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Sustainable Management of Brazil Nut in the Amazon: proposal of an Integrated Model

Gestão Sustentável da Castanha-do-brasil na Amazônia: proposição de um modelo integrado

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Abstract

The Brazil nut represents a strategic resource for the sustainable development of the Amazon, by combining income generation, environmental conservation, and social inclusion. This study proposes an integrated management model based on a systematic review of national and international scientific literature, focusing on sustainable practices, technological innovation, and the organization of the production chain. A total of 31 articles published between 2014 and 2024 were analyzed, enabling the identification of four structuring axes: sustainable management and environmental preservation; technological innovation and product diversification; governance structures and social inclusion; and market access and quality certifications. The integration of these axes aims to overcome structural bottlenecks, increase the added value of the Brazil nut, and strengthen its competitiveness in national and international markets. The model is adaptable to different Amazonian contexts and shows potential for replication in other non-timber forest product chains. Its validation is recommended in pilot communities, with monitoring of social, economic, and environmental indicators.

Keywords: Brazil Nut; Production Chain; Bioeconomy.

Resumo

A Castanha-do-brasil representa um recurso estratégico para o desenvolvimento sustentável da Amazônia, ao combinar geração de renda, conservação ambiental e inclusão social. Este estudo propõe um modelo de gestão integrada baseado em uma revisão sistemática da literatura científica nacional e internacional, com foco em práticas sustentáveis, inovação tecnológica e organização da cadeia produtiva. Foram analisados 31 artigos publicados entre 2014 e 2024, permitindo a identificação de quatro eixos estruturantes: manejo sustentável e preservação ambiental, inovação tecnológica e diversificação de produtos, estruturas de governança e inclusão social, e acesso a mercados e certificações de qualidade. A integração desses eixos busca superar gargalos estruturais, ampliar o valor agregado da castanha e fortalecer sua competitividade em mercados nacionais e internacionais. O modelo é adaptável a diferentes contextos amazônicos e apresenta potencial de replicação em outras cadeias de produtos florestais não madeireiros. Recomenda-se sua validação em comunidades-piloto, com monitoramento de indicadores sociais, econômicos e ambientais.

Palavras-chave: Castanha-do-brasil; Cadeia Produtiva; Bioeconomia.

Technological Area: Bioeconomy and Sustainable Production Chain Management.

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1 Introduction

Bertholletia excelsa Bonpl. belongs to the Lecythidaceae family and is widely known as the Brazil nut tree, while its kernels are referred to as Pará nuts, Brazil nuts, or Amazon nuts (Queiroz *et al*., 2022). Native to the Amazon, this tree can reach between 30 and 50 meters in height and, under favorable conditions, may begin fruit production after 3.5 years, although more consistent fruiting occurs between 8 and 12 years (Silva; Pontes; Albuquerque, 2020; Wadt *et al*., 2023).

Historically, Brazil nut extraction has played a significant role in the Amazonian economy, especially in the 1920s and 1930s, when it emerged as an alternative to natural rubber production, which had been weakened by the competitiveness of intensive latex cultivation (Barbosa; Moret, 2015; Krag; Santana, 2017). Currently, Brazil nuts remain essential to the livelihoods of traditional communities, both as an economic market resource and as an important element in the conservation of primary forests and biodiversity (Cunha; Magalhães; Adams, 2021; Guariguata *et al*., 2017; Kainer; Wadt; Staudhammer, 2018).

Between 2020 and 2022, the average annual production of Brazil nuts in the Legal Amazon generated BRL 135.3 million. Acre recorded the highest average annual revenue, with BRL 42.8 million, followed by Amazonas, with BRL 38.9 million, and Pará, with BRL 23.1 million (Fórum do Acre, 2023). In this context, although Acre's financial prominence is linked to public policies that have encouraged extractivism in recent decades, Amazonas leads in production volume, favored by the abundance of native Brazil nut groves and by the organization of cooperatives that facilitate collection and commercialization (IBGE, 2024).

Based on this scenario, the strengthening of the production chain in Acre is associated with the implementation of public policies between the late 1990s and 2010, focused on neoextractivism and the valorization of non-timber forest products (Bayma *et al*., 2014; Souza; Souza, 2019). Strategies such as community organization, support for cooperatives, and investments in agro-industries have significantly improved the efficiency of Brazil nut processing and commercialization. Nevertheless, challenges persist, including limited logistics infrastructure and restricted access to technologies (Araújo *et al*., 2024; Picanço; Costa, 2019; Queiroz *et al*., 2022; Silva; Souza; Souza Filho, 2020).

The versatility of Brazil nuts further increases their importance. Rich in proteins, healthy fats, and selenium, they are consumed fresh and processed into derivatives such as oil, plant-based extract, and flour, with growing acceptance in national and international markets (Carvalho *et al*., 2022; Silva *et al*., 2021; Souza, 2020). In this regard, extractivist cooperatives play a central role in value addition and in promoting the social inclusion of riverside and quilombola communities (Picanço; Costa, 2019; Silva; Souza; Souza Filho, 2020).

