass is managed. It requires a commitment to cascading utilization, the protection of smallholder equity, and the defense of global biodiversity. Only by embedding strict circularity and regenerative practices into global supply chains can the bioeconomy fulfill its promise as a catalyst for a sustainable, resilient, and equitable future.

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