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REVIEW

Circular Economy and Agricultural Decarbonization: An Integrated Multilevel Governance and Implementation Framework in Brazil

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ABSTRACT

Agriculture is the foundation of food systems but faces growing challenges. According to the United Nations, 40% of the world's land is already degraded, affecting both agricultural productivity and global food security. This study aimed to conduct an integrative literature review and a documentary analysis to map the evolution of international and national frameworks, highlighting their contributions to the Brazilian agribusiness. The methodology was based on a systematic literature review, crossing data from scientific databases (Scopus, Web of Science) with primary legal regulations. The analysis showed that the Brundtland Report (1987) and the Paris Agreement (2015) laid the foundations for sustainable development and shaped policies such as emissions accounting mechanisms. Focusing on the Brazilian context, the National Circular Economy Strategy and the Ecological Transformation Plan (2025) establish guidelines for integrating circular practices into the sector, including the use of organic waste, reverse logistics, bioeconomy, and agri-food systems. The ISO 59000 family standard and PR2030 Recommended Practice provide technical frameworks for measuring and standardizing circularity in agro-industrial chains. The discussion converges on a conceptual proposal of a multilevel framework specifically designed for the Brazilian regulatory scenario. However, gaps remain regarding traceability, the integration of Life Cycle Assessment (LCA), and circularity metrics. It is expected that legal and regulatory coordination offers strategic opportunities to reposition agribusiness as a driver of the circular economy and decarbonization.

KEYWORDS Agribusiness, Life cycle assessment, Bioeconomy, Environmental regulation, Sustainable development

1. Introduction

Agriculture constitutes the fundamental basis of global food systems, yet it currently faces unprecedented challenges that threaten its continuity and the planet's resilience (Craparo *et al.* 2024; Jayabal *et al.* 2025). According to the second edition of the Global Land Outlook (GLO2), from the United Nations Convention to Combat Desertification (UNCCD 2022), global food systems are today the primary drivers of land degradation. The report reveals that modern agricultural activities and the global demand for food account for 80% of deforestation, 70% of freshwater use, and 29% of greenhouse gas emissions, being the primary cause of biodiversity loss worldwide (Muscat *et al.* 2021). With 40% of the planet's land already degraded, the crisis transcends the sectoral sphere to become a systemic risk to food security and human survival itself (Agbelusi *et al.* 2024; Dash *et al.* 2025).

This critical context reveals a flaw in the worldview that has dominated modernity. Historically, a vision of the "environment" (from the Latin *ambientare*) has been consolidated as something

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surrounding, which merely "envelops" or "is around" humanity. This perspective of exteriority allowed the Earth to be treated as an object of extraction, a "standing reserve" (*Bestand*), following Martin Heidegger's critique of modern technology. To overcome this model, it is imperative to rescue the deep meaning of dwelling (*wohnen*). As explored in the thesis *The Art of Dwelling*, dwelling is not occupying an external geographical space, but rather the very condition of human existence that implies "saving and preserving" the earth (Lorentzen 2025). From this perspective, the UNCCD's alarming data on agricultural impact are not external events but processes internal to human identity and continuity; soil degradation is, ultimately, the degradation of dwelling itself.

In this context, understanding regulatory and political instruments is essential to identify pathways for the agricultural sector's transition to circular and low-carbon models (Chiaraluce *et al.* 2021; Dovgal *et al.* 2024). The Circular Economy (CE) emerges as the key to restoring this balanced dwelling, using Life Cycle Assessment (LCA) as the technical tool that allows monitoring and mitigating the system's entropy (Velasco-Muñoz *et al.* 2022; ISO 2006a; ISO 2006b).

The urgency of this paradigmatic and technological transition is intrinsically aligned with the Sustainable Development Goals (SDGs) established by the United Nations 2030 Agenda (United Nations 2015). The adoption of the Circular Economy in agribusiness acts as a direct catalyst for SDG 2 (Zero Hunger and Sustainable Agriculture), by ensuring resilient food production systems, and for SDG 12 (Responsible Consumption and Production), through the drastic reduction of waste and the efficient management of natural resources (Craparo *et al.* 2024; Rabbi and Amin 2024). Additionally, by reconfiguring agriculture from a source of emissions to a carbon sink, the sector fulfills a decisive role in SDG 13 (Climate Action), mitigating the impacts of climate change (Dash *et al.* 2025; Jayabal *et al.* 2025).

Although recent literature has extensively reviewed individual circular economy strategies and agricultural supply chains, there is a notable gap in integrating legal obligations, voluntary standardizations, and digital enabling technologies into a single operational architecture. Therefore, this study aims to conduct a triangulated technical analysis to propose a multilevel conceptual framework specifically focused on the Brazilian agribusiness context, demonstrating how laws stipulate limits, standards build comparability, and technologies act as practical implementation vehicles.

2. Methodology

The study was structured as a systematic integrative literature review, complemented by a documentary analysis of normative, regulatory, and institutional instruments. The integrative review was selected because it enables the gathering, critical evaluation, critical evaluation and synthesis of evidence from diverse research designs, as well as theoretical contributions, which is essential for understanding complex and interdisciplinary phenomena like the circular transition (Whittemore and Knafl 2005; Snyder 2019). This method requires the explicit definition of the research problem, the systematized search of sources, the evaluation of the selected documents, data analysis, and the transparent presentation of the synthesis produced (Whittemore and Knafl 2005).

To define the scope and analytical categories of the review, the following research questions were formulated: (i) which international, national, and organizational governance instruments influence the transition to circular and low-carbon models in the agro-industrial sector?; (ii) what methods, indicators, and evaluation frameworks allow measuring the environmental, climate, and circular performance of this transition?; and (iii) how can public policies, technical standards, performance metrics, and enabling technologies be articulated into an integrated implementation framework? The prior formulation of these questions aimed to delimit the scope of the review, guide the selection of sources, and establish the categories used in the analysis and synthesis of the results. Explicating these procedures is fundamental to increasing the transparency, consistency, and reproducibility of literature reviews (Snyder 2019).

To ensure transparency and reproducibility, the literature search and screening processes were guided by the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) flowchart principles (Page *et al.* 2021). Academic searches were conducted in two major scientific databases, Scopus and Web of Science. The search period was restricted from January 2015 to mid-2026, using 2015 as the foundational milestone of the Paris Agreement and the UN 2030 Agenda.

The search strings were constructed using Boolean operators combining the core themes of the study: ("Circular Economy" OR "Bioeconomy") AND ("Agriculture" OR "Agribusiness" OR "Agri-food") AND ("Decarbonization" OR "Governance" OR "Life Cycle Assessment" OR "Regulation").

Following the removal of duplicate records, a rigorous screening procedure was applied. The inclusion criteria comprised: (a) peer-reviewed articles and comprehensive reviews written in English or Portuguese; (b) studies explicitly addressing macro or meso-level circular economy implementation in agricultural supply chains; and (c) research discussing technological enablers, carbon metrics, or sustainability frameworks. The exclusion criteria filtered out: (a) purely technical or biochemical studies lacking a systemic supply chain or governance perspective; (b) non-peer-reviewed grey literature; and (c) studies outside the agricultural scope. The titles and abstracts were independently screened, followed by a full-text assessment of the eligible papers to ensure relevance and methodological quality.

To clarify the originality of this study, Table 1 summarizes recent review articles and highlights the specific knowledge gap addressed by this framework.

Table 1. Comparison of recent review articles on circular agriculture and the contribution of this study.