However, the production chain faces structural obstacles. Difficulties related to infrastructure for collection and transportation, inadequate storage practices that result in contamination by aflatoxins, toxic substances harmful to health, and dependence on intermediaries are among the main bottlenecks (Costa; Beitum, 2020; Krag; Santana, 2017). The lack of integration among chain actors compromises efficiency and prevents extractivists from capturing greater value, keeping them as the most vulnerable link in the chain (Krag *et al*., 2017; Silva; Pontes; Albuquerque, 2020).

In response to these challenges, studies by Krag *et al*. (2017), Silva, Souza and Souza Filho (2020), and Tavares and Burns (2023) indicate that local governance structures and collaborative management models help overcome structural barriers in the production chain, increasing its efficiency and competitiveness. In Acre, the strengthening of cooperatives and investments in agro-industries demonstrate the potential to add value to the product and expand commercialization capacity, although limitations related to logistics and technology dissemination still persist (Bayma *et al*., 2014; Souza; Souza, 2019).

Initiatives aimed at diversifying derivatives have also shown positive results. The reuse of the Brazil nut husk for the production of activated carbon and its application in the renewable energy sector, such as in biodiesel production, illustrate innovative strategies that enhance the value of local resources and promote sustainable development in the Amazon (Stachiw *et al*., 2016; Souza; Silva, 2021; Teixeira Alves *et al*., 2023). Brazil nuts represent an important source of income for thousands of extractivist families in the Amazon (Waldhoff; Souza; Vidal, 2022). Their importance is also reflected in the ecological context, as they contribute to forest conservation and are a focus of sustainable development policies (Alves; Silva, 2023; Souza; Souza, 2019).

Predominant in the states of Acre, Amazonas, Pará, and Rondônia, and present in neighboring countries such as the Guianas, southeastern Colombia, southern Venezuela, eastern Peru, and northern Bolivia, Bertholletia excelsa has its oleaginous seeds, or kernels, found inside the woody fruits, as its main marketable product. The kernels are valued for their nutritional content and economic importance. Although the wood is of high quality, its use is limited for sustainability reasons (Souza; Souza, 2019; Teixeira Alves *et al*., 2023).

The kernels can be consumed fresh, dried, or roasted and are used in culinary recipes and products such as nut mixes. The extracted oil is used in the food and cosmetics industries because of its bioactive properties (Pinheiro *et*

al., 2022). The high selenium content is associated with the prevention of chronic diseases, such as diabetes and cardiovascular conditions (Souza; Souza, 2019; Alves; Silva, 2023).

In Acre, Brazil nuts stand out as one of the main extractivist products. Between January and November 2024, the state exported more than USD 9.6 million in Brazil nuts, corresponding to approximately BRL 55.4 million (IBGE, 2024). Public policies related to extractivism have encouraged the organization of cooperatives and the adoption of sustainable management practices, favoring value addition and regional development (Barbosa; Moret, 2015; Fonseca; Cartaxo; Wadt, 2018; Fonseca; Silva; Rover, 2019). As a result, structural changes, such as increased processing efficiency and export growth, have consolidated Acre among the largest national producers (Bayma *et al*., 2014).

With approximately 85% of its territory covered by forests, the state offers favorable conditions for the sustainable extraction of non-timber forest products (NTFPs) (Fundo Amazônia, 2024). Products such as Brazil nuts, açaí, and rubber have historically supported the livelihoods of traditional communities and remain relevant to the regional economy (Souza; Souza, 2019; Silva; Souza; Souza Filho, 2020).

In this scenario, the promotion of NTFPs has encouraged practices that keep the forest standing and generate local income, especially in areas of high ecological value, where sustainable activities reduce pressure on natural resources (Fonseca; Cartaxo; Wadt, 2018; Souza D. *et al*., 2023; Wallace; Gomes, 2016). Growing demand, both nationally and internationally, expands economic opportunities for riverside and traditional communities (Afonso *et al*., 2022; Garcia *et al*., 2018; Giatti *et al*., 2021).

Cooperative practices optimize the economic and environmental benefits of sustainable production (Krag; Santana, 2017; Barbosa; Moret, 2015; Silva; Pontes; Albuquerque, 2020). Cooperatives promote integration among the links of the chain, facilitating access to markets, infrastructure, and technical training. They enable product processing into derivatives such as oils and flours, increasing competitiveness (Mariosa *et al*., 2024). These organizations also favor the shared management of natural resources, respecting regeneration cycles and preventing overexploitation (Guariguata *et al*., 2017). Their work strengthens environmental sustainability and promotes greater equity in income distribution (Tierling; Schmidt, 2021).

Despite these advances, structural bottlenecks such as poor infrastructure and limited technology continue to compromise the performance of the production chain (Silva; Souza; Souza Filho, 2020). Inadequate logistics negatively affect collection, transportation, and storage, increasing the risk of quality losses, such as aflatoxin contamination (Picanço; Costa, 2019).

