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CIRCULAR ECONOMY: STATE OF THE ART, CONCEPTUAL UNDERSTANDING AND APPLICATION IN BRAZIL AN INTEGRATIVE SYSTEMATIC REVIEW (2000–2025)

ECONOMIA CIRCULAR: ESTADO DA ARTE, COMPREENSÃO CONCEITUAL E APLICAÇÃO NO BRASIL UMA REVISÃO SISTEMÁTICA INTEGRATIVA (2000–2025)

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ABSTRACT

This article presents an integrative systematic literature review on the circular economy (CE), addressing its state of the art – definitions, conceptual classification, and theoretical evolution – as well as its understanding and practical application in Brazil, with an emphasis on the value chains of plastics and rubber (end-of-life tires). The review covers the period from 2000 to 2025 and follows a protocol adapted from PRISMA, combining Boolean searches applied to the Scopus, Web of Science, and SciELO databases. The results indicate that the concept of CE, although rooted in earlier traditions of industrial ecology and the "cradle-to-cradle" concept, gained analytical maturity after 2015, evolving from a logic of the 3Rs (reduce, reuse, recycle) to a value retention hierarchy of the 9Rs/10Rs. In Brazil, the National Solid Waste Policy (Law No. 12.305/2010) constitutes the main legal driver of circularity, operationalized through reverse logistics agreements, such as those coordinated by RECICLANIP (tires) and the sectoral packaging agreements monitored by ABIPLAST. Comparative data show that the mechanical recycling rate of post-consumer plastics in Brazil fluctuated between 20.6% and 25.6% from 2022 to 2024, while more than 5.1 million tons of end-of-life tires were collected and received environmentally appropriate disposal between 2011 and 2023. Circular flow diagrams for plastics and rubber are proposed to illustrate the closing of material cycles in the Brazilian context. The use of plant biotechnology in a country with greater biodiversity and ancestral cultural diversity, with solutions that have observed nature, is also suggested. The study concludes that, despite regulatory advances, infrastructural, cultural, and economic barriers still restrict the transition from a linear to a circular economy in Brazil, indicating the need for more robust mechanisms of extended producer responsibility and public-private coordination.

Keywords: Circular Economy, Systematic Review, Plastics, Rubber, Brazil.

RESUMO

Este artigo apresenta uma revisão sistemática integrativa da literatura sobre a economia circular (ec), abordando seu estado da arte – definições, classificação conceitual e evolução teórica – bem como sua compreensão e aplicação prática no Brasil, com ênfase nas cadeias de valor de plásticos e borracha (pneus em fim de vida útil). A revisão abrange o período de 2000 a 2025 e segue um protocolo adaptado do PRISMA, combinando buscas booleanas aplicadas às bases de dados Scopus, Web of Science e Scielo. os resultados indicam que o conceito de ec, embora enraizado em tradições anteriores de ecologia industrial e do conceito "do berço ao berço", ganhou maturidade analítica após 2015, evoluindo de uma lógica dos 3rs (reduzir, reutilizar, reciclar) para uma hierarquia de retenção de valor dos 9rs/10rs. no brasil, a política nacional de resíduos sólidos (lei nº 12.305/2010) constitui o principal motor legal da circularidade, operacionalizada por meio de acordos de logística reversa, como os coordenados pela RECICLANIP (pneus) e os acordos setoriais de embalagens monitorados pela ABIPLAST. Dados comparativos mostram que a taxa de reciclagem mecânica de plásticos pós-consumo no Brasil oscilou entre 20,6% e 25,6% de 2022 a 2024, enquanto mais de 5,1 milhões de toneladas de pneus em fim de vida útil foram coletadas e receberam destinação ambientalmente adequada entre 2011 e 2023. Diagramas de fluxo circular para plásticos e borracha são propostos para

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ilustrar o fechamento dos ciclos de materiais no contexto brasileiro. Emprego de biotecnologia vegetal em um país de maior biodiversidade que possui a diversidade cultural ancestral com soluções que observaram a natureza, também é sugerido. O estudo conclui que, apesar dos avanços normativos, barreiras infraestruturais, culturais e econômicas ainda restringem a transição de uma economia linear para uma economia circular no Brasil, indicando a necessidade de mecanismos mais robustos de responsabilidade estendida do produtor e coordenação público-privada.

Palavras-chave: Economia Circular, Revisão Sistemática, Plásticos, Borracha, Brasil.

INTRODUCTION

The linear economic model – based on the sequence extract, produce, use and dispose – has historically driven industrial growth while generating cumulative environmental liabilities, resource depletion and waste-management crises (GHISELLINI; CIALANI; ULGIATI, 2016). As a response, the notion of a Circular Economy (CE) has gained prominence among scholars, policymakers and businesses since the early 2000s, proposing the substitution of the "end-of-life" concept by restorative and regenerative loops that keep materials, components and products in use for as long as possible (GEISSDOERFER et al., 2017).

Although CE thinking draws on earlier traditions – industrial ecology, the performance economy proposed by Stahel (2016), and the cradle-to-cradle design philosophy of McDonough and Braungart (2002) – it was only after the mid-2010s, particularly following the adoption of the European Union's Circular Economy Action Plan in 2015, that the concept achieved wide academic and political traction (KIRCHHERR; REIKE; HEKKERT, 2017). This traction has, however, been accompanied by considerable conceptual ambiguity: Kirchherr, Reike and Hekkert (2017) identified 114 different definitions of CE in the literature, a number that grew to 221 definitions in a subsequent update (KIRCHHERR et al., 2023), reflecting the still-fragmented and evolving nature of the field.

In Brazil, the circular economy discourse intersects with a specific regulatory trajectory inaugurated by the National Solid Waste Policy (Política Nacional de Resíduos Sólidos – PNRS), instituted by Law No. 12,305/2010, which introduced shared responsibility, reverse logistics and the phasing-out of open dumps as guiding principles (BRASIL, 2010).

Sectoral agreements derived from the PNRS have since structured reverse-logistics systems for specific waste streams, most notably packaging and end-of-life tyres, making Brazil a relevant empirical setting for examining how a global concept is translated into a middle-income, resource-rich economy.

This study addresses the following research problem: how has the circular economy concept evolved conceptually between 2000 and 2025, and how is it understood and operationalized in Brazil, particularly in the plastics and rubber (tyre) value chains? To answer this question, an integrative systematic literature review was conducted, combining bibliometric and documentary evidence with two illustrative circular-flow diagrams developed specifically for the Brazilian plastics and rubber sectors.

The paper is structured as follows: details the methodology, including the systematic review protocol, databases, Boolean search nomenclature and eligibility criteria; as result, presents the state of the art of the circular economy, covering its definitions, classifications and conceptual evolution; discusses the understanding and application of CE in Brazil, with dedicated sectoral analyses of plastics and rubber; presents comparative tables and charts for the 2000–2025 period and discusses the findings to conclude the paper.