Reference	Geographical Scope	Primary Topics Covered	Governance & Standards Included	Technological Enablers	Gap Filled by Present Study
Velasco-Muñoz et al. (2021)	Global	CE strategies, agricultural indicators	Minimal	None	Integrates macro-level policies with micro-level metrics.
Craparo et al. (2024)	Global	SDGs, circular agriculture trends	None	Descriptive	Connects SDGs directly to national taxonomies and ESG rules.
Agbelusi et al. (2024)	Global	Decarbonization, supply chain, emerging tech	None	High	Bridges the gap between digital tools and mandatory carbon accounting.
Present study	Brazil (principal context)	CE, LCA, Decarbonization, Multilevel Governance	High (SBCE, TSB, ISO 59000)	High (IoT, blockchain, smart contracts)	Provides an integrated, verifiable architecture combining mandatory laws, voluntary ISO standards, and digital traceability specifically for the Brazilian context.

Parallel to the academic literature, a documentary analysis was incorporated to systematically examine primary sources that dictate guidelines, mandatory commitments, and implementation

mechanisms (Bowen 2009). The documents were purposively selected based on their direct regulatory impact on agribusiness and were classified into three analytical categories:

1. International Treaties & Agreements: e.g., the Paris Agreement and the UN SDGs.
2. National Legislation & Public Policies: focusing on the Brazilian regulatory ecosystem, including official legal texts such as the Brazilian Emissions Trading System (Law No. 15,042/2024), the National Circular Economy Strategy (ENEC), the Ecological Transformation Plan (PLANEC), and the Brazilian Sustainable Taxonomy (TSB).
3. Technical Standards & Market Guidelines: comprising voluntary compliance mechanisms, notably the ISO 14000 series, the recently published ISO 59000 circular economy family, and the ABNT PR 2030 ESG Recommended Practice.

Data Triangulation and Framework Development

The core methodological innovation of this study relies on a triangulated analysis. In this context, triangulation is defined as the qualitative cross-referencing, coding, and validation of data extracted from three distinct streams: (1) peer-reviewed academic evidence, (2) binding legal legislation, and (3) voluntary technical standardizations.

The data from both the systematic review and the documentary analysis were extracted into a thematic matrix and coded into four operational layers: conceptual foundations, regulatory pressure, standardization/metrics, and technological integration. The triangulation process directly informed the development of the final conceptual framework (Figure 1) by mapping the theoretical mechanisms identified in the scientific literature (e.g., Narrowing, Closing, and Regenerating strategies) against the mandatory targets imposed by environmental policies (e.g., SBCE, TSB) and the auditability rules provided by technical standards (e.g., ISO 59020). This integrated synthesis proves adequate for the multilevel nature of the object of study, demonstrating how governance structures, measurement instruments, and technological enablers must be articulated simultaneously to achieve a low-carbon agro-industrial system.

3. Theoretical Background: Circular Economy (CE) as a Control Strategy

3.1. Conceptualization and Principles of the Circular Economy in Agri-Food Systems

The fight against the climate crisis has proven incomplete regarding the distribution of global efforts, which have predominantly focused on the transition to renewable energies and energy efficiency. According to the Ellen MacArthur Foundation (2021) in the report Completing the Picture: How the Circular Economy Tackles Climate Change, these energy transitions address 55% of global greenhouse gas (GHG) emissions. The remaining 45% of emissions come from activities with high levels of difficulty for decarbonization, which are the way we manage land and produce goods such as cars, clothes, buildings, and food (Ellen MacArthur Foundation and ANSYS Granta 2019).

The 1987 Brundtland Commission report, entitled *Our Common Future*, defined sustainable development as the process that "meets the needs of the present without compromising the ability of future generations to meet their own needs." In this context, sustainability is defined as the ultimate goal of this development, representing a state of global balance that integrates the environmental, social, and economic dimensions (United Nations 2015).

The Circular Economy (CE), in turn, is defined as an economic system focused on maintaining the circular flow of resources, recovering, retaining, or adding value to them through a systemic approach (ISO 2024). Presenting itself as a regenerative and restorative alternative to the traditional linear economic model of "take-make-dispose", the CE is based on three fundamental principles: (i) eliminate waste and pollution from the outset; (ii) keep products and materials in use; and (iii) regenerate natural systems (Ellen MacArthur Foundation 2021; Morseletto 2020).

The intrinsic relationship between the two concepts establishes that the Circular Economy acts as a practical mechanism and an essential driver for achieving the sustainability defined in the *Our Common Future* report. This relationship can be demonstrated in the following ways:

- Decoupling growth and resource extraction: The Circular Economy allows for economic development and quality of life decoupled from the depletion of finite resources (Craparo *et al.* 2024). This directly fulfills the premise of not compromising the natural capital stock and the capabilities of future generations.
- Restorative rather than merely preventive action: While traditional approaches seek only to minimize the damage of industries, the intentionally regenerative design of the Circular Economy restores ecosystems, soil, and water reserves. This is critical to maintaining the Earth's ability to support long-term life and support the biosphere (Morseletto 2020; Selvan *et al.* 2023).
- Integration of the Triple Bottom Line: Reaching present and future needs requires balanced consideration of the three spheres of sustainability. The circular transition aligns economic (cost reduction, resilience), environmental (pollution reduction, climate mitigation), and social (job creation, equity, poverty eradication) benefits, strengthening these highly interdependent goals (Valencia *et al.* 2023).

In agri-food systems, this transition implies shifting the focus from isolated productivity to systemic soil health and natural capital preservation. As discussed by Muscat *et al.* (2021) and Rodias *et al.* (2021), circular agriculture seeks to close nutrient and energy loops, minimizing the input of external resources and losses to the environment. CE in agribusiness is not just waste management, but a new design of "biological metabolism" (Barros *et al.* 2023), where each byproduct of one stage becomes a nutrient for the next.

From the review of the studies, some systemic impacts of this transition in the climate context stand out:

- Emission reduction in industry and food: The application of circular principles in just five critical areas (cement, aluminum, steel, plastics, and the food system) can reduce global emissions from these sectors by almost half by 2050. In industry, this means intensely increasing asset utilization rates and recycling materials, reducing the demand for virgin raw materials (Ellen MacArthur Foundation 2021).
- Agriculture as a climate solution: Global agricultural production will need to increase by 70% by 2050 to meet food demand. Under the current linear model, this would deplete natural resources. However, by applying the circular economy with the elimination of food waste throughout the chain and adopting regenerative agriculture practices, the sector can actively sequester carbon from the atmosphere into the soil, transforming agricultural lands from emission sources into major carbon sinks (Nazir *et al.* 2024; Dash *et al.* 2025).
- Increased climate resilience: In addition to attacking the causes of global warming (mitigation), the circular economy also prepares society for its inevitable impacts (adaptation). By keeping products and materials in use for longer, companies decrease their dependence on raw material chains that are highly vulnerable to climate risks and disasters (Barman *et al.* 2025). Simultaneously, regenerative methods improve soil health, increasing its water retention capacity and making ecosystems more resistant to extreme droughts and floods (Dovgal *et al.* 2024).
- Benefits beyond climate: The circular transition offers broad economic and social benefits that help fulfill the UN Sustainable Development Goals (SDGs), especially SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action). The approach protects biodiversity, reduces water contamination, and stimulates innovations in business models (United Nations 2015; Craparo *et al.* 2024; Rabbi and Amin 2024).

Thus, the outlined panorama warns that the adoption of the circular economy in isolation (just the technique) will not be effective to achieve a future with net-zero emissions and zero waste. A systematized and joint action is required in which governments, corporations, standard-setting bodies, investors, and academic institutions actively integrate circular strategies into their agendas, guidelines, and climate action policies (Uvarova *et al.* 2023).

