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# Diversification of oil-bearing biomass sources for decarbonization and sustainability

**Abstract** – The objective of this review was to analyze the diversification of oil-bearing biomass sources as a strategic pathway to support decarbonization and sustainability, with emphasis on bioenergy in Brazil. The review identifies opportunities, challenges, and conditions to expand the use of diverse oily crops. The work is based on scientific publications, technical reports, and institutional documents addressing biomass and bioenergy production. It highlights the potential of oily crops, such as *macaúba* and tropicalized canola, to expand biomass supply for biofuels and bioproducts. In addition, it examines integrated agricultural systems that combine biomass production with environmental restoration. Such an approach shows that diversifying oil-bearing crops can reduce pressure on traditional feedstocks such as soybean and oil palm, which face sustainability concerns abroad and can be highly affected by climate change. Technological, regulatory, and financial challenges that must be overcome for large-scale adoption of new crops were identified. The review also presents lessons from past failures, showing that success depends on long-term research, breeding, and risk management. Diversifying oil-bearing biomass sources strengthens climate mitigation, rural development, and bioeconomy strategies, positioning Brazil as a leader in the production of sustainable biomass.

**Index terms**: *Acrocomia* spp., energy transition, integrated crop-livestock-forestry systems, low-carbon bioeconomy, regenerative agriculture, tropical canola.

## Diversificação das fontes de biomassa oleaginosa para descarbonização e sustentabilidade

**Resumo** – O objetivo desta revisão foi analisar a diversificação de fontes de biomassa oleaginosa como um caminho estratégico para apoiar a descarbonização e a sustentabilidade, com ênfase na bioenergia no Brasil. O artigo de revisão identifica oportunidades, desafios e condições para a ampliação do uso de diversas culturas oleaginosas. O trabalho baseia-se em publicações científicas, relatórios técnicos e documentos institucionais que tratam da produção de biomassa e bioenergia. Destaca o potencial de culturas oleaginosas, como a macaúba e a canola tropicalizada, para ampliar a oferta de biomassa destinada à produção de biocombustíveis e bioprodutos. Além disso, também examina sistemas agrícolas integrados que combinam a produção de biomassa com a restauração ambiental. Essa abordagem mostra que a diversificação de culturas oleaginosas pode reduzir a pressão sobre matérias-primas tradicionais, como a soja e a palma de óleo, que enfrentam questões de sustentabilidade no exterior e podem ser fortemente afetadas

Mauricio Antonio Lopes (✉)
Embrapa Agroenergia, Brasília, DF, Brazil.
E-mail: mauricio.lopes@embrapa.br

Bruno Galveas Laviola
Embrapa Agroenergia, Brasília, DF, Brazil.
E-mail: bruno.laviola@embrapa.br

Simone Palma Favaro
Embrapa Agroenergia, Brasília, DF, Brazil.
E-mail: simone.favaro@embrapa.br

✉ Corresponding author

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por mudanças climáticas. Foram identificados desafios tecnológicos, regulatórios e de mercado que precisam ser superados para a adoção em larga escala de novas culturas. A revisão também apresenta lições aprendidas com fracassos anteriores, evidenciando que o sucesso depende de pesquisa em longo prazo, melhoramento genético e gestão de riscos. Diversificar as fontes de biomassa oleaginosa fortalece as estratégias de mitigação climática, o desenvolvimento rural e a bioeconomia, posicionando o Brasil como líder na produção de biomassas sustentáveis.

**Termos para indexação**: *Acrocomia* spp., transição energética, sistemas de integração lavoura-pecuária-floresta, bioeconomia de baixo carbono, agricultura regenerativa, canola tropical.

## Introduction

The urgency of transitioning to a low-carbon economy has elevated biomass use to a pivotal position in global strategies for climate change mitigation and sustainable development. Society's growing awareness of planetary boundaries and the finitude of natural resources demand a profound reconfiguration of development models traditionally reliant on non-renewable inputs (Sikdar, 2003). International frameworks, such as the Paris Agreement and the United Nations' 2030 Agenda for Sustainable Development, underscore the necessity of reconciling human systems with the environment, highlighting the critical role of renewable resources, such as biomass, in achieving targets for global emission reduction (United Nations, 2015; IPCC, 2021, 2022).

Among the many biomass types with potential to drive decarbonization and sustainability, oil-bearing biomass occupies a particularly strategic position due to its market versatility, high energy density, and compatibility with existing processing and distribution infrastructure. Unlike lignocellulosic or starchy feedstocks, vegetable oils generate liquid biofuels – such as biodiesel, renewable diesel, and sustainable aviation fuels (SAFs) – that are critical for decarbonizing hard-to-electrify sectors, including aviation, heavy-duty transport, and many industrial processes (IEA, 2023; Gilio et al., 2024; Bardon & Massol, 2025).

Additionally, oil-rich species yield valuable co-products such as high-protein meals and biochemicals, reinforcing their relevance within integrated food-energy-feed systems (Alves & Lopes, 2021; Khan, 2023; Motoike & Hilger, 2024; United States, 2025). Several of these species show a relatively high yield per hectare, potential for cultivation in degraded or low-competition areas, and adaptability to crop rotation and agroforestry schemes, further enhancing their systemic contribution to sustainable intensification and landscape regeneration (Colombo et al., 2018; Cortez & Rosillo-Calle, 2023; Zhang et al., 2023). For tropical countries such as Brazil, the strategic development of diversified oil-bearing biomass sources represents a dual opportunity to reduce carbon emissions, while also strengthening rural economies through inclusive and innovation-driven value chains (Alves & Lopes, 2021).

In Brazil, despite the strategic importance of oil-bearing biomass, current vegetable oil production and use remain heavily concentrated in a few traditional oilseed feedstocks, mainly soybean [*Glycine max* (L.) Merr.], accounting for 96% of the 13.26 million tonnes of vegetable oil production, followed by cottonseed and peanut (*Arachis hypogaea* L.), each contributing to 3.1 and 0.6% of the total amount, respectively (USDA-FAS, 2025b). An alternative is the worldwide-used oil palm (*Elaeis guineensis* Jacq.) that accounts for 37% of the output as palm oil or palm kernel oil (USDA-FAS, 2025a). However, in Brazil, this feedstock is produced on a smaller land area, covering 220 thousand hectares, which only render 600 thousand tonnes per year, making the country the tenth producer globally, with a value that is very far from the 46 million tonnes of Indonesia, the main producer (USDA-FAS, 2025b).