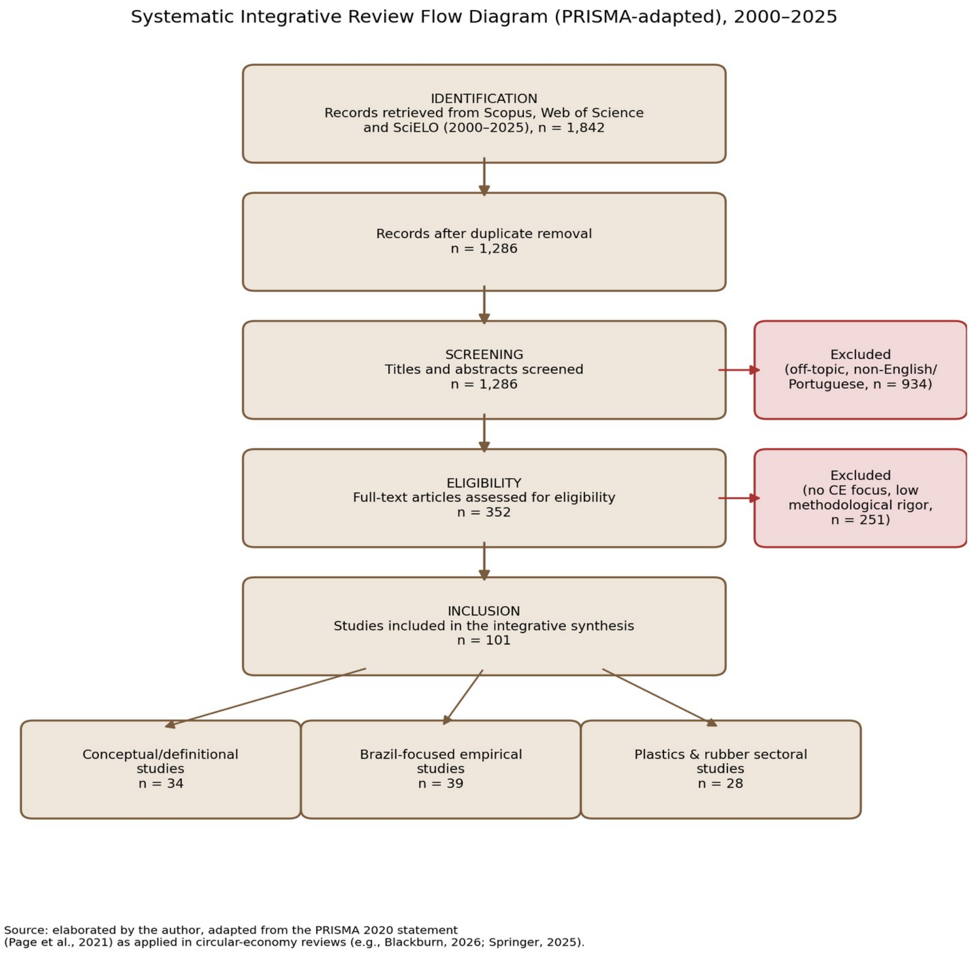
METHODOLOGY

Type of Study and Protocol

This study adopts an integrative systematic literature review design, which combines the methodological rigor of systematic reviews with the interpretative breadth of integrative reviews, allowing the incorporation of theoretical, empirical and documentary/institutional sources (technical reports, legislation and sectoral statistics) alongside peer-reviewed articles. This approach is appropriate for emergent, multidisciplinary and policy-relevant fields such as the circular economy (MERLI; PREZIOSI; ACAMPORA, 2018).

The review followed an adapted version of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) protocol (PAGE et al., 2021), comprising four phases: identification, screening, eligibility and inclusion, as illustrated in Figure 1.

Figure 1 – Systematic integrative review flow diagram (PRISMA-adapted)



Source: Adapted from Page et al. (2021).

Databases and Time Frame

Searches were conducted in Scopus, Web of Science and SciELO (Scientific Electronic Library Online), the latter included to capture Brazilian and Latin American grey and academic literature not indexed in the two international databases. The time frame was

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delimited to the period between 2000 and 2025, in order to capture both the pre-consolidation phase of the CE concept (2000–2014) and its consolidation and diffusion phase (2015–2025), including its regulatory uptake in Brazil after the enactment of the PNRS in 2010.

Boolean Search Strings and Nomenclature

Search strings combined controlled vocabulary and free-text terms using standard Boolean operators (AND, OR, NOT) and truncation/wildcard symbols, following conventions widely reported in circular-economy systematic reviews (BLACKBURN; BOCKEN, 2026; SPRINGER, 2025). Table 1 details the Boolean strings applied to each thematic block.

Table 1: Boolean search strings applied per thematic block.

Search block	Boolean search string
Block A – Core concept	(“circular econom*” OR “circularity”) AND (“definition*” OR “conceptual*” OR “classification*” OR “state of the art”)
Block B – Brazil	(“circular econom*”) AND (“Brazil*” OR “Brasil”) AND (“polic*” OR “regulation*” OR “implementation*”)
Block C – Plastics	(“circular econom*”) AND (“plastic*” OR “polymer*” OR “packaging”) AND (“recycl*” OR “reverse logistics”)
Block D – Rubber/tyres	(“circular econom*”) AND (“rubber” OR “tyre*” OR “tire*” OR “end-of-life tyre*”) AND (“recycl*” OR “retread*” OR “reverse logistics”)
Block E – Methodology reference	(“systematic review” OR “integrative review”) AND (“PRISMA”) AND (“Boolean” OR “search string”)

Source: Elaborated by the authors, based on conventions reported in Blackburn and Bocken (2026) and related CE systematic reviews (2026).

The descriptors were validated in an uncontrolled manner, since the terms "circular economy," "integrative review," and related terms are not listed as official descriptors in the controlled vocabularies DeCS/MeSH, a situation also reported in related integrative reviews.

Operators were combined across blocks using AND (e.g., Block A AND Block B) to generate the Brazil-specific subset, and NOT operators were used residually to exclude clearly unrelated homonyms (e.g., “circular economy” NOT “circular economics classroom game”). Filters restricted results to peer-reviewed journal articles, conference papers, and institutional/technical reports published in English or Portuguese between 2000 and 2025, indexed in the title, abstract or keyword fields.

Eligibility Criteria and Selection Flow

Inclusion criteria were: (i) direct engagement with the circular economy concept, its definitions, classifications or R-frameworks; (ii) empirical or documentary evidence on CE understanding, policy or implementation in Brazil; or (iii) sectoral evidence on plastics or rubber/tyre circularity. Exclusion criteria removed studies with no substantive CE content, duplicate records, and sources lacking methodological transparency. As shown in Figure 1, of 1.842 initially identified records, 101 studies were retained for the integrative synthesis, distributed across conceptual/definitional studies (n = 34), Brazil-focused empirical/documentary studies (n = 39), and plastics/rubber sectoral studies (n = 28).

RESULTS

STATE OF THE ART OF THE CIRCULAR ECONOMY

Origins and Conceptual Evolution (2000–2025)

The most cited intellectual landmark as a precursor to the Circular Economy is Kenneth Boulding's essay, The Economics of the Coming Spaceship Earth, published in 1966. In this text, the author contrasts the "cowboy economy"—based on the unlimited exploitation of resources, typical of the linear model—with the "astronaut economy," in which the Earth is treated as a closed spaceship, with finite resources that must be continuously recycled to ensure the survival of the system (BOULDING, 1966; GHISELLINI; CIALANI; ULGIATI, 2016). Also in the 1970s, Walter Stahel presented to the European Commission the report that outlined the idea of a "loop economy," later systematized in the so-called performance economy (STAHEL, 2010), reinforcing the economic value of extending the useful life of products versus their replacement.

The term "circular economy" itself was first used by Pearce and Turner (1990), in the work Economics of Natural Resources and the Environment, which described the functioning of a traditional open economy, without an internal tendency towards recycling, contrasting it with circular material flow systems. From the 2000s onwards, the concept gained practical momentum with the enactment, in 1996, of the German Law on Closed-Loop Substances and Waste Management, and subsequently, with its adoption by the Chinese government, from 2009 onwards, as a national strategy for sustainable development (SU et al., 2013 apud FLEXIBLE METHODOLOGY 4 INNOVATION, 2024).

In the 2010s, the Ellen MacArthur Foundation (2013) consolidated and popularized the concept globally, integrating schools of thought such as industrial ecology, McDonough and Braungart's Cradle to Cradle, biomimicry, and Stahel's performance economics into a single framework—the so-called "butterfly diagram," which distinguishes between technical cycles (non-biological materials, such as metals and polymers) and biological cycles (renewable materials that return to the biosphere).