3.2. Pillars of the Circular Economy in Agro-Industrial Systems

The pillars of the Circular Economy in agro-industrial systems are based on established universal principles, which have been specifically adapted to deal with the biological nature and the challenges of agriculture and food production. These pillars aim to transform agro-industrial chains into sustainable, resilient, and low-carbon models (Velasco-Muñoz *et al.* 2021; Chiaraluce *et al.* 2021):

Eliminate waste and pollution (Prevention)

In agro-industry, this pillar focuses on the effectiveness of the system by identifying and preventing negative environmental impacts from occurring right from the planning of activities (Batlles-delaFuente *et al.* 2022).

- Chemical reduction and ecosystem protection: Involves the gradual elimination of toxic substances, such as pesticides, herbicides, and synthetic fertilizers, replacing them with organic fertilizers and biological control methods. The goal is to avoid soil degradation and the contamination of soil and water sources (Dovgal *et al.* 2024).
- Design against waste: The circular transition rejects intensive monoculture models prone to failures and pests, seeking to create agri-food product designs that avoid losses throughout the entire supply chain (Hamam *et al.* 2021).

Keep products and materials in use (Efficiency and Valorization)

The focus of this pillar is to preserve and maximize the value of all resources, co-products, and by-products at all stages of the chain (Muñoz *et al.* 2024). In the linear agricultural economy, vast amounts of organic waste end up in landfills; in the circular pillar, they become the fuel of the bioeconomy.

- Closing loops (Circular metabolism): Imitates natural ecosystems, where the waste of one process is the input of another. Crop residues, prunings, animal manure, and food waste are reused in cascades (Rodias *et al.* 2021).
- Transformation into new assets: Instead of disposal, these materials are converted into renewable energy (such as biogas from biodigesters), compost, and biofertilizers that return to the soil, animal feed, or even high-value raw materials such as bioplastics, textiles, and biochemical extracts (Wagh *et al.* 2024).

Regenerate natural systems (Restoration of Natural Capital)

Agriculture is the sector with the greatest capacity to fulfill this pillar, which seeks to return valuable nutrients to the earth and replace the use of finite stocks with renewable resources.

- Regenerative Agriculture: The main tool for this pillar, covering practices such as agroecology, no-till farming (minimum soil disturbance), use of cover crops, crop rotation, and silvopastoral systems (crop-livestock-forest integration) (Selvan *et al.* 2023).
- Carbon sequestration and resilience: By building and nourishing organic matter levels in the soil, farms cease to be major emitters of greenhouse gases and begin to act as natural sinks, sequestering carbon directly from the atmosphere. This regeneration not only nourishes

beneficial soil microbes but also improves soil water retention, increasing crop resilience against extreme droughts and floods (Nazir *et al.* 2024; Jayabal *et al.* 2025).

3.3. Chain Vision and Responsibilities in Agro-Industrial Links

Developing the chain vision and distributing responsibilities across agro-industrial links requires abandoning the fragmented and linear vision (take-make-dispose), where each participant acts only to maximize their own short-term profit. Instead, it is necessary to adopt a systemic approach based on the "Shared Value Theory" and "Stakeholder Capitalism", where sustainability and the circular economy act as central focuses for long-term value generation for all involved (Agbelusi *et al.* 2024; Valencia *et al.* 2023).

For this vision to be consolidated, responsibility must be distributed and understood in a specific and interconnected way in each link of the system (Cahyadi *et al.* 2024):

Definition of Responsibilities by Chain Link

Although sustainable practices must permeate the entire network, the emphasis of actions varies according to the role of each actor (Cahyadi *et al.* 2024):

- Input Suppliers and Farmers: Are responsible for adopting sustainable sources, developing ecological inputs (such as biofertilizers), and applying regenerative and precision agriculture techniques, focusing on resource efficiency (water, energy, soil) and waste management right at the farm level.
- Processors: Their responsibility focuses on energy efficiency in factories and the valorization of by-products (*upcycling*), transforming what would be organic waste into new products, bioenergy, or animal feed (Wagh *et al.* 2024).
- Distributors and Retailers: Are responsible for optimizing logistics and cold chain management (reducing transport emissions), introducing innovations in packaging, and creating retail strategies to reduce food waste and promote sustainable products.
- Consumers: Play a crucial dual role that enables the circular economy. They are responsible for consuming products from circular sources and ensuring the correct disposal or return of products and packaging at the end of their useful life, allowing materials to return to the chain (Zimmermann *et al.* 2024).

Strategies to Develop and Integrate the Chain Vision

To connect these links and ensure they assume their responsibilities, agro-industrial organizations must implement practical integration actions:

- Supplier Engagement and Evaluation: Leading organizations must exert influence over their chain by establishing consistent ESG (Environmental, Social, and Governance) criteria for selecting and auditing their business partners (ABNT 2022). This includes rewarding suppliers with good practices and assisting them in their technical and managerial development, collaboratively mitigating negative impacts.
- Fostering Industrial Symbiosis ("Agro2Agro" Models): The chain vision is strengthened when inter-cooperation networks are created where the waste of one property becomes the raw material of another. For example, grains can go to a neighboring property, while animal manure feeds a biodigester in a cooperative, whose biofertilizer returns to the crops. These exchanges elevate farms to a new technological level, generating innovation and joint competitive advantage (Barros *et al.* 2023).
- Information Sharing and Traceability: In a digitized economy, data traffic is as vital as material traffic to optimize resources. The implementation of traceability systems, such as the use of *Blockchain*, allows all links to identify the origin of production, management methods, and the

actual carbon footprint of products (Alotaibi *et al.* 2024; Wang *et al.* 2020; Vilkov and Tian 2023). This reduces operational risks, builds trust, and prevents greenwashing to the consumer.

- Multisectoral Partnerships (Public-Private): The transition does not happen in isolation. Building this vision requires cooperation between governments, corporations, NGOs, and farmers themselves (Marthalia *et al.* 2024). This may involve research consortiums, financing for technological innovations, and the establishment of public policies and financial incentives that reward the rural producer for adopting circular practices.

By adopting these strategies, the agro-industrial chain ceases to be a straight line of isolated commercial transactions and begins to act as a collaborative and resilient ecosystem, in which risks, information, and sustainable value are widely shared.

4. Normative Evolution and Regulation

The transition to circular and low-carbon production models in the Brazilian agro-industrial sector is supported by a normative ecosystem that articulates international commitments, national policies, and technical standardizations (Batlles-delaFuente *et al.* 2022; Cahyadi *et al.* 2024). It is critical to differentiate that while treaties and national laws impose mandatory legal obligations, ISO standards and ESG guidelines function as voluntary market mechanisms designed to support compliance and standardization.

The Paris Agreement is a legally binding international treaty on climate change, adopted by 196 Parties at COP 21 in Paris, in December 2015. Its main objective is to limit the increase in global average temperature to well below 2 °C above pre-industrial levels, pursuing efforts to limit this increase to 1.5 °C. To meet this goal, the Agreement requires countries to prepare and communicate their Nationally Determined Contributions (NDCs), which are action plans for the rapid reduction of greenhouse gas (GHG) emissions. Regarding the relationship with agricultural systems, this commitment signed between the parties also establishes the global premise of safeguarding food security in the face of climate vulnerabilities (Craparo *et al.* 2024; Jayabal *et al.* 2025). In Brazil, this commitment is operationalized by the NDC in its 2024 update, which institutionalized the circular economy as a mitigation strategy. The transition to circular systems ceases to be a sectoral option and becomes a climate compliance requirement, aiming to mitigate the so-called "transition risks" (Velasco-Muñoz *et al.* 2021).

Transition risks (also called market risks) refer to the financial and commercial consequences that the agricultural sector may face due to regulatory changes and global demands associated with decarbonization, environmental preservation, and respect for human and labour rights (Marthalia *et al.* 2024; Valencia *et al.* 2023).