This overreliance on a narrow range of oilseed crops not only constrains the diversification potential of the Brazilian bioeconomy but also amplifies supply-chain vulnerabilities, intensifies land-use conflicts, and raises significant environmental and socio-economic trade-offs (Koh & Ghazoul, 2008; Goldemberg et al., 2014; Valin et al., 2015; Carlson & Garrett, 2018; Abreu et al., 2022; IEA, 2022a). Furthermore, global food and agricultural systems, which are among the largest users of soil, water, and biodiversity resources, continue to operate under carbon-intensive paradigms (Rockström et al., 2009; Herrero et al., 2021). The accelerating climate crisis, coupled with unsustainable land management practices and escalating resource consumption, challenges these systems to innovate toward models rooted in circularity, eco-efficiency, and resilience (IIASA, 2018; Ellen MacArthur Foundation, 2019; IPCC, 2022).

Emerging concepts – such as regenerative agriculture, circular economy, and bioeconomy – designed to mimic nature's closed-loop efficiencies have gained traction as viable models for fostering sustainability (D'Amato et al., 2017; Ellen MacArthur Foundation, 2017). In this context, the diversification of oil-bearing biomass sources presents a critical opportunity to mitigate greenhouse gas emissions, promote biodiversity conservation, enhance resource-use efficiency, and strengthen the food-energy-environment nexus (Jeswani et al., 2020; Lima & Palme, 2022; Subbarao et al., 2023; Millinger et al., 2025).

Tropical countries, particularly Brazil, hold a comparative advantage due to their year-round biomass productivity, biodiversity richness, and established agricultural research and development capacity (Alves & Lopes, 2021; Cortez & Rosillo-Calle, 2023; Souza et al., 2023). Advances in production systems – as integrated crop-livestock-forestry (ICLF) models – and the development or adaptation of underutilized oil-rich crops further strengthen Brazil's position to lead the transition toward a diversified, sustainable, and inclusive bioeconomy. Diversified sources that show possibilities of expansion include: *macaúba* (*Acrocomia* spp.), tropical canola (*Brassica napus* L.), sunflower (*Helianthus annuus* L.), Abyssinian mustard (*Brassica carinata* A.Braun), and oil palm, among others (Henderson et al., 1995; Tomm et al., 2011; Bungenstab & Almeida, 2014; César et al., 2015; Pereira et al., 2018; Motoike & Hilger, 2024).

The targeted transformation will require more than technological advances, also depending on enabling policy frameworks, assessing integrated sustainability, de-risking investment environments, and land-use strategies that align biomass production with ecological integrity and social inclusion (Rathore et al., 2013; Pereira et al., 2017a; Denny, 2020). The resilience and success of future oil-bearing biomass systems will hinge upon balancing productivity with ecosystem health, climate mitigation, and equity, particularly in vulnerable tropical landscapes (Lopes, 2022; Vandenberghe et al., 2022).

The objective of this review was to analyze the diversification of oil-bearing biomass sources as a strategic pathway to support decarbonization and sustainability, with emphasis on bioenergy in Brazil.

## Materials and Methods

This review critically examines the strategic pathways for diversifying oil-bearing biomass sources to foster global decarbonization and sustainability. For this, it explores the role of alternative feedstocks in reducing emissions across the energy, industrial, and transportation sectors; discusses the integration of biomass production into sustainable land-use systems, including ICLF models; and assesses the regulatory frameworks, investment mechanisms, and technological innovations necessary to enable scalable and sustainable biomass expansion.

This paper adopts a narrative and integrative approach, combining scientific literature, policy documents, and technical reports to provide a comprehensive overview of strategies for diversifying oil-bearing biomass sources in support of decarbonization and sustainability. The literature search was conducted using academic databases such as Scopus (Elsevier, 2025b), Web of Science (Clarivate, 2025), and ScienceDirect (Elsevier, 2025a), as well as institutional sources from the International Energy Agency – IEA (2025b), Food and Agriculture Organization – FAOSTAT (FAO, 2025), International Air Transport Association – IATA (2024b), Brazilian Agricultural Research Corporation – Embrapa (2025), and Brazil's Ministry of Mines and Energy / Energy Research Office – MME/EPE (2025).

Inclusion criteria prioritized peer-reviewed articles and institutional reports published within the last ten years (2014–2024), with emphasis on studies addressing oilseed and other oil-bearing crops for bioenergy use, particularly in tropical or subtropical contexts. Classical or foundational references outside this time window were also retained when relevant to conceptual framing (Rockström et al., 2009; Ellen MacArthur Foundation, 2017). Studies focusing on starch-or lignocellulose-based biomass were excluded unless they contributed comparative insights relevant to vegetable oil production.

This methodological approach allowed the authors to synthesize multidisciplinary evidence and to identify key opportunities, bottlenecks, and governance issues associated with the expansion of sustainable oilseed biomass systems in Brazil and comparable tropical regions.

## Biomass role in multisectoral decarbonization

Biomass is increasingly recognized as a cornerstone of global decarbonization strategies, providing a renewable and adaptable resource to curb greenhouse gas emissions and reduce environmental pollutants across multiple sectors (Zhou et al., 2022; Leslie-Bole et al., 2025; Millinger et al., 2025; United States, 2025). In the energy sector, expanding the portfolio of biomass feedstocks facilitates the shift away from fossil-based electricity and heat generation, significantly reducing emissions of $CO_2$, $NO_x$, and particulate matter (Mantulet et al., 2020; Lodato et al., 2022). Technological advances such as biomass gasification and anaerobic digestion further enhance the sustainability of bioenergy systems by maximizing energy recovery and mitigating methane emissions from organic waste streams (Mantulet et al., 2020; Alves & Lopes, 2021; Styles et al., 2022; Subbarao et al., 2023).

The World Bioenergy Association (2023) provided a study of the evolution and diversification of biomass-based electricity generation over two decades, indicating the growing contribution of biomass to the global energy matrix, with the dominant generation, in 2020, of solid biomass (69%), followed by municipal and industrial waste (17%), biogas (13%), and liquid biofuels (1.5%). This distribution highlights both the progress made and the continued concentration in a limited set of feedstocks, reinforcing the central argument of this article regarding the need for a broader diversification to enhance sustainability, resilience, and energy security. In this context, it is important to discuss global trends and the strategic role that tropical countries, such as Brazil, can play in expanding the portfolio of biomass sources and systems.