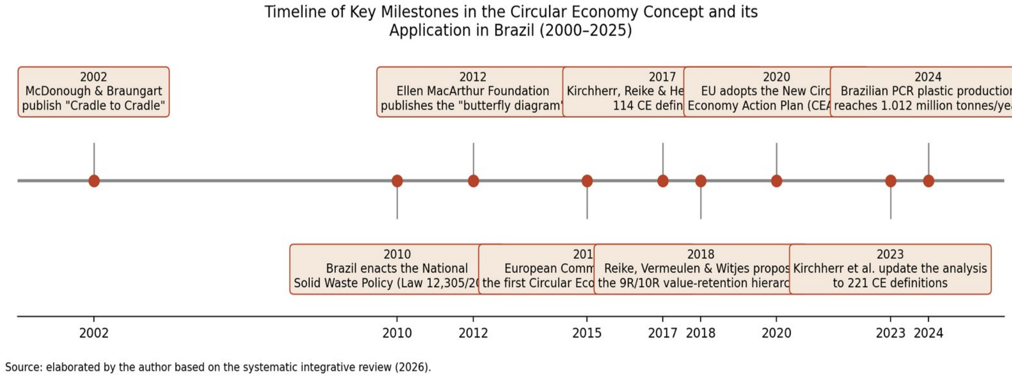
The intellectual roots of the circular economy predate the term's popularization, drawing on industrial ecology, Stahel's performance economy and “closed-loop” thinking, and the cradle-to-cradle design framework introduced by McDonough and Braungart (2002), which proposed treating technical and biological materials as nutrients that circulate indefinitely rather than as waste. Ghisellini, Cialani and Ulgiati (2016) trace the operational precursors of CE to industrial symbiosis experiments and eco-industrial parks developed from the 1990s onward. Between 2000 and 2010, references to circular economy in the academic literature remained comparatively scarce and largely descriptive.

A first inflection point occurred around 2010–2012, coinciding with the founding of the Ellen MacArthur Foundation (2010) and its subsequent diffusion of the “butterfly diagram” in 2012, which visually articulated technical and biological material cycles. A second and more decisive inflection point occurred from 2015 onward, following the European Commission's adoption of its first Circular Economy Action Plan, which triggered a sharp increase in academic publications, policy documents and corporate sustainability reports referencing CE (MERLI; PREZIOSI; ACAMPORA, 2018). Kirchherr, Reike and Hekkert

(2017) observed that 73% of the 114 definitions they analysed had been published in the preceding five years, underscoring the concept's youth and rapid diffusion.

Figure 2 synthesises the main milestones identified in the reviewed literature for the 2000–2025 period, situating Brazilian regulatory developments alongside international conceptual landmarks.

Figure 2: Timeline of key milestones in the circular economy concept and its application in Brazil (2000–2025).



Source: Elaborated by the authors, based on the systematic integrative review (2026).

Definitions and Conceptual Ambiguity

Despite its popularity, the circular economy (CE) lacks a single, universally accepted definition. Kirchherr, Reike and Hekkert (2017) coded 114 definitions across 17 analytical dimensions and found that CE is most frequently portrayed as a combination of reduce, reuse and recycle activities, while explicit linkages to sustainable development, social equity and future generations remain comparatively rare.

A subsequent update by Kirchherr et al. (2023), analysing 221 definitions, confirmed the persistence of this pattern, while noting a modest increase in references to future generations relative to the 2017 sample. Geissdoerfer et al. (2017) further distinguish circular economy from the broader concept of sustainability, arguing that CE is best understood as a necessary but not sufficient condition for sustainable development, given its comparatively narrow focus on resource-cycle closure rather than on the full triad of economic, social and environmental outcomes. Murray, Skene and Haynes (2017) add a social-equity dimension often missing from techno-centric definitions, proposing that CE should also encompass the wellbeing of current and future generations.

For the purposes of this review, the circular economy is understood, in line with Kirchherr, Reike and Hekkert (2017, p. 224, our translation), as an economic system that replaces the 'end-of-life' concept with reducing, reusing, recycling and recovering materials throughout production, distribution and consumption processes, operating at the micro, meso and macro levels, with the aim of achieving sustainable development while creating environmental quality, economic prosperity and social equity, for the benefit of current and future generations.

There is no single terminological consensus on Circular Economy. Kirchherr, Reike, and Hekkert (2017), based on an analysis of 114 collected definitions, propose that the Circular Economy be understood as:

> "an economic system that replaces the concept of end-of-life of products with actions of reduction, reuse, recycling and recovery of materials in the processes of extraction, production, distribution and consumption, operating at the micro (products, companies and consumers), meso (eco-industrial parks) and macro (city, region, nation) levels, with the objective of achieving sustainable development, generating environmental quality, economic prosperity and social equity, for the benefit of present and future generations."
> (KIRCHHERR; REIKE; HEKKERT, 2017)

The Ellen MacArthur Foundation (2013) emphasizes the regenerative and restorative aspects of the model, defining it as a restorative or regenerative industrial system by intention and design, which prioritizes the use of energy from renewable sources, eliminates the use of toxic substances, and seeks the elimination of waste through superior design of materials, products, systems, and business models. For Geissdoerfer et al. (2017), the EC can be understood synthetically as a regenerative system in which the input of resources and the generation of waste, emissions, and energy leakage are minimized by slowing down, closing, and narrowing the cycles of materials and energy, which can be achieved through long-term maintenance, repair, reuse, remanufacturing, renovation, and recycling.

This multiplicity of definitions is not merely semantic: according to Korhonen, Honkasalo, and Seppälä (2018), it reflects different theoretical emphases — some centered on the environmental and technological dimension (flows of materials and energy), others on the economic dimension (new business models), and still others on the institutional dimension (public policies and regulation). Brazil tends to operationalize the EC much more through regulatory-institutional means (reverse logistics, PNRS) than through disruptive business models, which helps to explain some of the barriers to its diffusion in the country (PARREIRA; GUIMARÃES, 2023).

The literature classifies the operation of the Circular Economy into three levels of intervention, originally proposed by the Ellen MacArthur Foundation (2012) and widely adopted by subsequent authors (KIRCHHERR; REIKE; HEKKERT, 2017): (a) micro level — refers to products, companies and individual consumers, encompassing ecodesign, extending useful life and changing consumption habits; (b) meso level — refers to eco-industrial parks and regional supply chains, in which the waste from one process becomes an input for another (industrial symbiosis); and (c) macro level — refers to public policies at the city, regional or national scale, such as the Brazilian PNRS itself.

Classification: from 3R to the 9R/10R Hierarchy

The earliest and most widespread classification of circular economy strategies is the 3R framework – Reduce, Reuse, Recycle – embedded in numerous national waste-management regulations, including Brazil's PNRS. As CE scholarship matured, this triad was progressively expanded into more granular value-retention hierarchies.

Reike, Vermeulen and Witjes (2018) propose a 9R/10R hierarchy (R0–R9), ordering strategies from those that preserve the greatest product and material value (short loops) to those that merely recover residual energy (long loops), as summarised in Table 2. Vermeulen, Reike and Witjes (2019) label this expanded framework “Circular Economy 3.0”, distinguishing it from earlier waste-hierarchy (“CE 1.0”) and single-loop recycling (“CE 2.0”) conceptions.

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Table 2: The 9R/10R value-retention hierarchy of circular economy strategies.