4.1. National Circular Economy Strategy (ENEC) and National Circular Economy Plan (PLANEC) in Brazil

The National Circular Economy Strategy (ENEC) is a public policy elaborated in partnership from the perspective of various government bodies and civil society, instituted by Decree No. 12,082 of June 27, 2024 (Brazil 2024a), whose central purpose is to promote the transition from the current linear economic model (take, make, consume, and dispose) to a Circular Economy. Its goal is to encourage the efficient use of natural resources and the adoption of sustainable practices throughout all production chains (ISO 2024).

To achieve this goal, the ENEC is structured on three universal principles: (i) Non-generation of waste and pollution; (ii) Circulation of materials and products at their highest values and for the longest possible time; and (iii) Regeneration of nature, permeated by the concept of circular redesign of production (Uvarova *et al.* 2023).

In addition to the environmental and economic fronts, the ENEC is based on social justice, with the strategic direction of ensuring that this productive transformation is just, inclusive, and

equitable, with the generation of decent jobs and the fight against gender, race, ethnic, and socioeconomic disparities (Valencia *et al.* 2023). The operationalization of the guidelines takes place in a structured manner through the National Circular Economy Plan (PLANEC) (Brazil 2025b). With this, the strategy aims to propel Brazil to the role of a global environmental power, making the country a worldwide reference in the management of natural wealth, low-carbon production, and the valorisation of traditional knowledge.

The ENEC and the respective PLANEC (Brazil 2025b) establish very specific guidelines and actions to guide the transition of the agricultural and agro-industrial sector towards circularity. The main criteria and actions directly aligned with agribusiness include:

- Fostering Sustainable and Regenerative Production: One of the official objectives of the strategy is the promotion of sustainable extractive, agricultural, and agroforestry production, which encompasses the entire chain, including distribution processes, trade, and associated services. In practice, this translates into the action of encouraging regenerative production through product design, procurement practices, and agricultural and proper land use policies (Selvan *et al.* 2023; Bollam 2025).
- Waste Reduction in Agro-industry and Agriculture: Axis 3 of the plan (Brazil 2025b) determines the creation of incentive programs focused specifically on agro-industry, agriculture, and the food and beverage sector. The criterion is to use circular practices to reduce waste generation and actively promote the reuse of components and products in these waste chains to promote the prevention of food waste and the valorisation of organic waste (Rabbi and Amin 2024), highlighting the implementation of the National Plan for the Reduction of Urban Organic Waste (Planaro). In addition, the text defines the promotion of short food production and distribution circuits.
- Government Integration and Bioeconomy: The circular transition of agribusiness is treated in an integrated manner with the guidelines of the Ecological Transformation Plan (PTE) of the Ministry of Finance, which established "Bioeconomy and Agri-food Systems" as one of its six central axes of action to ally economic growth with environmental conservation (Muscat *et al.* 2021; Wagh *et al.* 2024).

The National Circular Economy Plan (PLANEC) explicitly determines the need to align the Brazilian Sustainable Taxonomy with its guidelines through Action 4.1.5 (Brazil 2025b). This action is part of the axis aimed at proposing financial aid instruments, with the purpose of ensuring that the technical financing criteria of the taxonomy require and reward the fulfilment of circularity goals (Morseletto 2020; Figueirinhas *et al.* 2025). The inclusion of this circular transition as an objective of the taxonomy is highlighted by the government as one of the significant recent advances to ensure sustainability and social inclusion in the country (Brazil 2023).

4.2. Eligibility Mechanism and Financial Targeting: Brazilian Sustainable Taxonomy

The Brazilian Sustainable Taxonomy (TSB) acts as the main classification mechanism for environmentally sustainable economic activities. Officially instituted by Decree No. 12,705 on October 31, 2025 (Brazil 2025a), the prioritization of Sector A (Agriculture, Livestock, Forest Production, Fishing, and Aquaculture) in the TSB is based on its magnitude in the national emissions matrix, where agriculture accounts for 28.5% of direct GHG emissions.

It acts as a central instrument to mobilize and redirect capital flows (public and private) to sustainable investments, providing a common and reliable terminology for companies, financial institutions, investors, and governments in order to coordinate public policies and combat *greenwashing* (ABNT 2022).

For an activity to be classified as sustainable by the Brazilian taxonomy, it must meet three general criteria simultaneously: (i) Contribute specifically to one or more of the environmental, climate, or

social objectives; (ii) Do no significant harm to any of the other objectives; (iii) Comply with minimum safeguards of respect for human rights, labour rights, and transparency rules (Brazil 2025a; ABNT 2022).

The Brazilian tool was designed under the principle of interoperability, meaning that, although adapted to the socioeconomic and environmental reality of Brazil, it uses standards and principles functionally equivalent to those of other global taxonomies to facilitate communication, the attraction of foreign investments, and data comparability. Among the international initiatives, the following stand out:

- European Union: Brazil adopted the same mechanical structure of the European taxonomy (the three criteria mentioned above) and the classification of "transition activities" for hard-to-abate sectors (Uvarova *et al.* 2023).
- Colombia: Inspired by the Colombian tool, the Brazilian taxonomy included "Sustainable land use and forest conservation" as a central environmental objective, recognizing the importance and impact of the agricultural and forestry sector in our region.
- Mexico: Like Mexico, Brazil innovated by including direct economic-social objectives in the taxonomy (such as generating decent work and reducing regional, racial, and gender inequalities), reflecting the urgency to treat the country's structural disparities in an integrated manner with the climate agenda (Valencia *et al.* 2023).

Alignment with Global Treaties and Agreements: The taxonomy is the practical financial instrument to help Brazil meet the goals signed before the international community (Brazil 2023):

- Paris Agreement: The technical thresholds for the climate mitigation objective of the taxonomy are oriented to help Brazil fulfil its Nationally Determined Contributions (NDCs) and follow the decarbonization scenarios pointed out by the Intergovernmental Panel on Climate Change (IPCC).
- 2030 Agenda (UN): The taxonomy's objectives are deeply aligned with the Sustainable Development Goals (SDGs), ranging from climate action to poverty alleviation and institutional partnerships (United Nations 2015).
- Convention on Biological Diversity (CBD): The tool seeks to harmonize financial flows with the Kunming-Montreal Global Biodiversity Framework, whose objective is to halt biodiversity loss and conserve ecosystems.
- Human and Labor Rights: The "minimum safeguards" required for any sustainable project in Brazil are based on international business conduct guidelines (ABNT 2022).

The Brazilian Sustainable Taxonomy acts to reinforce the regulatory pillar of circularity in the agricultural sector by officially establishing the "Transition to the circular economy" as one of its central environmental objectives and acting as a guiding financial instrument for the State's new public policies (Morseletto 2020).

The relationship of the Taxonomy with agri-food and agro-industrial activities takes place through several fronts:

- Mitigation of emissions and environmental impacts: The agricultural sector is the second-largest emitter of greenhouse gases (GHG) in Brazil. The taxonomy will seek to guide investments toward activities that combat the unsustainable practices responsible for soil degradation, biodiversity loss, and water scarcity (Nazir *et al.* 2024; Agbelusi *et al.* 2024).
- Pollution control in agro-industry and the field: Agro-industrial activities have considerably increased water demand and the release of contaminating effluents into water sources. The taxonomy seeks to address these issues through the objective of preventing and controlling contamination (Rodias *et al.* 2021; Dovgal *et al.* 2024).

- Exposure to climate and market risks: The sector has a high exposure to physical climate risks, as the increased frequency of extreme events directly impacts crop productivity. Concurrently, the sector faces transition risks, restricting the access of agricultural products to global markets (Craparo *et al.* 2024).
- Sustainable land use as a central objective: Agricultural projects will need to prove substantial contribution and ensure they do not cause significant harm, actively curbing deforestation and fostering area restoration (Dash *et al.* 2025).
- Incentives for low-carbon practices (ABC+ Plan): The taxonomy acts in synergy with existing public policies, supporting less carbon-intensive technologies, such as Crop-Livestock-Forest Integration (ILPF) and the recovery of degraded pastures (Selvan *et al.* 2023).
- Intersection with rural credit and regularization: Obtaining agricultural credit under favourable conditions will increasingly depend on the environmental regularity of the properties (Barros *et al.* 2023).