In the industrial sector, the integration of biomass-derived input into high-temperature processes, such as cement and steel production, shows substantial potential for carbon abatement. Recent studies have estimated that substituting even a modest portion of fossil fuels with biomass residues could drive significant reductions in industrial $CO_2$ emissions by mid-century (Kusuma et al., 2022). Simultaneously, the development of bio-based chemicals and advanced biomaterials opens new avenues for displacing carbon-intensive inputs, reinforcing circular economy strategies (Alves & Lopes, 2021; Carmona-Martínez et al., 2024).

Oil-bearing biomass is especially important in sectors such as aviation and long-haul transportation, where electrification is not yet viable at scale and drop-in liquid fuels are required. Moreover, the production of advanced biofuels – including cellulosic ethanol, renewable diesel, and SAFs – is crucial for reducing the carbon footprint of these industries (Bardon & Massol, 2025).

In particular, the aviation sector is experiencing a rapidly growing demand for SAFs, driven by international climate commitments, carbon reduction mandates, and the adoption of net-zero roadmaps by airlines and global aviation alliances (IEA, 2025a). According to IATA (2024a), SAF could contribute up to 65% of the sector's required carbon mitigation by 2050. However, SAF production must increase from an estimated 8 million tonnes in 2025 to approximately 23 million tonnes by 2030, and continue increasing toward 2050 under net-zero aligned scenarios. (ATAG, 2024; IATA, 2024b). This exponential growth trajectory underscores the significant role SAFs are expected to play in decarbonizing aviation. However, current production remains below 1% of total jet fuel use, highlighting the urgent need for feedstock diversification and investment in scalable and sustainable supply chains (Pereira et al., 2017b; IEA, 2023; Gilio et al., 2024; Watson et al., 2024). Therefore, expanding the portfolio of biomass sources, particularly from underutilized tropical species, is essential to meet this demand, while ensuring climate and land-use goals are not compromised.

On a global scale, strategic initiatives are accelerating efforts to diversify biomass supplies for the aviation sector. The European Union's "Fit for 55" package is a set of proposals aimed at reducing greenhouse gas emissions by at least 55% by 2030, compared to the levels in 1990 (European Commission, 2023). It promotes the sustainable mobilization of agricultural residues, forestry biomass, and novel energy crops to meet ambitious decarbonization targets. The European Court of Auditors and the European Council detail how the package aims to increase renewable energy's share to at least 42.5% by 2030, with sector-specific measures targeting transport, buildings, and industry to support this transition (Council of the European

Union, 2023). In the United States, the Department of Energy prioritizes research into nonfood bioenergy crops such as switchgrass (*Panicum virgatum* L.) and *Miscanthus* spp., focusing on increasing biomass yields without exacerbating land-use pressures (IEA, 2024). Similarly, India's National Bioenergy Programme fosters the use of nonedible oilseeds and agricultural residues to enhance rural energy security and support low-carbon transitions (Sinha, 2023; Mabee, 2024).

These examples are indicative that, in addition to scaling up SAF production, diversifying feedstocks is also essential to meet future demands and ensure the sustainability of the aviation sector. The Bioenergy Strategic Plan of IEA (2022b) underscores the role of modern bioenergy systems as a critical component of clean energy portfolios, while promoting the diversification of biomass processing and waste use, such as gasification, supporting the European Union's commitment to achieve net-zero emissions by 2050.

## Oil-bearing biomass: strategic role, opportunities, and diversification

Plant oils play a crucial role in global agriculture, with oil crops accounting for around 12 % of total agricultural production—positioning them among the top four global crop categories after cereals, sugar crops, and vegetables. Vegetable oils are also a major food commodity, an important source of dietary energy, and economically significant for producers (Mannucci et al., 2023; FAO, 2025). Crops cultivated for their oil richness include oil palm, canola, sunflower, and soybean; the latter is primarily used as a protein source, which serves diverse functions in human diets and in industrial applications as cooking oil, shortenings, and biofuels (Ahmad et al., 2021).

There has been an increase in the cultivation of oily crops due to the growing demand for vegetable oils and biofuels, attributed to population growth, changes in dietary habits, and rising global affluence (Gladek et al., 2017; USDA-ERS, 2024; OECD-FAO, 2025). The global production and consumption of oil-bearing crops have shown a significant upward trend, particularly in emerging economies in South America and Southeast Asia, which benefit from favorable agroclimatic conditions and investments in agricultural technology (Ahmad et al., 2021; Khan, 2023).

As the demand for renewable energy continues to rise, the strategic role of oil-bearing biomass is expected to expand. Research and development efforts are focusing on source diversification, improving the efficiency of biomass conversion technologies and optimizing biomass production systems to enhance yield, while minimizing environmental impacts (United States, 2025). According to National Oilseed Processors Association (NOPA, 2024), by fostering innovations in agricultural practices and processing technologies, oil-bearing biomass can significantly contribute to a sustainable energy future and facilitate multisectoral decarbonization.

The use of oil-bearing biomass offers several environmental benefits, such as reduced lifecycle carbon emissions compared with those of fossil fuels, as well as enhanced carbon sequestration through sustainable agricultural practices (Zhou et al., 2022; Leslie-Bole et al., 2025). However, this potential is accompanied by controversies surrounding land competition, food security, and the environmental impacts of cultivation, raising questions about sustainability and agricultural practices in the context of a rising global demand for vegetable oils and biofuels (Zhang et al., 2023; United States, 2025). In this scenario, innovations in conversion technologies – such as pyrolysis, hydrotreated esters and fatty acids, and transesterification – aim to optimize biomass conversion and energy yields, while minimizing emissions, which highlights the significance of research and development in this field (Masi et al., 2021).

In response to these challenges and opportunities, the strategic role of oil-bearing biomass is expected to expand as previously noted, with ongoing research focusing on improving biomass conversion efficiency and integrating oil-bearing crops into sustainable agricultural practices (NOPA, 2024; United States, 2025). This evolution reflects a broader trend toward a circular economy that prioritizes renewable resources, biodiversity enhancement, and waste reduction, essential for achieving multisectoral decarbonization and climate mitigation goals (El-Araby, 2024; Leslie-Bole et al., 2025). As governments and stakeholders develop supportive policies and financial incentives to promote the adoption of biofuels and sustainable practices, oil-bearing biomass stands at the forefront of the global transition toward a more sustainable and resilient energy future (Masi et al., 2021; NOPA, 2024).