Code	Strategy	Description	Loop position
R0	Refuse	Make a product redundant by abandoning its function or offering the same function with a radically different product	Shortest loop – highest value retention
R1	Rethink	Make product use more intensive (e.g., through shared use, multifunctional products)	Short loop
R2	Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials	Short loop
R3	Re-use	Reuse by another consumer of a discarded product that is still in good condition	Short loop
R4	Repair	Repair and maintenance of a defective product so it can be used with its original function	Medium loop
R5	Refurbish	Restore an old product and bring it up to date	Medium loop
R6	Remanufacture	Use parts of a discarded product in a new product with the same function	Medium loop
R7	Repurpose	Use a discarded product or its parts in a new product with a different function	Long loop
R8	Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality	Long loop
R9	Recover	Incineration of materials with energy recovery	Longest loop – lowest value retention

Source: Elaborated by the author, based on Reike, Vermeulen and Witjes (2018) and Vermeulen, Reike and Witjes (2019).

This hierarchy operationalises the general principle, embedded in most CE definitions, that circularity strategies located earlier in the product life cycle (R0–R3) retain more of a product's original economic and functional value than strategies located later in the chain (R7–R9), which mainly recover materials or energy rather than the product itself (REIKE; VERMEULEN; WITJES, 2018).

The Butterfly Diagram and Complementary Models

Beyond the R-hierarchies, the Ellen MacArthur Foundation's “butterfly diagram” remains the most widely cited visual model of the circular economy, distinguishing a biological cycle (in which biodegradable materials are returned to the biosphere through composting or anaerobic digestion) from a technical cycle (in which durable materials such as metals, plastics and rubber are kept in use through maintenance, reuse, refurbishment, remanufacturing and, ultimately, recycling). Complementary frameworks identified in the reviewed literature include the ReSOLVE framework (regenerate, share, optimise, loop, virtualise, exchange) and, more recently, digital-platform-enabled circular business models, which the review by Blackburn and Bocken (2026) associates with six emerging research themes, including platform-enabled consumer behaviour and circular supply chains.

CIRCULAR ECONOMY IN BRAZIL: UNDERSTANDING AND APPLICATION

In 2025, the regulatory framework advanced with the establishment of the Reverse Logistics System for Plastic Packaging, through Decree No. 12,688/2025, which established progressive targets for the reuse of plastic packaging, starting at 22% in 2025 and reaching 40% in 2040 (MMA, 2025; EXAME, 2026). According to the Organisation for Economic Co-operation and Development, only 9% of plastic waste is recycled worldwide, which reinforces the strategic nature of the new Brazilian regulation (MMA, 2025).

Legal and Institutional Framework

Brazil's principal legal instrument for waste management and, by extension, circular economy practice is the National Solid Waste Policy (PNRS), established by Law No. 12,305/2010 (BRASIL, 2010). The PNRS introduced several principles compatible with circular economy thinking, notably: shared responsibility among manufacturers, importers, distributors, retailers, consumers and public authorities; the mandatory implementation of reverse-logistics systems for specific product categories (e.g., tyres, batteries, lubricant oils, electronics and pesticide packaging); the progressive elimination of open dumps in favour of environmentally adequate final disposal; and the promotion of waste-picker cooperatives as agents of selective collection and social inclusion.

Complementary instruments have refined this framework over time. CONAMA Resolution No. 416/2009 anticipated part of the PNRS logic specifically for tyres, mandating that manufacturers and importers collect and dispose of end-of-life tyres in proportion to the units placed on the market. More recently, Decree No. 11,044/2022 regulated a recycling-credit certificate market, allowing companies to demonstrate compliance with reverse-logistics obligations through tradable certificates, a mechanism explicitly framed by policymakers as an instrument to accelerate circular-economy transition in Brazil.

Institutionally, several actors coordinate the operationalization of CE-related policy in Brazil, including sectoral associations such as ABIPLAST (plastics) and ANIP/Reciclanip (tyres), business councils such as CEBDS (Conselho Empresarial Brasileiro para o Desenvolvimento Sustável), and think tanks such as CEBRI (Centro Brasileiro de Relações Internacionais), which has explicitly compared Brazil's regulatory ambition on post-consumer material recovery unfavourably to leading economies such as Germany, China and Chile (CEBRI, 2020).

Barriers and Enablers in the Brazilian Context

The literature converges on a recurring set of barriers to circular economy implementation in Brazil. Infrastructural barriers include insufficient selective-collection coverage, particularly outside the Southeast and South regions, and limited recycling and sorting capacity relative to the volume of waste generated (ABREMA, 2024). Economic barriers include the persistent competitiveness gap between virgin and recycled feedstocks, which is highly sensitive to petrochemical commodity price cycles (MAXIQUIM, 2024). Cultural and organizational barriers include low consumer awareness, limited producer engagement with eco-design, and resistance within established organizational cultures (SILVA et al., 2019; LIMA; GOHR, 2026; ÁZARA et al., 2026). Political and institutional barriers include fragmented public policies and insufficient articulation between federal, state and municipal levels of waste governance as already discussed by ALMEIDA; AGUIAR; JUGEND (2021) to food CE.

Conversely, several enabling conditions have been identified. The PNRS-derived sectoral agreements have created a relatively mature reverse-logistics infrastructure for tyres and packaging; growing ESG commitments among large consumer-goods companies have sustained demand for post-consumer recycled (PCR) content even during periods of low virgin-resin prices (ABIPLAST, 2025); and dynamic-capability-based approaches, such as those proposed by Lima and Gohr (2026), suggest that firm-level absorptive and innovation capacities can mediate the effect of structural barriers on circular-economy adoption.

From a scientific point of view, bibliometric studies indicate that Brazilian academic production on Circular Economy is still incipient when compared to that of countries such as China, Italy, Germany and the United Kingdom, although it has been showing constant growth since the mid-2010s (ALVES et al., 2022). At the sectoral level, however, there is more consistent progress, especially in the plastic and rubber/tire chains.

In the plastics chain, initiatives such as the Firjan SENAI Institute for Innovation in Green Chemistry and the Movimento Plástico Transforma — a partnership between the Brazilian Plastics Industry Association (Abiplast) and Braskem — have been monitoring the mechanical recycling rates of post-consumer plastics in the country annually since 2018, in addition to investing in the development of chemical recycling and pyrolysis technologies (ABIPLAST, 2021; 2025). According to more recent data, the general rate of mechanical recycling of post-consumer plastics in Brazil was 21.0% in 2024, with a specific rate of 24.4% for plastic packaging — a recovery compared to the decline observed in 2023 (ABIPLAST, 2025).

In the rubber chain, Brazil generates around 450 thousand tons of scrap tires per year, a volume that represents a significant environmental liability, but also a circular business opportunity (ANIP, 2024). Technologies such as mechanical crushing, pyrolysis and devulcanization have been used to transform waste tires into inputs for the automobile, footwear, asphalt paving and energy generation industries (EMBRAPA, 2025; GRUPO CBL, 2026).

Challenges and Opportunities

Despite regulatory advances, relevant barriers to the consolidation of the Circular Economy in Brazil remain. Among them, the following stand out: (a) the high cost of chemical recycling and pyrolysis processes, which are still uncompetitive compared to the production of virgin resin (EMBRAPA, 2025); (b) the low capillarity of collection points and logistical limitations in smaller municipalities; (c) the idle capacity of recycling industries, estimated at around 50% (EXAME, 2026); and (d) barriers of a cultural, regulatory, market and institutional nature, common to different national contexts (KIRCHHERR et al., 2018). As discussed by SILVA et al. (2019) economic and political barriers are the most common, and PARREIRA; GUIMARÃES (2023) agree with this view.