Similar situations occur in Pará, where logistical bottlenecks and the lack of coordination among actors hinder chain integration and value addition (Bayma *et al*., 2014). In the Calha Norte region, extractivist communities face inequalities in relation to agro-industries and intermediaries, which control flows and prices, limiting producers' ability to capture value (Krag; Santana, 2017; Picanço; Costa, 2019). In the international market, Brazil, Bolivia, and Peru lead Brazil nut production and exports. The main markets are the United States, European countries, and Australia. Although Brazil is one of the largest producers, Bolivia stands out in exports because of investments in processing and commercial strategies (Coslovsky, 2014; Queiroz *et al*., 2022).

The diversification of Brazil nut uses has promoted job creation and increased income. The production of cosmetics, functional foods, and derivatives, combined with the strengthening of local agro-industries, reduces dependence on intermediaries (Bayma *et al*., 2014). Initiatives such as the Green Markets Project and the Bolsa Verde Program encourage sustainability and support extractivist families (Freire *et al*., 2020; Silva; Souza; Souza Filho, 2020). These policies, together with technical support from Embrapa, enable the adoption of technological innovations that ensure quality and safety in production (Fonseca *et al*., 2021).

Based on this body of evidence, Brazil nuts are consolidated as a strategic resource for sustainable development in the Amazon. When based on responsible management and robust organizational structures, their exploitation promotes forest conservation and stimulates the regional economy. In Acre, these actions integrate environmental protection and socioeconomic development, positioning the state as a leading actor in the Amazonian production chain (Bayma *et al*., 2014).

In this context, the present study aims to propose an integrated model for the Brazil nut production chain, based on a systematic literature review and empirical evidence, with a focus on environmental sustainability, technological innovation, market access, and the strengthening of extractivist communities. The model seeks to improve existing practices, promote product diversification, and consolidate the role of Brazil nuts as a strategic resource for sustainable socioeconomic development in the Amazon. Unlike approaches that address isolated aspects of the production chain, the proposal integrates responsible management, technological innovation, participatory governance, and market insertion within an interdependent framework. Accordingly, this study seeks to answer the following question: how can an integrated management model be structured to overcome the fragmentation of the Brazil nut production chain and promote, in a balanced manner, environmental conservation, increased value addition, and the strengthening of social cohesion?

2 Methodology

This study is characterized as applied research with a qualitative nature and an exploratory approach. The methodology combined Systematic Literature Review (SLR) procedures with categorical analysis to support the development of an integrated management model for the Brazil nut production chain. The approach was based on the methodological guidelines proposed by Shaffril, Samsuddin, and Samah (2021), aiming to gather empirical and theoretical evidence to guide the formulation of the model. Figure 1 presents the methodological stages developed throughout the study.

The first stage consisted of conducting the SLR through searches in the SciELO, CAPES Periodicals, and Scopus databases, selected for their relevance, multidisciplinary coverage, and recognized role in the dissemination of national and international scientific knowledge. The search covered the period from 2014 to 2024 and employed strategies combining keywords and Boolean operators to maximize the precision of record retrieval.

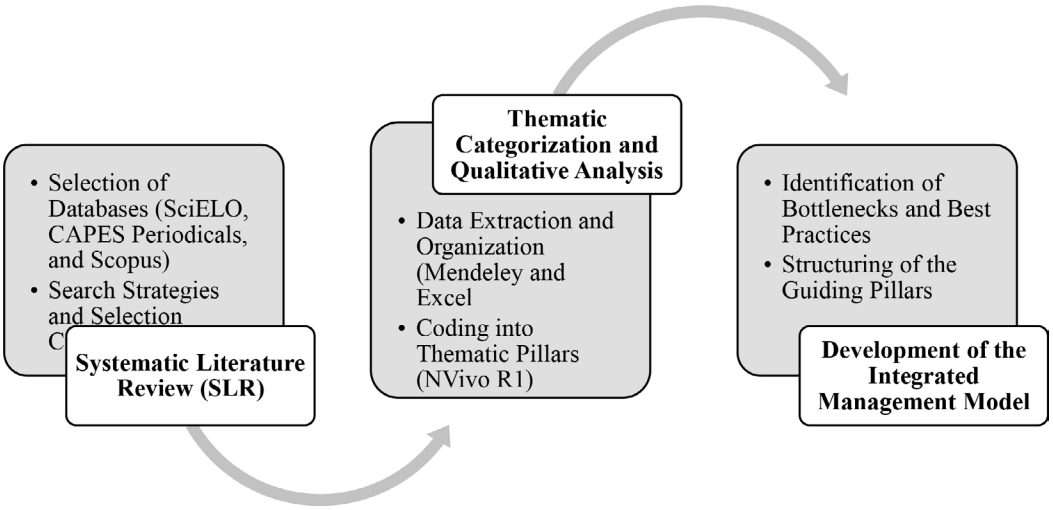
The primary term, "Brazil Nut," was combined with related keywords such as "Potentialities," "Sustainability," "Governance," "Production Chain," "Management," "Acre," and "Northern Region." Search strategies included expressions such as: "Brazil Nut AND Potentialities," "Brazil Nut AND (Sustainability OR Governance OR Management)," and "Brazil Nut AND (Production Chain OR Acre OR Northern Region OR Amazon)." These combinations enabled a broad yet targeted search, capturing studies that addressed both general and specific aspects of the production chain, with particular emphasis on sustainable practices, technological innovation, and governance.