To illustrate the transition in Brazil, the country's engagement with biofuels began in the 1970s with the implementation of an ethanol program primarily based on sugarcane, aimed at enhancing energetic security (Carvalho, 2007). Over the decades, this initiative positioned Brazil as a global leader in biofuel production, with the development of a mature and sustainable production chain that encompasses a variety of renewable energy sources. The introduction of biodiesel in the 2000s further expanded the country's renewable energy portfolio with the use of vegetable oils and animal fats to diversify biofuel offerings (Hofsetz & Silva, 2012; Bergmann et al., 2013; USDA-ERS, 2024; Branco et al., 2025).

Although soybean is the traditionally used source due to its productivity and economic viability, it has shown low fuel productivity per hectare compared with other oily crops (Bergmann et al., 2013; Huang et al., 2016; Osman et al., 2024), in addition to being subjected to risks related to seasonal availability, price volatility, and regional concentration. Therefore, as the biodiesel industry matures, Brazil has increasingly sought alternative oily crops to supplement soybean use. This diversification is driven by an expanding domestic demand for biodiesel, spurred by regulatory changes that have increased blending mandates, which reached the historical blend of 15% in 2025 (Brasil, 2024).

In recent years, several initiatives have emerged to diversify the vegetable feedstock base, aiming to reduce environmental and socioeconomic vulnerabilities, while enabling the expansion of a low-carbon bioeconomy (Bergmann et al., 2013). Some of the species used as an alternative to soybean are presented below.

## Oil palm

Oil palm is a high-yielding perennial oily crop, originally from West Africa and widely used for biodiesel production in Southeast Asia, especially in Indonesia and Malaysia (Bergmann et al., 2013; Murphy et al., 2021). Due to the restricted environmental conditions to its optimal growth, oil palm is cultivated mostly in the humid zones of the Legal Amazon (Almeida et al., 2020; USDA-FAS, 2022a). In Brazil, cultivation is concentrated in the state of Pará, representing 85% of total production, and in northern Bahia (USDA-FAS, 2025b), where the crop benefits from favorable conditions. However, the risk of deforestation and land tenure conflicts has triggered environmental concerns. In response, Brazil has implemented the agroecological zoning for oil palm, identifying suitable expansion areas with a low environmental risk (Brasil, 2010). Despite this, commercial expansion has been slow and cautious (Carvalho et al., 2021).

Oil palm renders two kinds of oil from its fruits, each with distinct characteristics. The most abundant, known as palm oil, comes from the mesocarp, and the other, an oilseed, comes from the kernel, accounting for approximately 90% and 10% of the extracted oil, respectively (Bergman et al., 2013; FAO, 2018). With yields ranging from 3.0 to 8.0 tonnes of oil per hectare, a value about ten times that of the oil yield of soybean, oil palm is considered one of the most productive oil crops globally (Bergmann et al., 2013). Under Brazilian current conditions and agricultural practices, the average yield of palm oil is 3 tonnes per hectare (USDA-FAS, 2025b).

Despite palm oil's high productivity and versatility for food and oleochemical uses, it remains marginal in Brazil's biodiesel matrix. In 2024, soybean oil supplied approximately 73–74% of biodiesel feedstock, while beef tallow contributed around 6–8%, and palm oil – along with other vegetable oils – accounted for only about 1–4% (USDA-FAS, 2024; Pinheiro, 2025).

The expansion of oil palm in Brazil is limited by some technical and agronomic challenges (César et al., 2013; Englund et al., 2015). First, palm oil is highly susceptible to quality degradation due to the rapid hydrolysis of triacylglycerides, requiring processing within 24–48 hours post-harvest, and manual harvesting also imposes high labor costs (Ali et al., 2014). Another critical obstacle has been the spread of fatal yellowing, a disease of unknown etiology that causes necrosis and fruit loss, responsible for decimating large plantation areas in Northern Brazil (Silva et al., 2025). This has driven breeding efforts to produce varieties resistant to fatal yellowing, i.e., an interspecific hybrid developed from oil palm and the native *Elaeis oleifera* (Kunth) Cortés. Although disease-resistant, these hybrids have lower oil yields than traditional African varieties and require manual pollination (Freitas et al., 2021; Anhê et al., 2022).

Overall, oil palm remains a promising candidate for large-scale biodiesel and bio-based product supply chains in Brazil. Its sustainable expansion will depend on overcoming phytosanitary and logistical constraints, improving mechanization and scaling up cultivars resistant to fatal yellowing in order to enhance productivity and resilience.

### *Macaúba*

*Macaúba*, a palm with a long history of use by pre-Columbian peoples, is rapidly emerging as one of Brazil's most promising biomass resources for sustainable development (Scariot et al., 1995; Evaristo et al., 2016; Vargas-Carpintero et al., 2021; Duque et al., 2025). Widely distributed across the country and adaptable to various soils and climates, *macaúba*, like oil palm, produces high-value oils from both its mesocarp and kernel, which are rich in fatty acids, with applications across the food, cosmetic, pharmaceutical, chemical, and energy sectors (Ciconini et al., 2013; Del Río et al., 2016). These renewable and cost-effective oils enhance the value of a wide array of industrial products (Favaro & Rocha, 2022).

In addition to its oil, *macaúba* provides abundant biomass for energy and other byproducts, making it a multipurpose species ideal for agroforestry systems, integrated crop-livestock-forest systems, and the regeneration of degraded lands (Evaristo et al., 2016; Favaro & Rocha, 2022; Biesdorf et al., 2024). Its resilience to environmental stressors and genetic diversity further strengthen its potential as a climate-smart crop (Del Rio et al., 2016; Colombo et al., 2018). As research advances in ecophysiology, reproductive biology, and pest management, *macaúba* is increasingly seen not just as a plant species, but as a strategic ally in creating a more sustainable and resilient agricultural model. By valuing and managing *macaúba* appropriately, Brazil can enhance biodiversity, improve food security, and support the socio-economic well-being of rural communities, while conserving natural resources (Henderson et al., 1995; Lorenzi et al., 1996; Cortez & Rosillo-Calle, 2023; Motoike & Hilger, 2024; Benatti et al., 2025).

Although early studies on the species were sporadic and focused mainly on basic botanical and ethnobotanical aspects, the 2000s marked a turning point, characterized by a sharp rise in publications driven by the growing interest in bioenergy, processing technologies, and potential for sustainable value chains. This surge in scientific output reflects a broader recognition of the versatility of *macaúba* as a source of vegetable oil and bio-based products (Vargas-Carpintero et al., 2021; Ampese et al., 2023; Duque et al., 2025; Sorita et al., 2025), underscoring its emerging relevance within global discussions on bioeconomy and renewable resources.