Thus, the Brazilian sustainable taxonomy corroborates to establish clear, objective, and scientifically based criteria that will define whether an agricultural project is eligible to receive sustainable investments (ABNT 2022). To access these green capitals, agribusiness activities will need to prove that they meet technical limits aimed at promoting changes in production patterns, reducing the waste of raw materials, and increasing efficiency in the use of scarce resources (Chiaraluce *et al.* 2021).

The Paris Agreement, the Brazilian Sustainable Taxonomy (Brazil 2025a), the National Circular Economy Strategy / PLANEC (Brazil 2024a; Brazil 2025b), and the ABNT PR 2030 Recommended Practice (ESG) form an integrated ecosystem of norms and strategies. The agricultural and forestry sector is the central convergence point among them. The relationship between these documents regarding agribusiness is established on the following main fronts:

- Food Security and Climate Vulnerability: The Paris Agreement establishes the global premise by recognizing the fundamental priority of safeguarding food security. The TSB internalizes this guideline, warning that Brazilian agribusiness has a high exposure to physical climate risks and transition (market) risks.
- Combating Deforestation and Sustainable Land Use (The ESG Practice): The Paris Agreement encourages the reduction of emissions from deforestation. As a corporate implementation tool, ABNT PR 2030 (ESG) details the practices the sector must adopt, recommending supplier engagement in actions to combat degradation, the adoption of the No-Till Farming System (SPD), and ILPF systems (ABNT 2022).
- Transition to Regenerative and Circular Models: PLANEC inserts agribusiness into the "Bioeconomy and Agri-food Systems" Axis. This connects directly with the TSB and the need to adopt the circular economy in the field, transforming agri-food business models to reuse resources and regenerate nature (Hamam *et al.* 2021).
- Financing the Transition (The Engine of Change): All documents converge on the need to mobilize capital to make this transformation viable. While the TSB acts as the "compass" to guide this money in Brazil, PLANEC provides for the creation of specific credit lines for sectors operating with circular businesses (Marthalia *et al.* 2024).

In summary, the Paris Agreement defines the global goal; the TSB (Brazil 2025a) creates the financial rules; ABNT PR 2030 translates these requirements into measurable ESG practices (ABNT 2022); and PLANEC (Brazil 2025b) ensures that this new rural production operates under a circular logic.

Additionally, the governance of environmental assets in the national scenario was deeply impacted by the institutionalization of Law No. 15,042/2024 (Brazil 2024b), which regulated the

Brazilian Emissions Trading System (SBCE). The establishment of this regulated carbon market imposes mandatory emission limits for large industrial players, transforming agricultural decarbonization into a source generating compensatory credits (Vilkov and Tian 2023). This market dynamic is reinforced in the sphere of corporate governance by Resolution No. 193/2023 of the Securities and Exchange Commission (CVM) (CVM 2023) and by alignment with the international guidelines of the IFRS S1 and IFRS S2 standards (B3 2025). These financial and reporting mechanisms require the mandatory disclosure of climate risks and greenhouse gas emissions inventories. Consequently, exporting agribusiness is compelled to transition to measurable circular metrics, under the risk of suffering severe restrictions in raising funds in international capital markets (Alotaibi *et al.* 2024; Wang *et al.* 2020).

5. Circularity Measurement Methodologies, Indicators and Frameworks

Analytical tools constitute the fundamental computational modelling and inventory methods necessary to parameterize the input and output variables of agro-industrial systems.

- Life Cycle Assessment (LCA): Regulated by the ISO 14040 and ISO 14044 standards (ISO 2006a; ISO 2006b), LCA is the predominant method for estimating the cumulative potential environmental impacts throughout all life cycle phases of a product or process (Velasco-Muñoz *et al.* 2022). The incorporation of LCA into the Environmental Management System (EMS), as advocated by sustainability guidelines such as ABNT PR 2030 (ABNT 2022), provides the scientific support to mitigate pollution and ensure regulatory compliance, avoiding burden shifting between environmental categories.
- Material Flow Analysis (MFA): Based on the principle of mass conservation, MFA performs the systematic balance of material flows and stocks within a defined spatial and temporal boundary (Brunner and Rechberger 2004; Barros *et al.* 2023). It is a critical analytical tool for waste engineering, as it enables the modeling of scenarios resulting from the insertion of circular strategies, accurately quantifying recycling efficiency rates and the reduction of waste sent to landfills.
- Analytic Hierarchy Process (AHP): As a multi-criteria decision-making (MCDM) method, AHP structures qualitative and quantitative factors into weighted hierarchical diagrams. In the scope of the circular economy, AHP is employed to assign relative weights to multiple performance indicators, such as the priority levels of the 9R taxonomy, converting multidimensional variables into a unified quantitative circularity index (Muñoz *et al.* 2024).

5.1. Synthetic Indices and Circularity Measurement Tools

Synthetic indices configure mathematical models that aggregate the data generated by analytical tools to determine the degree of cycle closing of a given organization or supply chain.

- Material Circularity Indicator (MCI): Proposed by the Ellen MacArthur Foundation, the MCI is restricted to the flow of technical and biological materials, computing variables such as the fraction of virgin-origin inputs, the efficiency of the restoration process, and the proportion of unrecoverable linear waste. The model results in a dimensionless score ranging from 0 to 1, where unity represents the theoretical limit of a perfectly circular system (Ellen MacArthur Foundation 2021; Figueirinhas *et al.* 2025).
- Percentage of Material Circularity (% CTI): Developed under the WBCSD's Circular Transition Indicators framework, this index is based on the percentage quantification (0 to 100%) of circular input flows versus the actual recovery potential of the outputs. The method penalizes linear flows and provides a performance metric linked to the dependence on finite resources.
- 9R Circularity Index: A methodological framework based on a bottom-up approach that integrates the logic of the AHP method with the thermodynamic hierarchy of the 9R strategies (from

prevention in design, such as Refuse and Reduce, to energy recovery, such as Recover). This index weights the quality of the retention of the economic and physical value of resources, mathematically discounting the use of virgin raw materials and final disposal in landfills (Muñoz *et al.* 2024; Uvarova *et al.* 2023).

5.2. Reporting Frameworks and Emissions Inventories

To ensure that circularity and decarbonization metrics are equivalent to the requirements of national legislation (such as the Brazilian Sustainable Taxonomy) and international legislation (such as the Paris Agreement NDCs), standardized reporting frameworks are used.

- Greenhouse Gas (GHG) Accounting: The GHG Protocol and the ISO 14064 standard establish the methodological requirements for the emissions inventory. While related, these frameworks are not identical; the GHG Protocol categorizes emissions into Scopes 1, 2, and 3, whereas ISO 14064 categorizes them by direct and indirect emission sources. In agro-industrial systems, these tools are inseparable from circular economy metrics, since the substitution of fossil inputs for regenerative biological flows directly alters the gas emissions profile of the system (Agbelusi *et al.* 2024).
- ESG Reporting Frameworks (GRI, SASB, CDP, and TCFD): Provide guidelines and materiality matrices for the public disclosure of environmental, social, and governance performance. The Global Reporting Initiative (GRI), for example, standardizes the presentation of socioeconomic compliance data, and the associated use of these structures allows auditing extended producer responsibility along the value chain (ABNT 2022).
- Market Sustainability Indices: Instruments such as the ISE-B3, the Ethos Indicators, and the B Corp certification function as third-party external auditing mechanisms, assessing the alignment of the corporate business model with planetary boundaries and the generation of social value (B3 2025; Valencia *et al.* 2023).
- ISO 59000 Series: The recently published ISO 59000 family standardizes the circular economy globally. It is crucial to distinguish their roles: ISO 59004 defines the terminology and principles, ISO 59010 provides guidance on transitioning business models, and ISO 59020 establishes the definitive framework for measuring and assessing circularity performance (ISO 2024).