The inclusion criteria were established to select articles addressing relevant topics related to Brazil nuts, published in either Portuguese or English, and available in full text within the consulted databases. Studies exploring practices, technological advances, or gaps in the production chain were included, provided that they demonstrated methodological quality and direct relevance to the study objectives. Exclusion criteria encompassed duplicate articles across databases, studies misaligned with the research focus, and publications that, after full-text review, did not provide relevant contributions. Articles published in non-peer-reviewed outlets or presenting methodological limitations were also excluded.

The initial screening was conducted independently by two reviewers, who assessed titles and abstracts according to the predefined criteria. Articles considered potentially relevant were subsequently subjected to full-text review. In cases of disagreement, a third reviewer was consulted to ensure well-founded decisions.

The extracted data were systematically organized and analyzed using the Mendeley reference management software. Information such as title, year of publication, database source, objectives, authors, key findings, and identified gaps was recorded in a structured spreadsheet developed in Microsoft Excel 2021. This record was complemented by thematic categorization in NVivo R1, which enabled the organization of data into predefined categories and the identification of textual patterns and connections.

Figure 1 – Stages for developing the integrated management model



Source: Prepared by the authors (2025)

Systematic coding in NVivo R1 encompassed areas such as sustainable management, technological innovation, governance, and market access, allowing the visualization of relationships among the analyzed studies and enabling more in-depth qualitative analyses. This approach facilitated cross-referencing between study objectives and the regional or institutional contexts addressed, thereby broadening the understanding of initiatives related to the Brazil nut production chain and its sustainability. Based on this systematization, the second stage was initiated, focusing on the development of the integrated management model.

2.1 Development of the Integrated Management Model

The integrated management model was developed based on a detailed analysis of the data obtained from the SLR, which enabled the identification of recommended practices and highlighted the main bottlenecks within the production chain. This analytical process made it possible to map priority areas requiring structured interventions, with a focus on increasing operational efficiency and strengthening economic, social, and environmental sustainability. In this context, particular emphasis was placed on the integration of processes and the promotion of sustainable practices throughout the entire value chain.

Based on these priority areas, the guiding pillars of the proposed model were established: sustainable management, governance, processing technologies, and product diversification. These pillars were defined according to the best practices identified in the literature and aligned with widely recognized scientific and operational standards. For each pillar, specific actions were proposed to support practical implementation, promoting targeted interventions while ensuring integration among the different segments of the production chain.

This proposal represents an approach not identified in the reviewed literature, as it systematically integrates the main components of the production chain into a single management framework. The model underwent an initial validation process through the alignment of its guiding pillars with the data coded during the previous stages, ensuring consistency between the model components and the needs identified in the analyzed studies. The result is a replicable and adaptable system capable of addressing sustainability challenges. The model was designed to align environmental conservation objectives, socioeconomic development, and competitiveness in global markets, providing an integrated and practical framework for managing the Brazil nut production chain.

3 Results and Discussion

The Brazil nut production chain is a strategic component of sustainable development in the Amazon, as it combines income generation, environmental conservation, and social inclusion. To provide a foundation for the proposed integrated management model, a systematic search was conducted in the SciELO, CAPES Periodicals, and Scopus databases, initially identifying 423 articles related to the topic.

In the initial stage, 73 duplicate studies were excluded. Subsequently, 25 articles published in non-eligible languages (other than Portuguese or English) and 145 publications outside the thematic scope were removed, resulting in 180 articles eligible for title and abstract screening. During this screening process, 125 studies were excluded for failing to meet the inclusion criteria, such as relevance to the topic or methodological quality, reducing the sample to 55 articles. These studies underwent full-text review and, following detailed analysis, 24 articles were excluded because they did not directly address the potentialities of Brazil nuts or presented significant limitations, such as a restricted scope, absence of empirical data, insufficient description of the methods employed, or lack of alignment with the study objectives. Consequently, 31 articles constituted the *corpus* analyzed in this study.

Figure 2 presents the flowchart of the selection stages, illustrating the rigorous application of the methodological procedures.