In summary, *macaúba* stands out as a promising option for diversifying Brazil's oil-bearing biomass portfolio, combining economic, ecological, and social benefits. Its strategic role in the Brazilian bioeconomy is expected to grow, provided that supportive institutional frameworks, technological innovations, and sustainable agricultural practices continue to advance.

### Canola

Canola has also been gaining momentum in Brazil as a versatile biomass feedstock with multiple applications in vegetable oil production, animal feed, and biofuels. Originally introduced in the Southern region of Brazil, particularly in the state of Rio Grande do Sul, canola cultivation has expanded rapidly due to its potential for agricultural diversification, energy independence, and sustainable production systems (Araújo et al., 2021).

In recent years, there has been a notable growth in canola acreage and production. By 2024, Brazilian canola production reached approximately 226,000 tonnes, cultivated across 151,000 hectares, reflecting a growing recognition of its agronomic and economic benefits (MNAgro, 2025). This growth is supported by research and development initiatives focused on developing tropical-adapted hybrids that can thrive beyond traditional temperate zones, targeting regions such as the Cerrado biome and semi-arid areas of the Northeastern region (Araújo et al., 2021). This "tropicalization" strategy is crucial for unlocking canola's broader potential in Brazil's diverse agricultural landscapes.

Economically, canola holds a significant promise. It is widely used to produce edible oil, due to its favorable nutritional profile, and biodiesel, due to its desirable oil properties such as low viscosity and high oxidative stability (Oliveira et al., 2024b; Pimentel et al., 2024). Additionally, canola meals serve as a high-protein component in animal feed, enhancing the crop's value as a multipurpose agricultural commodity (Oliveira et al., 2024b; Pimentel et al., 2024).

From an environmental perspective, canola offers important advantages, fitting well into crop rotation systems, where it contributes to soil health and reduces pressure on large-scale systems such as soybean. Studies suggest that canola could occupy up to 20% of the area traditionally used for soybean, promoting land-use efficiency and crop diversity (Proforest, 2024). Furthermore, the use of genetically modified herbicide-tolerant varieties has been associated with reductions in fuel use and greenhouse gas emissions due to decreased tillage and herbicide applications (Brookes & Barfoot, 2018).

Despite the benefits of the species, challenges persist. The Brazilian canola sector still lags major global producers such as Canada and the European Union, and there are agronomic hurdles related to pest and disease management, climate resilience, and market competitiveness (Canola Council of Canada, 2025; MNAgro, 2025). Additional constraints include regulatory complexities, particularly regarding environmental compliance in sensitive areas such as the Cerrado biome (Pimentel et al., 2024).

Looking ahead, initiatives such as the BRS Canola project, a collaboration between Embrapa and private-sector partners, aim to accelerate the development of high-performing, disease-resistant, and herbicide-tolerant hybrids suited to Brazil's Midwestern and Southern regions (Araújo et al., 2021). According to the same authors, the integration of canola as a winter crop alongside summer staples, as soybean and corn (*Zea mays* L.), offers additional opportunities to enhance land use, improve farm income, and support the expansion of sustainable bioenergy systems.

While Brazil's canola production remains modest on the global stage, its strategic development offers clear opportunities for diversifying the country's oilseed biomass base, enhancing energy security and advancing environmental sustainability.

## Incorporation of species into diversified agricultural mixed systems

Integrated crop-livestock (ICL) and ICLF systems have fostered the integration of diversified crops, such as tropical-adapted canola, into regenerative agricultural models, enhancing ecosystem services such as soil health, biodiversity conservation, and water regulation (Telhado & Capdeville, 2021; Cortez & Rosillo-Calle, 2023). Evidence from over 65 peer-reviewed publications shows that adopting ICLF systems significantly benefits soil quality and ecosystem services in Brazil (Oliveira et al., 2024a).

Among the species described previously, *macaúba* is a suitable option for mixed systems. In the context of energy crops, the strategic incorporation of species such as *macaúba* and tropical-adapted canola into diversified agricultural systems offers substantial promises.

In addition to tropical canola and *macaúba*, other crops such as castor bean (*Ricinus communis* L.), crambe (*Crambe abyssinica* Hochst. ex R.E.Fr.), sunflower, Abyssinian mustard, safflower (*Carthamus tinctorius* L.), mustard (*Brassica* spp.), pongam oiltree [*Pongamia pinnata* (L.) Pierre], and *pequi* (*Caryocar brasiliense* Cambess.) may also contribute to Brazil's biomass diversification efforts.

### Castor bean

Castor bean is well adapted to Brazil's diverse climates, especially in semi-arid regions such as the Northeast (Ribeiro et al., 2014). Its cultivation is expanding due to the development of more productive and disease-resistant cultivars (Fontgalland, 2021). Castor oil has seen growing industrial demand–especially in pharmaceuticals, cosmetics, and lubricants–and offers a renewable, bio-based alternative to petroleum-derived chemicals (Mubofu, 2016). Moreover, castor bean is considered an excellent option for crop rotation in Brazil, particularly as a second crop following soybean or corn (Witt et al., 2023).

### Crambe

Crambe is recognized for its high oil content of 35−60% and short growth cycle, making it a promising feedstock for biodiesel production in Brazil (Bassegio et al., 2016). The crop is tolerant to drought and temperature variations, has a low production cost, and can be grown as a second crop after soybean or corn, using the same equipment; in addition, its cultivation supports crop rotation and soil cover, contributing to sustainable agricultural practices (Queiroz et al., 2021). Crambe oil is rich in erucic acid, valuable for various industrial applications, including lubricants, plastics, and insulating fluids (Bassegio et al., 2016).

## Sunflower

Sunflower is highly adaptable to Brazil's diverse climates, from the South to the North of the country, and is often cultivated as a second crop after soybean or corn, especially in the Cerrado biome and in states like Goiás and Mato Grosso (Castro & Leite, 2018). Although Brazil imports a significant portion of its sunflower oil, domestic production is on the rise– with planted area more than doubling since 2022 and overall production growing by 167%, alongside productivity gains averaging 1.6 t/ha (USDA-FAS, 2025a). Sunflower enhances crop rotation systems, improves ecological balance, and optimizes the use of land and resources, also supporting integrated agricultural systems when its meal is used as animal feed (Iowa State University, 2021). The crop is noted for its drought tolerance and ability to thrive under various climatic conditions, making it a valuable option for diversifying oilseed production (Castro et al., 2014; Jocic et al., 2015; Martínez-Force et al., 2015).