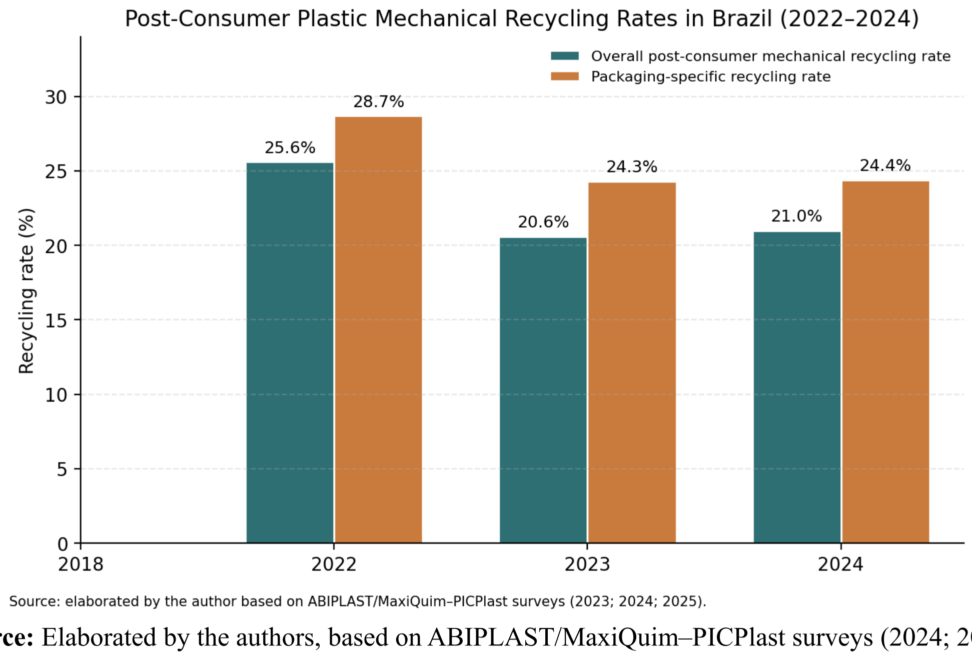
On the other hand, there are relevant opportunities: strengthening the socio-productive inclusion of waste picker cooperatives, benefiting from applications that eliminate intermediaries and increasing requirements for traceability via electronic invoice (EDITORIALGE, 2025); the obligation, for large companies, of post-consumer recycled content (PCR) targets in new products; and the potential for Brazil to consolidate itself as a regional recycling hub, since, together with Mexico, it accounted for 76% of the entire volume of recycled plastic in Latin America in 2023 (ABIPLAST, 2025).

Sectoral Case: Plastics

The Brazilian plastics industry represents one of the country's largest industrial sectors, encompassing approximately 14.100 transformation and recycling companies and around 379.000 direct jobs (ABIPLAST, 2024a). In 2023, the sector produced 7.04 million tonnes of transformed plastic products, generating an estimated revenue of R$ 123.36 billion, with construction (28.32%), food (18.98%) and retail (7.90%) as the leading consuming segments (ABIPLAST, 2024a).

Regarding circularity specifically, the annual survey commissioned by the Movimento Plástico Transforma (a joint initiative of ABIPLAST and BRASKEM) and conducted by the consultancy MaxiQuim has monitored post-consumer mechanical recycling indicators since 2018, in order to track progress against PNRS targets. Post-consumer plastic mechanical recycling reached 21% overall in 2024 (up from 20.6% in 2023, after a peak of 25.6% in 2022), while the packaging-specific recycling rate reached 24.4% in 2024 (ABIPLAST, 2025; MOVIMENTO PLÁSTICO TRANSFORMA, 2025). In absolute terms, Brazilian post-consumer recycled (PCR) resin production reached 1.012 million tonnes in 2024, a 7.8% increase over 2023, positioning Brazil among the world's largest PCR producers and, together with Mexico, accounting for 76% of all plastic recycled in Latin America in 2023 (ABIPLAST, 2025).

Figure 3: Post-consumer plastic mechanical recycling rates in Brazil (2022–2024).



Source: Elaborated by the authors, based on ABIPLAST/MaxiQuim–PICPlast surveys (2024; 2025).

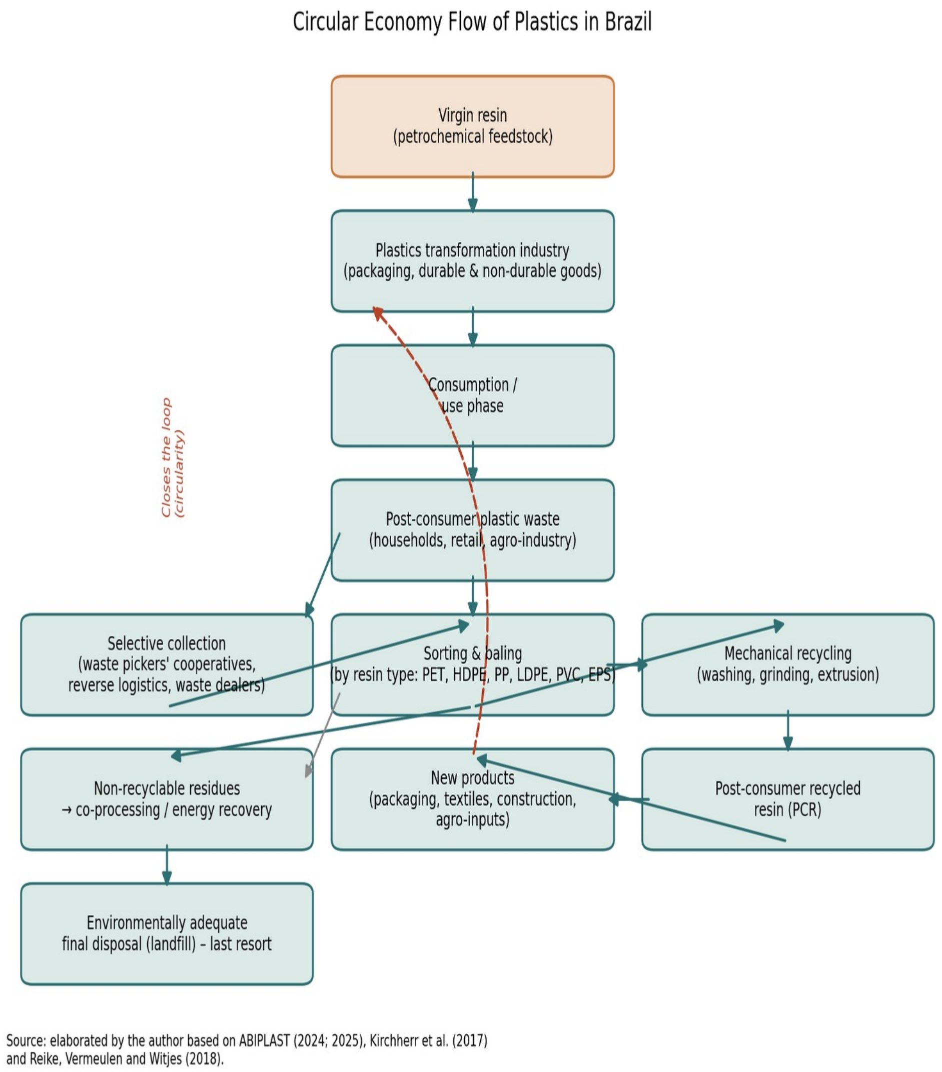
The plastic production chain begins with the extraction of petrochemical naphtha and the production of resins (PET, HDPE, PP, LDPE), followed by the manufacture of packaging and products. After use and consumption, closing the cycle depends on the effectiveness of selective collection and reverse logistics, a stage in which collector cooperatives and logistics operators operate (ABIPLAST, 2025; EDITORIALGE, 2025).

The collected material is sorted by type of polymer and sent to two main recycling routes: (a) mechanical recycling, which involves grinding, washing and extrusion to obtain pellets; and (b) chemical recycling — including pyrolysis, glycolysis and depolymerization —, a more recent technology that allows plastic to be reconverted into monomers or hydrocarbons with a quality close to that of virgin resin (BRASKEM, 2020; PLÁSTICO EM REVISTA, 2024).