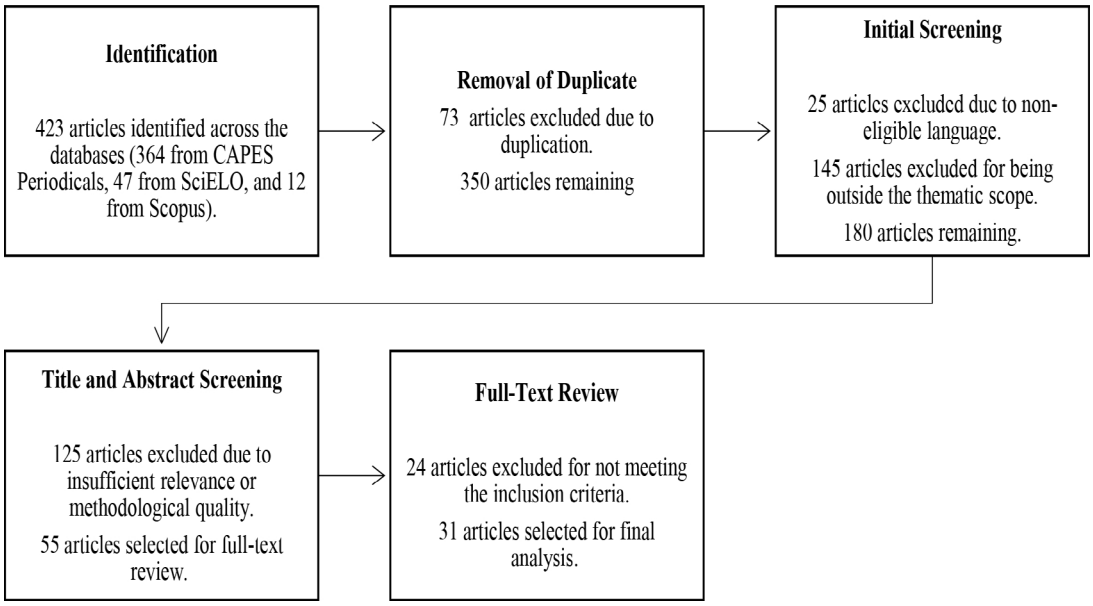
The thematic categorization of the 31 selected articles was carried out using NVivo R1 software through systematic coding based on semantic similarity. This analysis enabled the identification of recurring thematic groupings, organized into four main clusters. Each cluster comprises coded subthemes (NVivo nodes), which served as the foundation for defining the guiding pillars of the proposed model. Box 1 presents the correspondence between the clusters, the coded subthemes, and the resulting guiding pillars.

Based on these thematic groupings, guiding pillars were defined using specific nomenclature that more accurately reflects the themes consolidated in the literature. These pillars emphasize the need for sustainable practices, the adoption of advanced technologies, the strengthening of participatory governance, and the development of approaches aimed at integration into competitive markets. Their purpose is to promote environmental conservation, add value to products, and organize the stakeholders involved in the production chain.

Box 2 details the characteristics and guidelines associated with each guiding pillar, forming the conceptual foundation of the proposed integrated management model.

The pillar of Sustainable Management and Environmental Conservation highlights the importance of practices that ensure biodiversity conservation and minimize environmental impacts. Studies such as those conducted by Silva, Pontes, and Albuquerque (2020) and Picanço and Costa (2019) demonstrate that proper management of Brazil nut groves is essential for maintaining long-term productivity, ensuring that forests

Figure 2 – Flowchart of the article selection process



Source: Prepared by the authors (2025)

Box 1 – Relationship Between Thematic Clusters and Guiding Pillars

Thematic Cluster (Parent Code)	Coded Subthemes (NVivo Nodes)	Corresponding Guiding Pillar
Sustainability and Management	Forest conservation, low-impact practices, indicators, by-products	Sustainable Management and Environmental Conservation
Technological Innovation	Processing technologies, agro-industries, cosmetics, functional foods	Technological Innovation and Product Diversification
Governance and Social Inclusion	Cooperatives, public policies, participatory management, regional equity	Governance Structures and Social Inclusion
Market Access	Certifications, traceability, commercial strategies, international market integration	Market Access and Quality Certifications

Source: Prepared by the authors (2025)

Box 2 – Guiding pillars of the integrated management model

Pillar	Description
Sustainable Management and Environmental Conservation	Focus on low-impact practices to ensure forest conservation and the sustainability of the production chain, including the utilization of by-products.
Technological Innovation and Product Diversification	Development of new products, such as functional foods and cosmetics, through the use of advanced technologies to improve quality and increase value addition.
Governance Structures and Social Inclusion	Implementation of cooperative models and public policies to address logistical bottlenecks, improve commercialization, and promote local development.
Market Access and Quality Certifications	Facilitation of access to strategic markets and enhancement of Brazil nut value through quality certifications, traceability systems, and internationally recognized sustainable practices

Source: Prepared by the authors (2025)

continue to provide indispensable ecosystem services. The valorization of by-products, such as the woody fruits used in the production of activated carbon, represents a strategy that reduces waste while adding economic value to the production process (Alves *et al*., 2023).

Regarding Technological Innovation and Product Diversification, the use of modern technologies expands the range of applications for Brazil nuts. Examples such as cookies produced with Brazil nut plant-based extract, as reported by Lopes *et al*. (2023), have demonstrated growing consumer acceptance, while Carvalho *et al*. (2022) highlight the increasing demand for high-quality cosmetics based on Brazil nut oil. These initiatives not only increase product value addition but also enhance competitiveness in international markets.

With respect to Governance Structures and Social Inclusion, the importance of community organization and participatory management in addressing logistical bottlenecks and improving coordination among production chain stakeholders is evident. Cooperative models, such as those described by Mariosa *et al*. (2024), have contributed to expanding market access and optimizing commercialization conditions. In Acre, public policies aimed at strengthening cooperatives and agro-industries have promoted the integration of extractivists into formal markets, generating significant impacts on local development and social inclusion (Souza; Souza, 2019).