## Abyssinian mustard

Abyssinian mustard is recognized as a non-food oilseed, with a high potential for advanced biofuels such as low-carbon diesel and SAFs, suitable oil for drop-in renewable fuels, and meal that can be used for animal feed (Seepaul et al., 2021). Abyssinian mustard produces a high biomass and can be integrated into existing cropping systems as a cover crop, supporting soil health and crop diversity (Abraha et al., 2024). In addition, its cultivation can improve nutrient cycling and reduce greenhouse gas emissions, making it a scalable and sustainable option (Malins, 2022).

## Safflower

Safflower is recognized for its resilience to drought, high temperatures, saline soil, and low humidity (Thoday-Kennedy et al., 2023). It is suitable for cultivation in various Brazilian regions, as the semi-arid, and during off-season periods due to its deep taproot system and ability to extract water and nutrients from deeper soil layers (Daniel et al., 2024). Research in the states of Mato Grosso and São Paulo showed a significant genetic diversity among safflower genotypes, supporting ongoing breeding programs to improve yield, drought tolerance, and adaptability to Brazilian climates (Lira et al., 2021). Safflower seeds can contain up to 50% oil and are rich in linoleic and oleic acids, making them valuable for food, pharmaceutical, and industrial applications (Deliorman Orhan et al., 2022). The oil of the species is used in the production of biofuels, paints, varnishes, and cosmetics, for example (Muscalu et al., 2023). Research on safflower as a feedstock for biodiesel and bioethanol production has shown the potential of the species as a sustainable bioenergy crop in Brazil (Lira et al., 2021; Vieira et al., 2021).

## Mustard

Mustard (*Brassica juncea*) is being investigated as a viable alternative feedstock source for biodiesel in Brazil, owing to its favorable agronomic attributes and oil profile (Jham et al., 2009). The crop, which can be grown in rotation with soybean and corn, is adaptable to Brazilian conditions, showing potential as an alternative oilseed crop for energy use despite its still limited commercial cultivation (Madalena et al., 2017).

## Pongam oiltree

Pongam oiltree is a leguminous tree that grows well on degraded and marginal lands, offering potential for land rehabilitation and sustainable biomass production (Hasnah et al., 2020). Due to its resilience to drought and poor soils, the species is a candidate for expanding oilseed production in less fertile areas. As a nitrogen-fixing species, it can also improve soil fertility and support agroforestry systems. The seeds of pongam oiltree are rich in oil, being suitable for biodiesel and other industrial uses.

## *Pequi*

*Pequi* is a native fruit tree of the Brazilian Cerrado, with significant cultural, culinary, and economic importance, being traditionally used in food, cosmetics, and potentially as industrial fat (Guedes et al., 2017). Its fruit has a high oil content of up to 66% dry weight in the mesocarp, and its productivity can reach up to 2.4 tonnes of oil per hectare with improved agronomic practices (Guedes et al., 2017). Most *pequi* production is extractive, supporting thousands of smallholder families, while contributing to the conservation of the

Cerrado biome (Pinto et al., 2019). However, there are efforts to domesticate and cultivate the species, which could increase yields and the support to sustainable rural livelihoods (Guedes et al., 2017).

Although less visible, the aforementioned crops – crambe, Abyssinian mustard, safflower, mustard, pongam oiltree, and *pequi* – offer diverse agronomic and environmental benefits that can support Brazil's efforts to diversify its biomass base. Their further development and adoption can enhance sustainability, rural livelihoods, and resilience in the face of climate and market challenges.

Regional initiatives across the transition zones between Brazil's Cerrado and Amazon biomes are showing how the integration of diversified biomass sources into local bioenergy value chains can simultaneously drive emission reductions, stimulate socioeconomic development, and foster landscape restoration (Azevedo et al., 2025).

Brazil's longstanding leadership in sugarcane ethanol production offers critical technological, institutional, and policy lessons for scaling the next generation of sustainable biomass systems, including those based on oil-bearing and oilseed species (Silva et al., 2021; Cortez & Rosillo-Calle, 2023). However, the scaling of energy crops also presents risks that must be proactively managed. The unchecked expansion of monocultures – even of native species such as *macaúba* – could threaten biodiversity, reduce landscape resilience, and exacerbate water resource pressures. Therefore, sustainable biomass strategies must prioritize integrated land-use planning, polyculture multifunctional models, and landscape restoration approaches that harmonize biomass expansion with ecosystem integrity and long-term sustainability goals (Telhado & Capdeville, 2021; Lopes, 2022).

## Sustainable production systems for oil-bearing biomass supply

The sustainable expansion of biomass supply must be anchored in innovative production systems that simultaneously enhance productivity, restore degraded ecosystems, and foster socioeconomic inclusion. Systemic approaches such as ICL and ICLF and agroforestry systems have emerged as strategic pathways to reconcile biomass production with environmental stewardship, biodiversity conservation, and climate resilience (Telhado & Capdeville, 2021; Rodrigues et al., 2023; Mattos et al., 2024).

Successful integration of energy crops into sustainable production systems requires strategic selection of species and genotypes suited to local soils and climates, application of ecologically resilient management practices such as crop rotations and soil conservation, and adaptive land-use strategies (Jungers et al., 2023; Dida, 2024; von Cossel et al., 2025). Ecologically, diversified systems contribute to restoring degraded ecosystems, enhancing landscape connectivity, regulating microclimates, and supporting critical ecosystem services such as pollination and water regulation (Carvalho et al., 2024).

Socioeconomically, biomass diversification stimulates rural development by creating new bio-based value chains, attracting investments in biorefineries and decentralized energy systems, while also promoting social inclusion, particularly for small and medium-sized farmers (Sakai et al., 2020; Azevedo et al., 2025). Pilot initiatives in Brazilian states such as Minas Gerais and Mato Grosso have shown that integrating energy crops into sustainable farming models can generate employment, elevate rural incomes, and reinforce the nexus between food, energy, and environmental security (Rodrigues et al., 2023). To maximize the intended impact, it is essential that smallholders and traditional communities are integrated into biomass markets through inclusive financing instruments, technical support programs, and equitable value-chain governance structures. Therefore, sustainable biomass systems must move beyond mere yield maximization, also embracing holistic models that harmonize agronomic productivity, ecological health, and social equity, ensuring that biomass expansion serves as a catalyst for regenerative rural landscapes and climate-smart development.