Non-recyclable waste is often sent to co-processing in cement kilns as a form of energy recovery (R9 in the 9R hierarchy). The recycled material returns to the production chain as secondary raw material (PCR — Post-Consumer Resin), closing the cycle (closed loop) recommended by the EC.

Figure 4 presents a circular-flow model developed for the Brazilian plastics sector, integrating virgin-resin input, transformation, consumption, post-consumer waste generation, selective collection (largely performed by waste-picker cooperatives and waste dealers), sorting by resin type, mechanical recycling into PCR resin, reintroduction into new products, and residual flows directed to co-processing or environmentally adequate final disposal.

Figure 4: Circular economy flow of plastics in Brazil.



Source: Elaborated by the author, based on ABIPLAST (2024; 2025), Kirchherr, Reike and Hekkert (2017) and Reike, Vermeulen and Witjes (2018).

A relevant finding from the reviewed sectoral evidence is the changing destination profile of recycled resin: whereas in 2018 construction was the leading application for PCR resin, by 2024 food and beverage and personal-care/cosmetics applications had become dominant, reflecting tightening regulatory requirements and the increasing weight of Environmental, Social and Governance (ESG) criteria in corporate sourcing decisions among consumer-goods brands (ABIPLAST, 2025).

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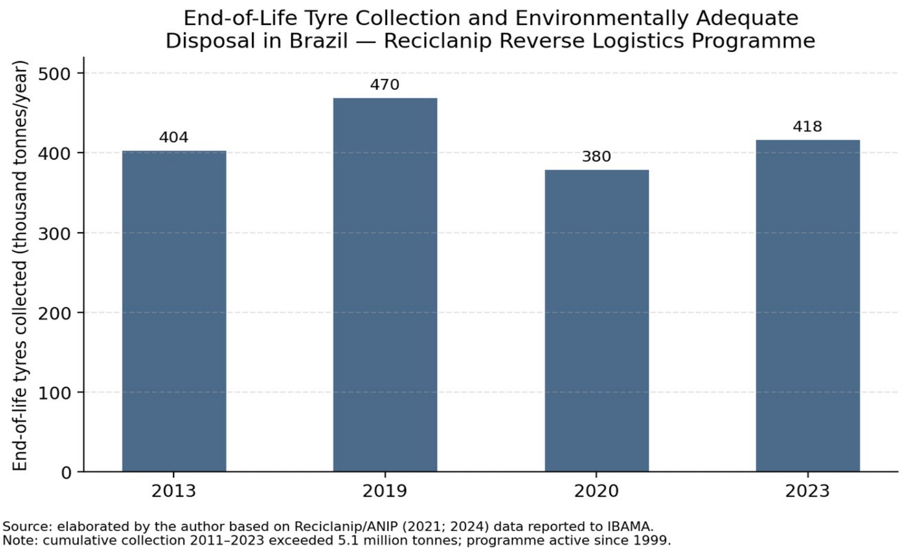
Sectoral Case: Rubber and End-of-Life Tyres

The rubber sector, and specifically end-of-life tyre (ELT) management, constitutes one of the most institutionally consolidated examples of circular economy implementation in Brazil. Reciclanip, a non-profit entity created in 2007 by the tyre-manufacturing industry (linked to the national tyre-manufacturers association, currently operating within the ANIP/Sinpec framework), manages the national ELT reverse-logistics programme, which has been in continuous operation since 1999 (RECICLANIP, 2021; EMBRAPA, 2025).

Between 2011 – the first year the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) published reverse-logistics reports for tyres – and 2023, more than 5.1 million tonnes of end-of-life tyres were collected and given environmentally adequate disposal, consistently exceeding annual collection targets (ANIP, 2024). Reciclanip currently operates a network exceeding 824 collection points across all 27 Brazilian states, supported by a fleet of dozens of trucks and, in the Amazon region, river barges, cataloguing more than 3.580 logistics routes nationwide (RECICLANIP, 2012; 2021). The tyre industry has invested a cumulative total exceeding R$ 1.8 billion in this reverse-logistics operation (ANIP, 2024).

Figure 5: End-of-life tyre collection and environmentally adequate disposal in Brazil, selected years.



Source: Elaborated by the authors, based on Reciclanip/ANIP (2014; 2021; 2024) data reported to IBAMA.

The rubber supply chain, exemplified by the case of tires, begins with manufacturing from natural and synthetic rubber, steel, and carbon black. During use in vehicles, a first circularity strategy (R4/R5 — repair/renew) is retreading, which recovers the tire carcass and extends its useful life without the need for disposal (INMETRO, 2020). When the tire becomes effectively unusable, it is sent, through reverse logistics systems such as the one operated by Reciclanip, to three main technological routes: (a) mechanical shredding, which generates granules and rubber powder; (b) pyrolysis, a heating process in an oxygen-free environment that separates the tire into oil, combustible gas, and carbon black; and (c) devulcanization, a chemical process that partially reverses vulcanization, making the rubber malleable again (EMBRAPA, 2025; MAGMA-MIX, 2025).

The recovered materials are used in rubberized asphalt and paving projects, industrial flooring and mats, shoe soles, rubber products, and, in the case of carbon black and oil recovered via pyrolysis, can return to the automotive industry itself as raw material for new tires, closing the materials cycle. Co-processing in cement kilns, with a calorific value of approximately 8.3 to 8.5 kWh per kilogram of rubber, constitutes an energy recovery route for non-recyclable fractions (EMBRAPA, 2025).

End-of-life tyres are, according to their technical condition, redirected into three broad destinations: retreading, for tyres still structurally suitable for reuse in the vehicle fleet; mechanical shredding, separating rubber crumb from embedded steel and textile fibres for use in rubberised asphalt, rubber artefacts (mats, industrial and sports-court flooring, footwear soles, ducts and conveyor belts) and other manufactured goods; and co-processing, in which non-recoverable rubber fractions are used as an alternative fuel in cement-kiln operations, replacing part of the fossil-fuel input under controlled emissions conditions (RECICLANIP, 2014; PORTAL SUSTENTABILIDADE, 2023).

Figure 6 depicts this circular flow for the Brazilian rubber/tyre sector.