Concerning Market Access and Quality Certifications, strategies designed to position Brazil nuts competitively in national and international markets have gained prominence. Certifications such as organic production and fair-trade certification, highlighted by Krag *et al*. (2017) and Picanço and Costa (2019), are effective tools for increasing product acceptance in demanding markets, particularly in Europe and North America. Traceability systems and sustainable marketing practices have also proven relevant for adding value and strengthening product credibility.

Based on this overview, it is evident that the guiding pillars operate in an interdependent manner, reinforcing one another. Sustainable management establishes the ecological foundation for more efficient technologies; innovation expands product applications and value; governance organizes supply chain stakeholders and facilitates integration into formal markets; and market access depends directly on the adoption of sustainable practices, consistent technological advancement, and well-structured governance. Collectively, these elements support the competitiveness, sustainability, and resilience of the Brazil nut production chain.

3.1 Structure of the Integrated Management Model

The integrated management model was structured based on the interconnection of four fundamental pillars that operate in a complementary manner: Sustainable Management and Environmental Conservation; Technological Innovation and Product Diversification; Governance Structures and Social Inclusion; and Market Access and Quality Certifications. These pillars were organized to align practices that promote forest conservation, strengthen the productive base, and encourage the integration of extractivist communities into more competitive markets.

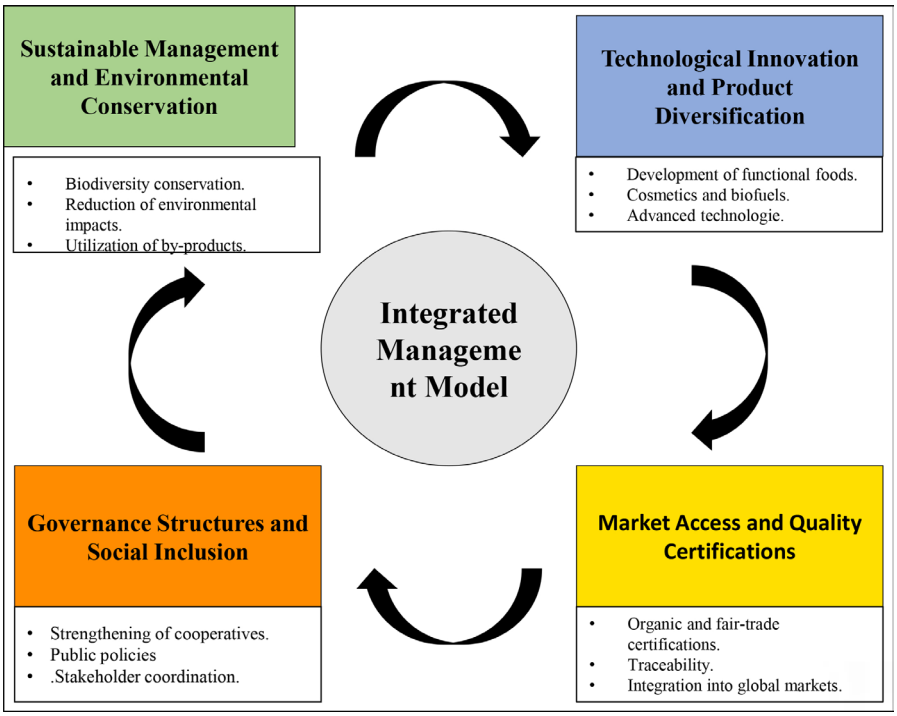
Figure 3 presents the conceptual framework of the proposed model, highlighting the interdependence among the four pillars and their articulation in promoting sustainability, competitiveness, and social inclusion within the Brazil nut production chain.

With regard to the Sustainable Management and Environmental Conservation pillar, the focus is on consolidating practices that ensure the maintenance of native Brazil nut groves, reduce environmental impacts, and enhance the ecosystem services provided by forests. The use of geospatial technologies for monitoring extractive areas, combined with technical training for producers, contributes to the sustainability of management practices (Costa; Beitum, 2020). The valorization of by-products, such as the use of Brazil nut husks for activated carbon production, exemplifies strategies that minimize waste and generate new sources of income.

Regarding the Technological Innovation and Product Diversification pillar, the objective is to expand the potential applications of Brazil nuts as a high-value-added raw material. The introduction of modern equipment and appropriate industrial processes has enabled the development of functional foods, cosmetics, and other high-quality derivatives. Studies by Barbosa and Moret (2015) and Silva, Pontes, and Albuquerque (2020) indicate that products such as cookies made from water-soluble Brazil nut extract and refined vegetable oils have gained increasing acceptance in specialized markets. Collaboration with research centers and technological development programs further strengthens this process.