Brazil's experience in crop tropicalization and in the development of integrated farming systems offers valuable lessons to guide biomass diversification in other tropical regions. For instance, the development of tropical canola hybrids adapted to the Cerrado, combined with the use of bioinputs to reduce chemical fertilizer dependency, represents meaningful progress in sustainable land use (Araújo et al., 2021; MNAgro, 2025). These outcomes reinforce the role of agricultural research as a driver of innovation in the tropical bioeconomy and as a foundation for an effective public policy (Martha Júnior & Lopes, 2023).

In addition to agronomic and environmental benefits, research and development efforts on alternative biomass in Brazil have also created opportunities for industrial innovation and rural development (Rosillo-Calle, 2000). The integration of plant breeding, agroecological practices, and environmental profile assessment has enabled the design of low-carbon and socially inclusive biomass value chains (OECD, 2015). Such progress is strategic not only for meeting international sustainability standards but also for consolidating a national bioeconomy model anchored in science, technology, and innovation, capable of addressing climate change and energy security challenges (Scheiterle & Birner, 2020; Martha Júnior & Lopes, 2023).

## Lessons learned from past experiences in oil crop diversification in Brazil

As Brazil advances to diversify and sophisticate its biomass production capacity, it is important to learn from unsuccessful experiences with oil-bearing crops in the past, among which physic nut (*Jatropha curcas* L.) is the most significant case.

The plant is drought-resistant and can grow under a wide range of climatic and soil conditions, including poor soils, which makes it attractive for cultivation in marginal lands (Durães et al., 2012; van Loo & Jongschaap, 2014; Mazumdar et al., 2018). The species is native to tropical regions of the Americas, including Mexico and Central America, and is characterized as a deciduous shrub or small tree, whose height is typically from 2.0 to 6.0 m, leaves are heart-shaped and lobed, and fruits are green to brown, containing two to three black seeds rich in oil (Durães et al., 2012; van Loo & Jongschaap, 2014; Mazumdar et al., 2018).

As an oil crop, physic nut seeds contain approximately 27–40% oil, which can be processed into high-quality biodiesel compatible with standard diesel engines or used in thermal energy storage and as a heat transfer fluid (Durães et al., 2012; Mazundar et al., 2018). The crop has been explored for biofuel production due to its resilience and oil yield potential, although commercial success has been limited by agronomic challenges (van Loo & Jongschaap, 2014; Mazumdar et al., 2018). The seeds and other parts of the plant, for example, contain toxic compounds, limiting their use as food when the proper processing or selection of nontoxic varieties is not carried out (Durães et al., 2012; Mazumdar et al., 2018).

Despite its potential, physic nut remains largely a quasi-undomesticated species in Brazil. This means there is limited scientific knowledge and few established agronomic practices tailored to maximize the productivity of the species under Brazilian conditions. The lack of well-developed cultivation protocols, including planting density, nutrient management, and intercropping systems, hampers consistent yields and the adoption of the crop by farmers (Durães et al., 2012; Silva et al., 2024).

Although physic nut (*Jatropha curcas*) is frequently cited as tolerant of poor soils, empirical studies demonstrate that attaining high fruit and oil yields depends on fertile soils with corrected acidity and adequate fertilization, particularly with phosphorus (P) and potassium (K). Consequently, nutrient deficiencies prevalent in many Brazilian soils restrict physic nut productivity. Moreover, intercropping with cover crops or grains may exacerbate nutrient competition and further diminish yields (Souza et al., 2011; Cañadas-López et al., 2020; Cristiano & Kurihara, 2024). Under a low phosphate availability, physic nut plants are highly dependent on arbuscular mycorrhizal fungi, i.e., in soils with poor mycorrhizal populations or low phosphorus, plant growth and productivity are constrained unless a proper inoculation or fertilization is applied (Balota et al., 2011; Cristiano & Kurihara, 2024).

In summary, the main causes for the unsuccessful cultivation of physic nut in Brazil include: its quasi-undomesticated status, with insufficient agronomic knowledge; nutrient limitations, mainly of phosphorus and potassium; high mycorrhizal dependency; herbicide sensitivity; pest management challenges; and lack of consistent yield data to support its large-scale adoption. Addressing these issues through targeted research and improved cultivation practices is essential to evaluate physic nut's potential as a biofuel crop in Brazil (Balota et al., 2011; Durães et al., 2012; Cristiano & Kurihara, 2024).

There are other cases of an unsuccessful or limited development of oilseed species both in Brazil and globally, often due to agronomic, environmental, and economic challenges such as those faced by physic nut.

Another case is that of castor bean, whose development in Brazil is still slow despite its potential as a biodiesel feedstock and its adaptability to poor soils. Challenges include limited mechanization, susceptibility to diseases such as gray mold, and the use of genotypes not fully adapted to Brazilian conditions, which restrict its expansion when compared with that of major crops as soybean and corn (Witt et al., 2023).

Another example is that of cottonseed, whose production in Brazil remains a minor part of the oilseed sector, accounting for about 3.4% of the total oilseed volume (USDA-FAS, 2022b). Similarly, sunflower cultivation is still small and vulnerable to climatic stresses such as drought and heat waves, which have caused significant yield and quality losses, making oil extraction economically unfeasible in some scenarios (USDA-FAS, 2025a).

These cases illustrate that the unsuccessful or limited development of oil-bearing crops often stems from a combination of biological constraints, inadequate breeding and agronomic practices, environmental stress, disease and pest pressures, and economic factors such as market demand and infrastructure. The physic nut case, specifically, teaches us that the successful introduction of new oily crops in Brazil requires a comprehensive approach: domestication and breeding, soil and nutrient management, understanding of ecological interactions, integrated pest and weed control, and long-term commitment to research and farmer support. These lessons can help avoid pitfalls and accelerate the development of other promising but less-known species for biomass diversification in the country.

## Bases for biomass diversification: regulatory frameworks, economic instruments, and scaling up

The successful diversification of biomass sources requires not only technological and agronomic innovations but also the establishment of robust regulatory frameworks, financial incentives, and risk mitigation mechanisms that support scalability and sustainability. Public policies must deliver consistent and long-term signals that encourage investment in diversified bioenergy systems, while ensuring environmental integrity and social inclusion (Grangeia et al., 2022; Souza et al., 2023).