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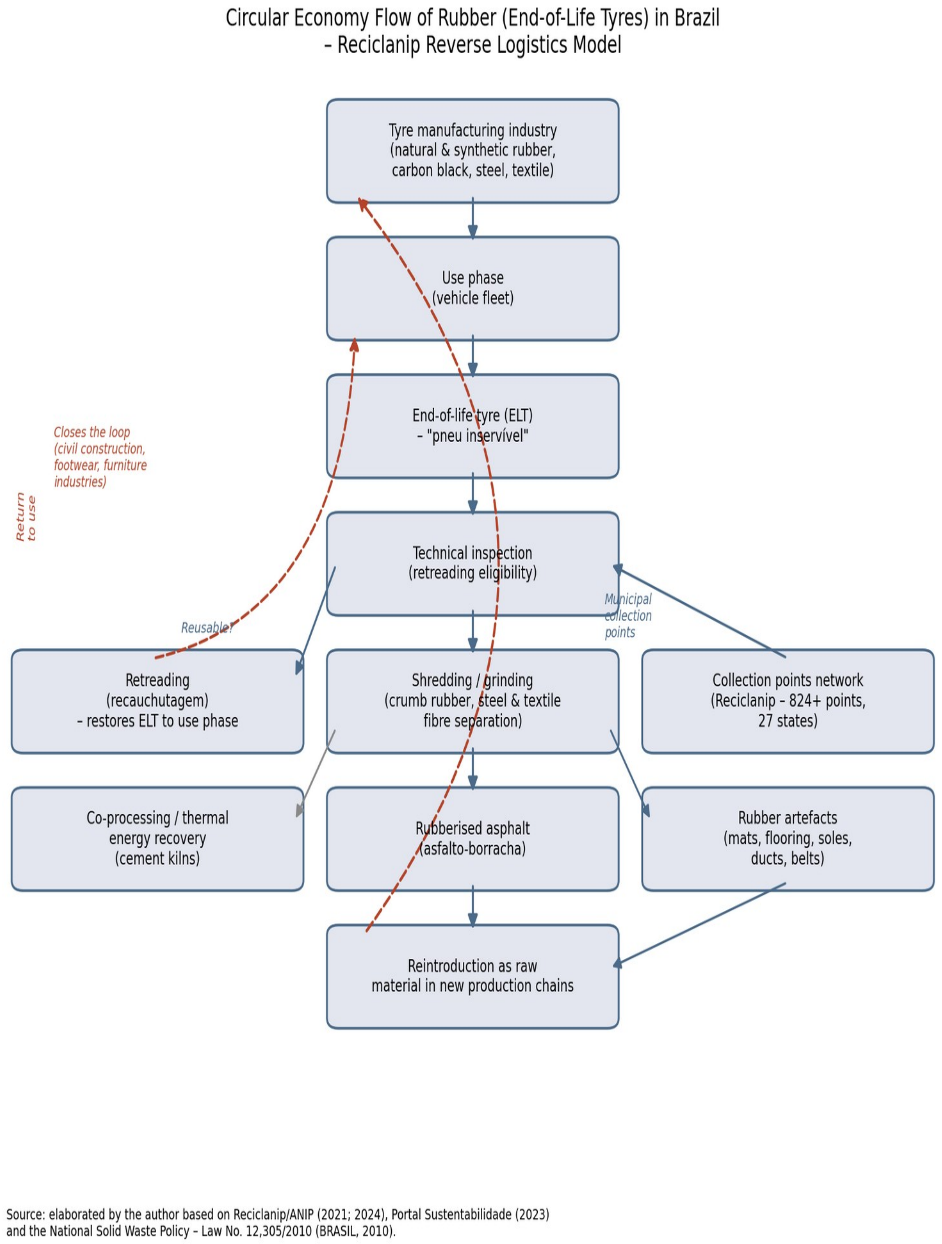
Figure 6: Circular economy flow of rubber (end-of-life tyres) in Brazil – Reciclanip reverse-logistics model.



Source: Elaborated by the authors, based on Reciclanip/ANIP (2021; 2024), Portal Sustentabilidade (2023) and Law No. 12,305/2010 (BRASIL, 2010).

Despite this institutional maturity, technical challenges persist, notably the loss of mechanical properties when rubber crumb substitutes conventional aggregates in concrete and asphalt applications, and the continued existence of an estimated environmental liability of 332 million kilograms of uncollected end-of-life tyres attributable to importers who have not fully met their collection targets (RECICLANIP, 2021; EMBRAPA, 2026).

COMPARATIVE DATA: 2000–2025

This section consolidates the comparative quantitative evidence gathered through the integrative review, organized into three tables (3, 4, 5) and complemented by the charts presented above.

Table 3: Evolution of post-consumer plastic recycling indicators in Brazil.

Year	Overall mechanical recycling rate	Packaging-specific recycling rate	PCR resin produced (million t)	Notes
2018	n.a.[1]	n.a.[1]	n.a.[1]	First year of the Abiplast/MaxiQuim monitoring series; construction civil was the leading PCR-resin application
2022	25.6%	28.7%	n.a.[1]	Peak of the historical series to date
2023	20.6%	24.3%	0.939	Sharp downturn linked to the petrochemical commodities down-cycle
2024	21.0%	24.4%	1.012	Timid recovery; agro-industry demand grew over 35% year-on-year

Source: Elaborated by the authors, based on ABIPLAST (2024; 2025) and MaxiQuim (2024).
Legend: [1] Precise figures for 2018 were not disclosed in the retrieved sources.

Table 4: Milestones and volumes of end-of-life tyre collection in Brazil.

Year(s)	Milestone / indicator	Thousand tonnes
1999	National Programme for the Collection and Disposal of End-of-Life Tyres launched by ANIP	–
2007	Reciclanip created as a dedicated non-profit entity	–
2013	Reciclanip annual collection	404
2019	Reciclanip annual collection	470
2020	Reciclanip annual collection (pandemic year)	380

Year(s)	Milestone / indicator	Thousand tonnes
2023	Reciclanip annual collection	418
2011–2023	Cumulative collection since first IBAMA reverse-logistics report	>5,100 (cumulative)

Source: Elaborated by the authors, based on Reciclanip/ANIP (2012; 2014; 2021; 2024).

Table 5: Comparative synthesis of major circular-economy conceptual/classification studies.

Study	Number of definitions / framework	Year	Main finding
Kirchherr, Reike and Hekkert (2017)	114	2017	Combination of reduce/reuse/recycle predominates; weak link to social equity and future generations
Kirchherr et al. (2023)	221	2023	Confirms 2017 pattern; slight increase in references to future generations
Reike, Vermeulen and Witjes (2018)	10R hierarchy (R0–R9)	2018	Explicit ordering by loop length and value retention
Geissdoerfer et al. (2017)	– (conceptual distinction)	2017	CE treated as necessary but not sufficient condition for sustainability

Source: Elaborated by the authors, based on the cited studies.

DISCUSSION

The integrative review evidences a two-speed pattern in the circular economy field. At the conceptual level, the 2000–2025 period shows clear cumulative maturation: from a scattered set of precursor ideas (industrial ecology, performance economy, cradle-to-cradle) to a codified, if still contested, family of definitions and an increasingly granular R-hierarchy that has moved well beyond the original 3R triad (KIRCHHERR; REIKE; HEKKERT, 2017; REIKE; VERMEULEN; WITJES, 2018; KIRCHHERR et al., 2023).

At the operational level in Brazil, however, progress has been considerably more uneven across sectors. The rubber/tyre chain, structured around a single mandatory and well-enforced reverse-logistics obligation since 1999–2010, exhibits a mature, high-coverage collection network with more than two decades of continuous operation and a positive record of exceeding collection targets (RECICLANIP, 2021; ANIP, 2024). The plastics chain, by contrast, remains considerably more sensitive to macroeconomic cycles – as illustrated by the

2023 downturn in recycled-resin output – and continues to display recycling rates below 30% even for the best-performing packaging segment (ABIPLAST, 2025).

This asymmetry suggests that regulatory design matters: single-material, single-obligated-industry reverse-logistics systems (as with tyres) appear more resilient than multi-material, multi-actor systems (as with plastic packaging), where responsibility is more diffusely distributed across manufacturers, retailers, waste-management companies and consumers, and where competitiveness with virgin feedstock is directly exposed to global commodity-price volatility. This is consistent with CEBRI's (2020) assessment that Brazilian post-consumer material-recovery ambition remains modest compared with leading circular economies, and with the barriers catalogued by Silva et al. (2019) and Lima and Gohr (2026), spanning infrastructural, economic, cultural and institutional dimensions.

From a conceptual standpoint, the persistence of definitional plurality identified by Kirchherr et al. (2017; 2023) is not merely an academic curiosity: it has practical implications for Brazilian policy design, since ambiguity regarding what precisely constitutes a circular economy strategy (as opposed to conventional waste management) can weaken the specificity of regulatory targets and corporate ESG commitments alike.

The adoption of an explicit R-hierarchy, as proposed by Reike, Vermeulen and Witjes (2018), offers a more operational vocabulary that could usefully inform future refinements to Brazilian sectoral agreements, shifting emphasis further upstream – towards refuse, rethink and reduce strategies – rather than concentrating almost exclusively on downstream recycling and recovery, as is currently the case in both the plastics and rubber sectors examined in this integrative systematic literature review.