Concerning the Governance Structures and Social Inclusion pillar, the importance of community organization and shared management among the various actors in the production chain becomes evident. Experiences involving extractivist cooperatives demonstrate that collaborative models facilitate coordination among producers, agro-industries, and consumers. In Acre, public policies aimed at strengthening production chains have supported the establishment of local agro-industries, the development of logistics infrastructure, and the integration of traditional producers into formal markets, generating positive impacts on regional development (Alves; Silva, 2023; Bayma *et al*., 2014; Fonseca; Silva; Rover, 2019).

Figure 3 – Structure of the integrated management model for the brazil nut production chain



Source: Prepared by the authors (2025)

Within the Market Access and Quality Certifications pillar, the model proposes mechanisms to enhance the competitiveness of Brazil nuts in both national and international markets. Certifications such as organic and fair-trade labels are identified as effective tools for differentiating the product, promoting sustainable practices, and ensuring traceability (Krag *et al*., 2017; Picanço; Costa, 2019). The adoption of these strategies contributes to increasing consumer confidence and consolidating the presence of Brazil nuts in demanding markets, particularly in Europe and North America.

Despite growing demand in international markets, Brazil nut exports continue to face technical, sanitary, and logistical constraints. The Bolivian experience highlights the importance of investments in processing capacity, distribution infrastructure, and export-oriented strategies, even when part of the raw material originates from Brazil (Queiroz *et al*., 2022). In this regard, the integrated management model proposes actions within the Market Access pillar, including export-oriented technical training, compliance with sanitary requirements, logistics development, and alignment with public support policies aimed at expanding the presence of Brazil nuts in global markets.

The implementation of the model should be gradual and adapted to local realities. The starting point lies in strengthening sustainable management practices, which establish the ecological foundation for all subsequent actions. Investments in technology and product diversification then increase value addition, while governance structures strengthen coordination among supply chain stakeholders. Market access initiatives subsequently consolidate the results achieved, fostering virtuous cycles of development.

To monitor the impacts of the model, the use of indicators such as increases in extractivist income, reductions in waste generation, diversification of Brazil nut-derived products, and greater participation of traditional communities in formal markets is recommended (Fonseca *et al*., 2021; Silva; Souza; Souza Filho, 2020). Pilot implementation in selected territories will allow methodological adjustments and adaptation to specific sociocultural and logistical contexts.

In summary, the integrated management model proposes a coordinated and scalable approach to addressing the structural and environmental challenges of the Brazil nut production chain. By integrating responsible management, innovation, governance, and market access, it contributes to consolidating this production chain as a benchmark for sustainability, productive inclusion, and the valorization of Amazonian resources.

3.2 Sustainable and Productive Integration of the Brazil Nut Supply Chain in the Amazon

The proposed integrated model presents the Brazil nut as a multifunctional strategic resource capable of combining sustainable development, environmental conservation, and

social inclusion in the Amazon. Although its implementation requires initial investments in infrastructure, capacity building, technology, and certifications, practical experiences (Coslovsky, 2014; Krag *et al*., 2017; Mariosa *et al*., 2024; Souza; Silva, 2021) demonstrate that these costs are largely offset by economic, social, and environmental benefits. The application of the model can contribute to the conservation of Brazil nut groves, product diversification, and the mitigation of production risks, thereby generating long-term sustainable benefits.

Achieving these outcomes requires coordinated actions capable of addressing challenges related to sustainable management, technological innovation, governance, and market access, which constitute the pillars supporting the competitiveness, resilience, and sustainability of the production chain in the face of climate change and market fluctuations.

Sustainable management is essential for preserving Brazil nut groves and maintaining their long-term productivity. Practices such as identifying productive trees beyond traditional collection trails expand harvesting areas, increasing overall production while reducing pressure on already exploited trees. Liana removal reduces competition for light and nutrients while preserving the structural integrity of Brazil nut trees by preventing falls caused by excessive weight (Kainer; Wadt; Staudhammer, 2018). In the Chico Mendes Extractive Reserve, for example, the use of participatory sustainability indicators, including tree health, the balance between harvesting and natural regeneration, and the efficiency of management practices, has enabled rapid adaptation to environmental changes, strengthening the resilience of the extractive system (Fonseca *et al*., 2021). However, extending these practices to other areas depends on stronger coordination among communities and governmental agencies.

Product diversification presents significant challenges. The reuse of residues, such as the woody fruits discarded after kernel extraction, for the production of activated carbon has the potential to generate high-value-added products used in water filtration and industrial applications (Souza; Silva, 2021). The development of functional foods, such as flours and oils, also expands market opportunities by serving specific consumer segments, including healthy and restrictive diets (Carvalho *et al*., 2022; Mariosa *et al*., 2024). Nevertheless, infrastructure deficiencies, such as inadequate transportation systems and the lack of appropriate equipment, hinder the efficient processing of these by-products. The shortage of technical training further limits the adoption of innovative practices, particularly in remote communities where access to training and technologies remains restricted (Souza; Silva, 2021). In this context, the establishment of regional innovation hubs, developed through collaboration among the productive sector, educational institutions, and government agencies, supported by technical assistance and public-private partnerships, represents a promising strategy for overcoming these barriers and strengthening local economies (Maritan *et al*., 2024).