5.3. Circularity Indicators in Agricultural Systems

The transposition of general circular economy concepts to the modelling of agricultural systems requires the decomposition of metrics into four fundamental resource flow management strategies (narrowing, closing, slowing, and regenerating). This categorization allows parameterizing the efficiency rates of the productive ecosystem and identifying critical points of energy and nutrient loss (Velasco-Muñoz *et al.* 2021).

5.3.1. Narrowing of Cycles

This strategy concentrates the highest density of metrics in the scientific literature and aims at the thermodynamic optimization of the system through the reduction of resource intensity per unit of product (Barros *et al.* 2023). In the agricultural sphere, narrowing is quantified by technical efficiency indicators and partial nutrient balance, highlighting nitrogen use efficiency (NUE) and greenhouse gas emissions associated with productivity per unit of soil area. Additionally, the measurement of the water footprint and indices of farm food/feed autonomy are inserted into this vector, mapping the reduction of the input of embodied energy external to the system's boundary (Dash *et al.* 2025; Jayabal *et al.* 2025).

5.3.2. Closing of Cycles

Closing is based on retaining materials and energy within production chains through cascading processes, preventing the leakage of biological fractions and the contamination of adjacent ecosystems (Wagh *et al.* 2024). The operational indicators of this dimension measure the internal recycling rate of macronutrients (N, P, K) and the capacity to substitute synthetic inputs with local organic compounds (Rodias *et al.* 2021). Engineering modelling in this pillar quantifies biotechnological conversion efficiency, such as the potential for biogas and biomethane generation from the anaerobic digestion of agricultural manure and lignocellulosic residues, converting environmental liabilities into circular energy fractions (Barros *et al.* 2023).

5.3.3. Regeneration of Systems

Unlike technical industrial systems, agricultural biological metabolism depends intrinsically on the restoration of natural capital for its long-term maintenance. Regeneration indicators evaluate the transition from the consumption of finite stocks to renewable flows (Ellen MacArthur Foundation and ANSYS Granta 2019). This dimension is monitored through the reduction in the consumption of fossil-based fertilizers (notably mineral phosphorus) and by physicochemical and biological descriptors of soil health, such as the evolution of Cation Exchange Capacity (CEC), the water retention rate of the surface horizon, carbon sequestration levels, and indices of agrobiodiversity (Dovgal *et al.* 2024; Nazir *et al.* 2024).

5.3.4. Slowing of Cycles

Cycle slowing imposes the greatest conceptual challenge on the agri-food sector, given the intrinsic perishability of biomass and the biological impossibility of applying classic remanufacturing or repair processes to food products. In this sense, the scientific literature adapts slowing for the monitoring of shelf-life extension and the control of losses along the supply chain (Velasco-Muñoz *et al.* 2021). Indicators focus on quantifying Food Loss and Waste (FLW) rates and the efficiency of downstream preservation and storage technologies. The literature points out, however, a chronic lack of standardized mathematical formulations to quantify slowing in the agricultural environment, constituting a persistent methodological gap in combating waste (Cahyadi *et al.* 2024; Rabbi and Amin 2024).

To systematically synthesize the measurement methodologies and frameworks discussed in this section, Table 2 presents a correlation matrix. This table illustrates how fundamental analytical tools, synthetic circularity indices, and reporting inventories intersect with both voluntary technical standards and mandatory Brazilian legislation (e.g., ENEC, PLANEC, and SBCE). By explicitly mapping these connections, the matrix highlights the necessary alignment between micro-level operational metrics and macro-level regulatory compliance within the agro-industrial sector.

Table 2. Systemic correlation table: legislations, standards, and CE measurement tools.

Tool Group	Tool / Methodology	Variable / Metric Measured	Associated Technical Standard	Linked Legislation / National Plan	Function in System Dynamic Control
1. Basic Methodological and Analytical	Life Cycle Assessment (LCA)	Cumulative environmental impacts ("cradle to grave").	ABNT NBR ISO 14040; ISO 14044 (ISO 2006a; ISO 2006b); Guidelines ABNT PR 2030 (ABNT 2022).	Climate Plan; National Climate Change Policy; National Solid Waste Policy (PNRS).	Avoid burden shifting between phases or ecological categories.

Table 2. (continued)

Tool Group	Tool / Methodology	Variable / Metric Measured	Associated Technical Standard	Linked Legislation / National Plan	Function in System Dynamic Control
	Material Flow Analysis (MFA)	Mass balance; Stocks, circular inputs, and waste outputs per time unit.	Eurostat Methodology; Research Line Mapping (Brunner and Rechberger 2004; Barros *et al.* 2023).	National Solid Waste Policy (PNRS); PLANEC (Brazil 2025b).	Physically quantify recycling efficiency rates and landfill diversion.
	Analytic Hierarchy Process (AHP)	Weighting and relative weights of multiple criteria in decision structures.	Multi-Criteria Approaches (MCDM) in Process Engineering.	TSB Multi-Criteria Evaluation Guidelines (Brazil 2025a).	Unify multidimensional qualitative and quantitative variables into single scores.
2. Synthetic Circularity Indices	Material Circularity Indicator (MCI)	Fraction of virgin inputs, linear waste, and biological restoration efficiency (Score 0 to 1).	Methodology (Ellen MacArthur Foundation and ANSYS Granta 2019; Figueirinhas *et al.* 2025).	PLANEC (Bioeconomy and Agri-food Systems Axis) (Brazil 2025b).	Assess the degree of dependence on finite resources.
	Percentage of Circularity (% CTI)	Percentage of linear flows eliminated and actual recovery rate (0 to 100%).	Circular Transition Indicators Framework (WBCSD).	New Industry Brazil (NIB - Mission 5).	Penalize industrial linearity in processing agri-food co-products.
	9R Circularity Index	Level of physical-economic value retention based on the 9R priority hierarchy (Muñoz *et al.* 2024).	Bottom-up structures associated with AHP methodology.	PNRS; ENEC (Brazil 2024a); PLANEC (Brazil 2025b).	Prioritize redesign and source reduction over final remediation strategies.
3. Reports and Inventories	GHG Protocol and ISO 14064	Inventories of greenhouse gas emissions in Scopes 1, 2, and 3 (tCO_2eq).	ABNT NBR ISO 14064; Sector Tools (ABC+ Calc / GHG Agro).	Paris Agreement (UNFCCC 2015); Law No. 15,042/2024 - SBCE (Brazil 2024b); CVM Res. No. 193/2023 (CVM 2023); CSRD.	Monitor physical progress towards CO_2 emissions neutrality goals.

Table 2. (continued)

Tool Group	Tool / Methodology	Variable / Metric Measured	Associated Technical Standard	Linked Legislation / National Plan	Function in System Dynamic Control
	ESG Reporting Frameworks (GRI, SASB, CDP, TCFD)	Public disclosure of materiality, socioeconomic compliance, and risk governance.	Universal and Sectoral Standards GRI/ SASB; IFRS S1 and IFRS S2 (B3 2025).	2030 Agenda (United Nations 2015); TSB Risk Guidelines (Brazil 2025a); CVM Res. No. 193/2023 (CVM 2023).	Allow auditing of extended responsibility and mitigation of market risks.
	Market Indices and Certifications (ISE-B3, Ethos, B Corp)	Alignment of the corporate business model with social capital and ecological limits.	Third-Party Audit Questionnaires.	ENEC Social Responsibility Guidelines (Brazil 2024a).	Connect internal sustainability performance to market value structures.
	ISO 59000 and ISO 14001 Standards Family	Framework for measuring and evaluating the circular economy; Continuous EMS improvement.	ABNT NBR ISO 59020 / ISO 59004 (ISO 2024); ISO 14001 (ISO 2015).	PLANEC (Brazil 2025b); Green Seal Brazil.	Conceptually harmonize economic and environmental efficiency indicators.