Biotechnological Potential of Natural Products

There are strong and diversified alternatives with biotechnological potential, aiming the use of natural products to sustainable practices most of them learnt with traditional knowledge, originary people and ethnobotanic informations (Chen et al., 2012; Varricchio; Lage, 2020; Gaspar et al., 2020; Bentes Lopes et al., 2024) besides through investigating their chemical-physical features and abilities (Rebelo et al., 2025, 2026a). Specifically to rubber and plastics, mainly laticifers plant species (Cazumbá et al., 2023; Delaunay de Souza et al., 2023; 2023a; Gomes et al., 2023, 2023a), frequently they are explained through their hydrophobicity (Varricchio et al., 2025; Rebelo et al., 2026a).

Just as a musical artist has a conductor behind him, the contemporary researchers seeking creative solutions observed in nature co-exist with ancestral ethno-knowledge and traditional wisdom, as guides, because their ancient solutions are very clever and harmonic (Varricchio; Lage, 2020; Vacite et al., 2023). Despite prejudice, risk and vulnerability (Kottow, 2011; Miguel, 2015; Delaunay; Rangel, 2019; Bastos et al., 2019; Brown Junior, 2021; Hansel – Martins et al., 2023; Vacite et al., 2023; Gaspar et al., 2024), beyond, there are conditions already scientifically investigated whose need decisions that involve socially responsible management. That’s the contemporary scientific approach to industrial challenges. Researchers deal with facts, describe phenomena, lend their psychic abilities to a broad rational understanding to search (and “re-search”) solutions to harm reduction.

That’s why civilization has transcended magical thinking and judgments based on issues described out of context and without meaning. Meanwhile, this buys time for the development of their own humanity and a sense of purpose in such a brief existence, as already discussed by International Society of Psychiatry (Patel et al., 2018) besides Cler et al. (2025), making it meaningful. In this sense, Winter's (2018) conceptual proposal remained relevant and continued to advance through the favorable results of its interdisciplinary and intercultural application, in the both aspects: emergency climatic accidents (Wasim et al., 2021), besides chronic problems to ethnodevelopment in an urban context (Gaspar et al., 2020; 2023; 2024a; De Almeida et al., 2024; Malfacini et al., 2024).

Expansion of the environmental technology approach to oil palm residues

After the chronological mapping (Table 1), it is possible to observe that the interdisciplinary trajectory of the group has progressively expanded from plant-based environmental indicators and phytoremediation strategies to broader environmental technology approaches involving the valorization of agro-industrial residues. In this context, *Elaeis guineensis* Jacq. represents a relevant example because the oil palm production chain generates not only crude palm oil and palm kernel oil, but also substantial amounts of lignocellulosic and mineral residues that may be converted into value-added materials for environmental and industrial applications.

Beyond the oil extracted from the mesocarp and kernel, the *E. guineensis* production chain generates palm bunch fibers, shells, ashes, and other by-products whose valorization can improve the sustainability and circularity of the sector. Therefore, oil palm residues should not be interpreted only as an environmental liability, but also as a renewable platform for environmental technology, bioproduct development, wastewater treatment, and bioenergy-related processes.

Barros et al. (2025) demonstrated the potential of oil palm bunch fiber waste from the Amazon region as a lignocellulosic source for the development of cellulose-based materials. In that study, palm bunch fibers, cellulose, and cellulose nanofibrils were obtained and characterized. The palm bunch fiber showed predominance of α-cellulose, followed by hemicellulose and lignin, while the cellulose nanofibrils obtained by disc ultra-refining exhibited nanoscale width, high aspect ratio, increased crystallinity, and distinct thermal behavior compared with the original fiber and isolated cellulose. These findings support the use of oil palm residues as renewable feedstock for sustainable materials, including polymeric reinforcements, films, packaging systems, hydrogels, and other cellulose-based products.

In a complementary environmental application, Freitas et al. (2025) evaluated in natura and chemically modified palm bunch fibers as biosorbents for the removal of methylene blue from aqueous media. According to the authors, alkaline modification favored higher porosity and a greater concentration of basic surface groups, resulting in superior adsorption performance. The NaOH-treated material reached high dye-removal efficiency and showed a maximum adsorption capacity of 67.56 mg g^{-1} at 45 °C, with adsorption data better described by the Langmuir isotherm. The maintenance of removal efficiency after reuse cycles also indicates the potential application of modified palm bunch fibers as low-cost and sustainable biosorbents for the treatment of dye-containing effluents.

The energy-related valorization of oil palm residues has also been investigated through the development of heterogeneous catalysts for biodiesel production. Novita et al. (2024) used palm kernel shell ash as a precursor for a green and recyclable catalyst applied to the transesterification of used cooking oil. The ash exhibited high SiO_2 content and the presence of K_2O, components that may contribute to its catalytic performance as a support and active phase in heterogeneous systems. Under optimized conditions, the process achieved a biodiesel yield of 99.01%, and the catalyst-maintained yields above 80% after six reuse cycles. These results indicate that mineral residues from the oil palm chain can be converted into technological inputs for biofuel production, contributing to waste reduction, circular economy, and the integration of bioenergy with environmental engineering.

Taken together, these studies broaden the environmental relevance of plant-based research by showing that sustainability may involve not only the direct use of plants as biological indicators or phytoremediators, but also the transformation of plant-derived residues into functional materials, biosorbents, and catalysts. Thus, the inclusion of *E. guineensis* in this interdisciplinary framework strengthens the connection between environmental health, environmental engineering, biotechnology, and circular bioeconomy, especially in the Amazonian context.

LIMITS

One limitation of this study is that the integrative review did not employ a formal methodological quality assessment of the primary studies (such as GRADE or Cochrane), which is consistent with the integrative—and not strictly systematic—nature of the approach adopted (WHITTEMORE; KNAFL, 2005). For future research, it is suggested that complementary quantitative bibliometric analyses be conducted, as well as in-depth case studies on the economic viability of chemical recycling in Brazil.

CONTRIBUTION

The present study contribute to environmental sciences, besides the deepening of sustainability concept and the useful application to production engineering and also to sanitary environmental engineering.

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CONCLUSION

This integrative systematic review examined the state of the art of the circular economy – its definitions, classifications and conceptual evolution between 2000 and 2025 – alongside its understanding and application in Brazil, with dedicated attention to the plastics and rubber (end-of-life tyre) sectors. The evidence indicates that the circular economy concept matured substantially over the period under analysis, evolving from a narrow 3R logic into a more comprehensive 9R/10R value-retention hierarchy, even as definitional plurality (114 definitions in 2017, rising to 221 in 2023) continues to generate interpretive ambiguity in both academic and policy discourse.

In Brazil, the National Solid Waste Policy (Law No. 12,305/2010) remains the central legal anchor for circular-economy practice, operationalised most successfully through the tyre reverse-logistics programme coordinated by Reciclanip, which has collected more than 5.1 million tonnes of end-of-life tyres since 2011, and less consistently through the plastics packaging chain, whose post-consumer recycling rates have fluctuated between roughly 20% and 26% since 2018 amid sensitivity to petrochemical commodity cycles. The circular-flow diagrams developed for both sectors in this study illustrate concrete pathways through which materials are kept in productive use, while also revealing persistent leakages towards final disposal and structural barriers – infrastructural, economic, cultural and institutional – that continue to constrain full circularity.

Future research should prioritise longitudinal, sector-disaggregated bibliometric analyses capable of quantifying the diffusion of CE research in Brazil more precisely, as well as comparative studies examining why single-material reverse-logistics systems, such as that for tyres, outperform more fragmented multi-material systems, such as that for plastics, in terms of coverage and resilience. Strengthening extended producer responsibility mechanisms, expanding selective-collection infrastructure beyond the Southeast and South regions, and adopting the R-hierarchy explicitly as a policy vocabulary emerge as the most actionable recommendations arising from this review.

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