Strengthening governance is indispensable for integrating the various actors involved in the production chain and overcoming structural bottlenecks. Experiences with agroindustrial cooperatives in Amazonas and Pará demonstrate that such organizations reduce dependence on intermediaries, increase producers' control over pricing, and promote social inclusion through community organization and access to shared resources. Nevertheless, challenges persist, including difficulties in internal management and compliance with the requirements necessary to access competitive markets (Krag *et al*., 2017; Mariosa *et al*., 2024). Fragmented public policies and the absence of fiscal incentives also hinder the implementation of integrated models capable of improving supply chain coordination.

Regarding market access, certifications such as organic and fair-trade labels add value to Brazil nuts by ensuring sustainable practices, product quality, and ethical working conditions. These certifications increase consumer confidence, justify premium prices, and expand product acceptance in demanding markets, particularly in Europe and North America (Picanço; Costa, 2019). Despite these advantages, the high costs and complexity of certification processes remain significant obstacles for many producers. The experience of Bolivia, where producer associations overcame regulatory barriers and established leadership in the European market, may provide useful guidelines for adaptation to the Brazilian context (Coslovsky, 2014).

The socioeconomic and environmental diversity of the Amazon poses additional challenges to the implementation of the integrated model, as conditions vary considerably across regions. Differences in forest density affect both the availability of Brazil nut groves and access to harvesting areas (Kainer; Wadt; Staudhammer, 2018; Bayma *et al*., 2014). Irregular rainfall patterns influence logistics, transportation, and storage, increasing costs and the risk of losses (Souza; Silva, 2021; Krag *et al*., 2017). Community practices, shaped by distinct livelihoods and cultural traditions, also influence management approaches and the acceptance of innovations (Fonseca *et al*., 2021; Kainer; Wadt; Staudhammer, 2018). To address this complexity, it is essential to adopt region-specific adaptations that take these particularities into account. Pilot projects implemented in different contexts may serve as effective tools for testing, refining, and applying the model, thereby optimizing its outcomes throughout the Amazon (Coslovsky, 2014; Bayma *et al*., 2014).

Finally, the lack of effective coordination among communities, governments, and market actors intensifies existing challenges, creating gaps that hinder financing and

the implementation of standardized practices throughout the production chain (Bayma *et al*., 2014; Krag *et al*., 2017; Ferreira Junior *et al*., 2024). This lack of coordination results in fragmented efforts, limiting the effectiveness of initiatives related to integrated management (Mariosa *et al*., 2024). To reverse this scenario, it is necessary to institutionalize intersectoral governance mechanisms based on the Triple Helix framework, promoting permanent dialogue forums and shared action plans. Investments in shared infrastructure and collaborative strategies that foster stakeholder integration and strengthen local networks are essential for overcoming these barriers (Coslovsky, 2014). The implementation of the integrated model represents a concrete opportunity to harmonize environmental conservation, social inclusion, and economic competitiveness, thereby expanding its benefits throughout the Amazon.

4 Final Considerations

The Brazil nut production chain represents a tangible opportunity to align environmental conservation, social inclusion, and income generation within the Amazonian context. This study contributes by proposing an integrated management model structured around four interdependent pillars: Sustainable Management and Environmental Conservation; Technological Innovation and Product Diversification; Governance Structures and Social Inclusion; and Market Access and Quality Certifications. These pillars were defined based on a systematic literature review and the analysis of consolidated empirical experiences across different producing regions.

The proposed model seeks to address the main bottlenecks that limit the efficiency and sustainability of the production chain by promoting coordinated and integrated actions. Sustainable management is presented as the ecological foundation for ensuring the productivity of Brazil nut groves and mitigating environmental impacts. Technological innovation enables product diversification and increases value addition. Governance structures are essential for coordinating local stakeholders and strengthening the role of cooperatives. Finally, market access supported by quality certifications contributes to product valorization and competitive integration into national and international markets.

The proposed framework offers an approach that can be adapted to different Amazonian contexts and may also be extended to other forest-based production chains facing similar challenges, such as those involving açaí and natural rubber. The model therefore provides both a conceptual and practical foundation for guiding public policies and sustainable regional development strategies.

5 Future Perspectives

The empirical validation of the proposed model requires its application in real-world contexts. Future studies should focus on implementation in pilot communities to assess its effectiveness and suitability across different socio-environmental realities. Evaluating outcomes through indicators such as increases in extractivist income, reductions in production losses, product diversification, and integration into formal markets will enable assessment of its practical impact. Complementary indicators, including export volume, access to certifications, number of products developed, and level of participation in commercialization networks, may support continuous monitoring and guide progressive refinements of the model.

These applications should be accompanied by technical training strategies, shared infrastructure development, and coordination among public and private stakeholders. The integration of policies promoting the bioeconomy and the strengthening of interinstitutional cooperation networks will be essential for enabling large-scale adoption.

Finally, future research should consider the specific cultural and territorial characteristics of extractivist communities, ensuring that model implementation respects local dynamics and practices. Continuous monitoring will enable gradual adjustments and support the development of solutions that reconcile ecological sustainability, productive efficiency, and social justice.

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