6. Technological Perspectives and Maturation of Low-Carbon Agriculture

The relationship between CE, decarbonization, and technologies in agriculture is established through a systemic transformation: the Circular Economy provides the guiding principles (eliminate waste, keep materials in use, and regenerate nature), decarbonization is the ultimate climate goal (achieve net-negative emissions), and technologies, implemented in a phased manner over time, are the practical facilitators that make this transition possible and economically viable (Cahyadi *et al.* 2024; Craparo *et al.* 2024).

This technological maturation roadmap, integrating automation tools, biotechnology, and *Blockchain* technology as the backbone to ensure the immutability, verification, and transparency of data (Wang *et al.* 2020; Alotaibi *et al.* 2024), is divided into three main phases:

6.1. Current Maturation Level: Optimization with Current Technologies and Basic Traceability

The immediate focus is on increasing operational efficiency through digitalization and the optimization of input use, utilizing technological infrastructures already available on the market.

- Digital and precision agriculture: The consolidation of the use of global positioning systems (GPS), predictive agronomic models, and IoT-based sensors acts directly in monitoring field variables. These sensors operate by capturing real-time data on soil moisture, temperature, and conductivity, allowing the accurate prediction of crops' biological demand and optimizing the application of water resources and chemical inputs, avoiding the waste that becomes residue (Agbelusi *et al.* 2024).
- Enhanced chemical additives: At the material level, fertilization efficiency is optimized via the introduction of advanced additives, such as nitrification inhibitors. These compounds delay the

transformation of ammonium in the soil, improving the rate of nitrogen uptake by plants and immediately reducing fugitive emissions of nitrous oxide (N_2O) — one of the most potent greenhouse gases in the agricultural sector (Dash *et al.* 2025; Jayabal *et al.* 2025).

- IoT-Blockchain Integration: The physical monitoring sensors installed in the field begin to transmit the collected parameters (energy consumption, machinery efficiency, and humidity) directly and automatically to encrypted digital ledgers (*Blockchain*). This mechanism mitigates the need for manual data entry, eliminating anthropogenic errors and ensuring an immutable and auditable inventory for initial environmental sustainability reports (Alotaibi *et al.* 2024).

6.2. Emerging Maturation Level: Substitution by Innovations and Smart Contracts

This intermediate phase projects the substitution of conventional high-carbon-intensity processes with technologies currently in the prototype or early adoption stage, foreseeing a chain managed by decentralized governance systems.

- Electrification and green ammonia: It is estimated that tractors and heavy machinery powered by fossil fuels will be replaced by electric or hybrid fleets powered by renewable matrices (Jayabal *et al.* 2025). Likewise, it is projected that conventional nitrogen fertilizers will give way to green ammonia, synthesized through hydrogen obtained via water electrolysis driven by renewable energy, decarbonizing the upstream input chain (Wagh *et al.* 2024).
- Root-oriented crop genetics: It is anticipated that the incorporation of new phenotyping and gene-editing technologies will allow these plants to present a greater capacity to extract and fix nutrients in the deep soil, maximizing biological efficiency and reducing the demand for external chemical fertilization (Batlles-delaFuente *et al.* 2022).
- Smart Contracts: *Blockchain* technology is anticipated to evolve from a passive ledger to an automated climate governance system. While it is expected that this ecosystem may reduce fraud and issue high-integrity reports, it is important to acknowledge implementation barriers such as data-oracle problems, sensor uncertainty, and high transaction costs (Wang *et al.* 2020; Vilkov and Tian 2023).

6.3. Future Conceptual Level: Systems Redesign and Deep Digital Ecosystem Projection

The long-term stage comprises estimates for the state of the art in environmental engineering applied to agro-industry, projecting the systemic redesign of operations to achieve ultra-low emissions and net negative carbon sequestration rates.

- Small-scale autonomous robotics: It is foreseen that the replacement of heavy machinery by swarms of small-scale autonomous robots will redefine agricultural operations. Equipped with advanced computer vision and artificial intelligence systems, these robots will perform the micro-localized and frequent application of nutrients and biopesticides directly onto the biological target, which should eliminate soil physical compaction and reduce the total volume of pesticides applied (Agbelusi *et al.* 2024).
- Local production and biological innovations: It is projected that the energy infrastructure of rural properties will integrate agrivoltaic systems, where solar generation will occur concomitantly with cultivation, providing direct electrical energy for the localized manufacture of diluted fertilizers. In the biotechnological vector, it is estimated that advanced biology seeds — including perennial crops modified with the intrinsic capacity to fix their own atmospheric nitrogen — will act in symbiosis with bio stimulants, boosting microbial activity in the rhizosphere, regenerating natural fertility, and permanently fixing carbon in deep soil layers (Nazir *et al.* 2024; Dovgal *et al.* 2024).
- Blockchain Ecosystem and Digital Twins: The highest level of digital maturity should be consolidated with the fusion between *Blockchain*, Artificial Intelligence, and Digital Twins (real-

time virtual replicas of the field's biophysical and logistical dynamics). This integration will enable granular, continuous, and predictive tracking of emissions throughout the supply chain, optimizing logistics routes based on exergy efficiency data (Alotaibi *et al.* 2024). Additionally, it is estimated that decentralized *Blockchain* architectures will operate as automated markets where producers themselves will conduct surplus renewable energy transactions in peer-to-peer systems or commercialize forest offset credits with cryptographic security (Vilkov and Tian 2023; Wang *et al.* 2020).

To consolidate the interrelationships between the theoretical foundations, regulatory frameworks, standardization metrics, and technological innovations discussed in this study, a systemic integration model (framework) is proposed. Figure 1 illustrates the mapping of this transition architecture for the agro-industrial sector, structured into five complementary and interdependent layers. This conceptual framework was derived inductively by mapping the regulatory requirements of Brazilian policies against international standards and grouping them into analytical categories.

Layer 0 (Theoretical Foundations) and Layer 1 (Regulatory & Political Direction) form the propelling base of the system, where the precepts of the Circular Economy and Life Cycle Assessment (LCA) support compliance with international climate agreements and national legislation (such as the SBCE and the Forest Code). This normative framework is translated into state strategy and financing instruments (such as the Brazilian Sustainable Taxonomy and PLANEC). In Layer 2 (Standardization, Metrics & Reporting), this regulatory pressure meets the technical rigor of ISO standards, ESG disclosure guidelines, and emissions inventory frameworks, culminating in obtaining Green Seals that attest to the producer's compliance.

At the practical level, Layer 3 (Operational Strategies) categorizes agribusiness mitigation actions through Narrowing (input optimization), Closing (nutrient and biogas recycling), and Regenerating strategies (practices such as no-till farming and ILPF systems). Finally, the model reaches its maturity in Layer 4 (Digital Integration & Market), where the automation of data collection via IoT and Digital Twins feeds Smart Contracts. These algorithms validate compliance with the Taxonomy and ISO standards, feeding back the system and enabling transparent and auditable access to green credits, Payments for Environmental Services (PES), and carbon markets.

This review presents limitations that must be considered in the interpretation of the results. The rapid updating of policies, taxonomies, technical standards, and market mechanisms may alter the regulatory framework presented. Furthermore, the diversity of productive systems, business scales, and territorial conditions limits the generalization of the recommendations to the entire agro-industrial sector. The proposed framework is conceptual in nature and requires validation through case studies, expert consultation, and application across different supply chains. Possible biases arising from the selection of sources, the predominance of Brazilian documents, and the unequal availability of empirical evidence on emerging technologies must also be considered.