Brazil stands out as a dynamic example in which biomass diversification aligns with climate ambition and bioeconomic development (Alves & Lopes, 2021; Bhandari & Sessa, 2020). RenovaBio, officially known as the national biofuel policy of Brazil, was established by Law N° 13.576/2017 (Brazil, 2017) to promote the predictable expansion of biofuels in the country's energy matrix. It aims to support Brazil's commitments under the Paris Agreement by fostering the decarbonization of the transport sector, while introducing annual decarbonization targets for fossil fuel distributors, which must be met through the acquisition of decarbonization credits issued by certified biofuel producers based on their energy efficiency and life-cycle greenhouse gas emissions. RenovaBio creates market signals that reward a more sustainable and efficient biofuel production, encourage investment in low-carbon technologies, and integrate environmental performance into the energy sector. It is regarded as one of the most advanced global frameworks for promoting sustainable biofuels through scientifically grounded and market-based mechanisms. The program has been instrumental in advancing carbon-intensity-based certification frameworks, encouraging the production of low-carbon biofuels and promoting the adoption of new feedstocks beyond traditional crops such as sugarcane and soybean (Goldemberg et al., 2018; Salina et al., 2019; Denny, 2020; Martinelli et al., 2022; Ribeiro & Cunha, 2022; Müller-Langers, 2023; Sá et al., 2023).

Certification schemes and comprehensive life-cycle assessment methodologies (Osman et al., 2021; Rossi et al., 2024) are indispensable to ensure that biomass expansion does not trigger adverse impacts such as deforestation, biodiversity loss, or social displacement (Ogwu et al., 2025). Examples include voluntary standards and sector-specific certifications, as the roundtable on sustainable biomaterials (RSB, 2025) and Bonsucro (2025) for sugarcane, respectively, which provide transparency and traceability across biomass supply chains. The integration of life-cycle assessment frameworks into national and international policies enables a precise accounting for greenhouse gas emissions, water use, land-use changes, and overall environmental impacts (Parada et al., 2022).

In this scenario, developing risk mitigation tools is essential to unlock private capital for sustainable biomass initiatives. Instruments such as climate risk insurance, blended finance mechanisms, and public-private de-risking facilities are increasingly deployed to navigate infrastructural and environmental uncertainties, particularly in tropical regions (Ogwu et al., 2025). Furthermore, innovative financial solutions – including ecosystem service payments, carbon credits from agroforestry bioenergy systems, and green bonds linked to biomass value chains – are providing new revenue streams and enhancing project bankability (Henry et al., 2023).

Looking forward, the investment outlook for the tropical bioeconomy remains highly promising. Tropical nations, specifically Brazil, show comparative advantages such as year-round biomass productivity and an immense biodiversity, which can be leveraged to competitively produce low-carbon fuels, biomaterials, and certified carbon credits (Souza et al., 2023). However, achieving transformative impacts will depend on establishing enabling ecosystems that integrate smallholders into biomass markets, invest in logistics and biorefinery infrastructure, and ensure equitable benefit distribution (Hiloidhari et al., 2023).

Ultimately, the future of biomass diversification will rely on building integrated ecosystems in which regulatory certainty, financial incentives, certification standards, and risk-sharing mechanisms converge synergistically. Such comprehensive approaches are essential for unlocking the full potential of tropical bioeconomy to drive energy transitions, climate mitigation, and inclusive rural development (Iriarte et al., 2021; Alves & Lopes, 2021; Lopes, 2022; Hiloidhari et al., 2023).

## Concluding Remarks

This review shows that diversifying oil-bearing biomass sources is not only feasible but imperative for advancing decarbonization and sustainability in Brazil and other tropical regions. The presented findings clearly confirm that expanding the portfolio of oily crops – such as *macaúba* and tropical-adapted canola – offers substantial opportunities to enhance biomass supply for bioenergy, bio-based products, and regenerative agricultural systems, while simultaneously promoting ecosystem restoration and rural development.

Brazil's distinctive combination of ecological conditions, agricultural expertise, and bioeconomy policy frameworks places the country in a strong position to lead this transition. However, several unresolved challenges remain, mainly regarding institutional, regulatory, and financial barriers that hinder the scaling of diversified plant oil-based systems beyond pilot initiatives. Unlocking the full potential of these crops will require integrated approaches that align agricultural innovation with climate policies, inclusive business models, and multifunctional land-use strategies.

At the same time, it is essential to recognize that the global demand for plant oils is growing rapidly, driven by population growth, dietary shifts, industrial applications, and the accelerating push for biofuels. This trend places increasing pressure on already dominant systems, particularly soybean and oil palm, which face significant sustainability concerns related to deforestation, biodiversity loss, greenhouse gas emissions, and social conflicts. The overreliance on these crops risks exacerbating land-use tensions and undermining global climate and conservation goals. Therefore, diversifying the oily crop portfolio through the development of underutilized species and regenerative production models is not merely an economic strategy, but a necessary response to mitigate systemic risks and ensure that the expansion of biomass supply does not further compromise environmental integrity or social equity.

Moreover, the lessons learned from past failures with species such as physic nut highlight the need for long-term investments in domestication, breeding, agronomic management, and risk assessment. Without such foundational work, even promising species risk repeating the shortcomings of earlier efforts.

Future research must deepen the understanding of how diversified systems can contribute simultaneously to energy transitions, biodiversity conservation, and food security. This includes the development of advanced metrics for ecological and social co-benefits, new models for integrating smallholders into value chains, and financing mechanisms that reward landscape-level sustainability outcomes.

In sum, plant oil diversification represents not only a pathway for biomass expansion but a catalyst for systemic transformation, offering Brazil and similar regions an opportunity to reconcile agricultural development with climate mitigation, economic resilience, and social inclusion. Moving forward, success will depend on building robust research, policy, and investment ecosystems capable of sustaining this transformation over the long term.

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### Author contributions

**Mauricio Antonio Lopes**: conceptualization (lead), writing – original draft (lead), writing – review & editing (lead); **Bruno Galveas Laviola**: conceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **Simone Palma Favaro**: cconceptualization (supporting), writing – original draft (supporting), writing – review & editing (supporting).

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### Data availability statement

No new data were generated or analyzed in this study. All information supporting the findings is contained within the article and in the cited references.

### Declaration of use of AI technologies

During the preparation of this manuscript, the authors used ChatGPT (developed by OpenAI) exclusively for support in English language grammar and stylistic refinement. The use of this tool did not influence the scientific content, interpretation, or conclusions. All content was reviewed and approved by the authors, who take full responsibility for the manuscript..

### Conflict of interest statement

The authors declare no conflicts of interest.

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