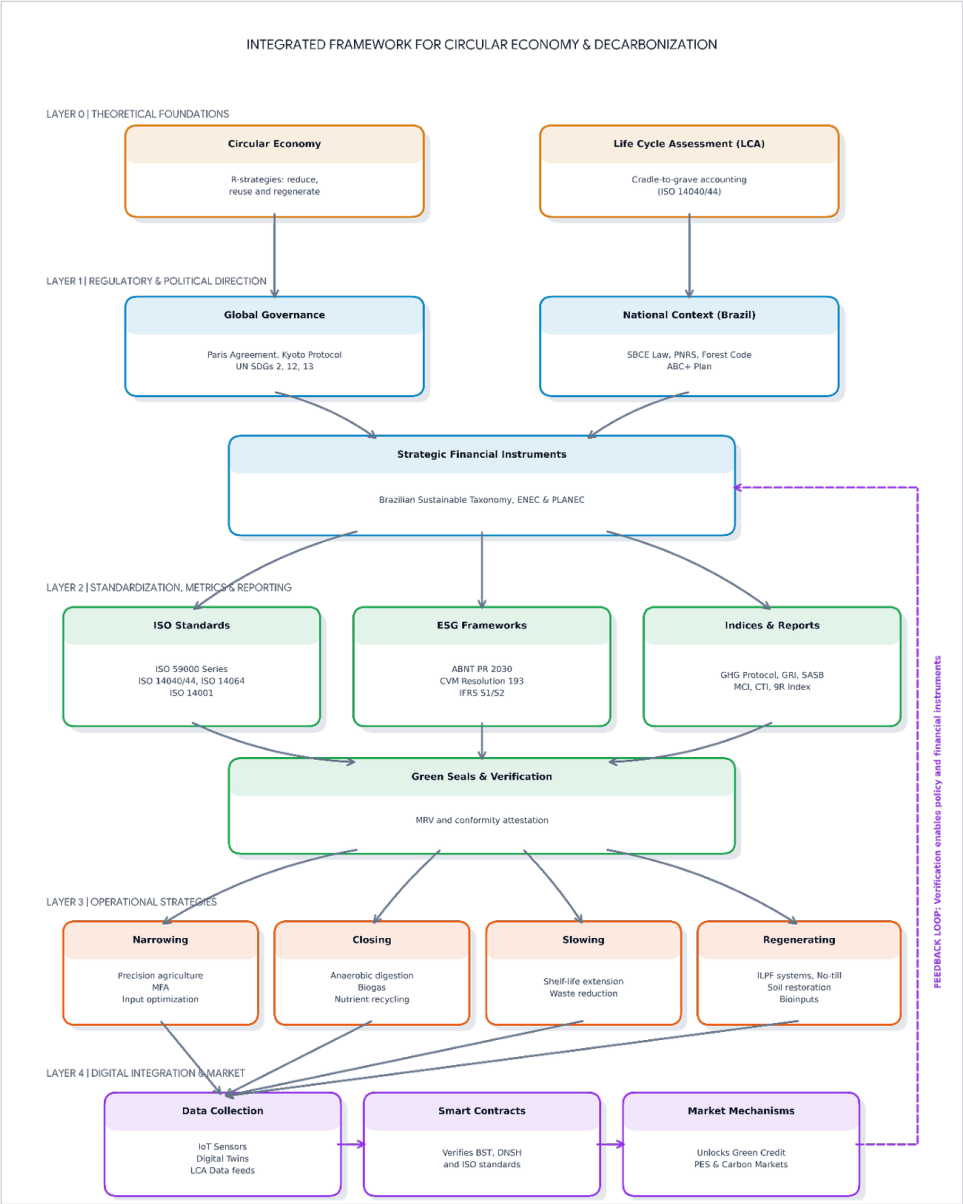


Figure 1. Integrated framework for circular economy and decarbonization in agribusiness.

Source: Elaborated by the author (2026).

7. Conclusion

The triangulated analysis conducted in this study demonstrates that the transition to a low-carbon and regenerative circular economy in the agro-industrial sector relies on a deeply interdependent normative and technological ecosystem. Based on the reviewed literature and regulatory documents, it is evident that isolated actions are insufficient to overcome the current linear extractive model. Instead, success requires continuous coordination among legal obligations, voluntary standardizations, and enabling technologies.

As a conceptual synthesis of these findings, this study proposed a multilevel implementation framework specifically oriented towards the Brazilian agribusiness context. The framework delineates how these spheres interact functionally: (i) Laws and Policies (e.g., Paris Agreement, SBCE, TSB) establish the regulatory boundaries and macroeconomic incentives; (ii) Standards and Frameworks (e.g., ISO 59000 family, ABNT PR 2030) translate these mandates into auditable metrics, mitigating transition risks and greenwashing; and (iii) Circular Technologies (e.g., precision

agriculture, anaerobic digestion) provide the practical tools for executing Narrowing, Closing, and Regenerating strategies in the field.

Furthermore, as a prospective proposition, this study identifies the potential of deep transparency architectures—integrating IoT sensors, Blockchain, and Smart Contracts—to function as automated control loops. While these emerging technologies offer promising pathways for the real-time verification of climate targets and decentralized access to green financing, their integration into the proposed framework remains conceptual and represents a frontier for future maturation.

Finally, it is crucial to acknowledge the limits of generalization of this study. Given its strong orientation towards Brazilian public policies and regulatory frameworks, the proposed architecture requires adaptations before being applied to other geopolitical contexts. Future research should focus on the empirical validation of this conceptual framework through field case studies across different agricultural supply chains, assessing the practical viability, socioeconomic barriers, and actual scalability of the proposed digital and circular interventions.

Abbreviations

Abbreviation	Description
ABC+	Low Carbon Emission Agriculture Plan (Plano Agricultura de Baixa Emissão de Carbono)
AHP	Analytic Hierarchy Process
CBD	Convention on Biological Diversity
CDP	Carbon Disclosure Project
CE	Circular Economy
CTI	Circular Transition Indicators
CVM	Securities and Exchange Commission of Brazil (Comissão de Valores Mobiliários)
ENEC	National Circular Economy Strategy (Estratégia Nacional de Economia Circular)
ESG	Environmental, Social, and Governance
GHG	Greenhouse Gas
GRI	Global Reporting Initiative
IFRS	International Financial Reporting Standards
ILPF	Crop-Livestock-Forest Integration (Integração Lavoura-Pecuária-Floresta)
IoT	Internet of Things
LCA	Life Cycle Assessment
MCI	Material Circularity Indicator
MFA	Material Flow Analysis
NDC	Nationally Determined Contribution
PES	Payment for Environmental Services
PLANEC	National Circular Economy Plan (Plano Nacional de Economia Circular)
PNRS	National Solid Waste Policy (Política Nacional de Resíduos Sólidos)
SASB	Sustainability Accounting Standards Board
SBCE	Brazilian Emissions Trading System (Sistema Brasileiro de Comércio de Emissões)
SDG	Sustainable Development Goal
TCFD	Task Force on Climate-related Financial Disclosures
TSB	Brazilian Sustainable Taxonomy (Taxonomia Sustentável Brasileira)

Declarations

Author contributions. Leticia Barbosa Fidanza: Conceptualization, Methodology, Writing (original draft). Ariane Mayer Ferreira Embden: Writing (review and editing). Giancarlo Alfonso Lovon Canchumani: Methodology, Supervision, Writing (review and editing). Leda Maria Saragiotto Colpini: Methodology, Supervision, Writing (review and editing).

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