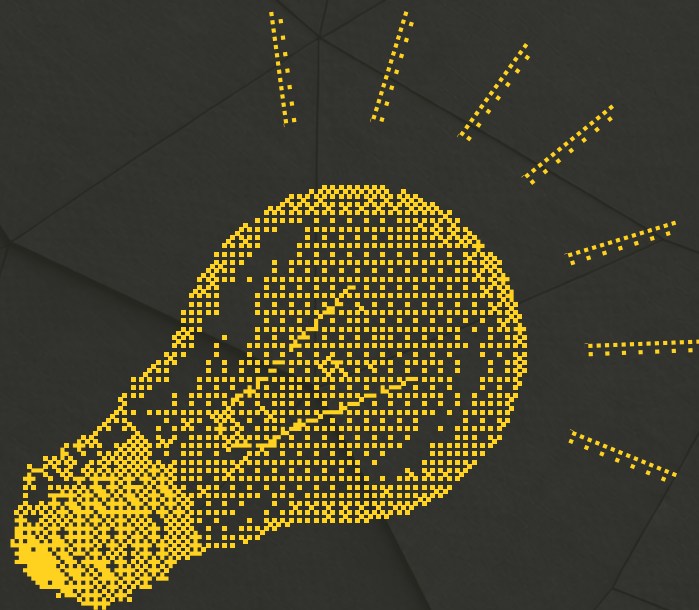


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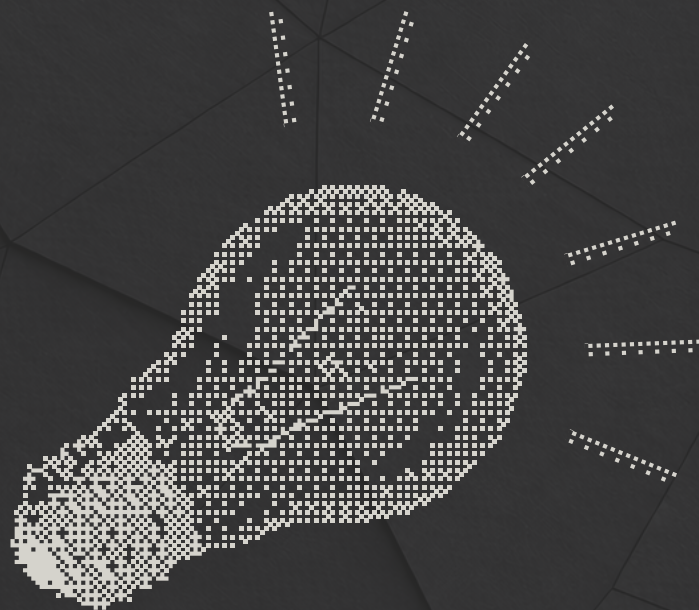
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THE RURAL ZONE BEYOND PAPER: MATERIALIZING AGRICULTURAL SPACE IN RIO DE JANEIRO (1917-1935)

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Leonardo Soares dos Santos¹

Abstract

Only in the 1920s would the then-delimited rural zone of Rio de Janeiro incorporate concerns about fostering a specific set of agricultural activities and infrastructure. That was when the idea that Rio's rural hinterland could become a sort of 'breadbasket' for the Federal District gained momentum. The agricultural rural zone emerged through zoning implementation as a tool of government authority to regulate land-use. The rural zone was no longer a static space, merely subject to taxation, but rather a dynamic territory interpreted and understood in conjunction with its prevailing social relations, not as something separate. This article aims to reconstruct this process between 1917 and 1935.

Keywords: Rio de Janeiro, Rural area, Supply, Urban agriculture, Local history.

INTRODUCTION

In the 19th century, a prevalent debate emerged over modernizing the then-capital of the Republic — Rio de Janeiro. An unexpected outcome of such debates was the solidification of the idea that the city should be divided into three districts: urban, suburban, and rural. One reason for this approach was that dividing the territory would help improve public health by removing unhygienic land uses and activities, such as animal husbandry and crop farming, from the urban core, where most of the population lived. The notion that rural areas, far from urban centers, should accommodate such uses was gaining popularity. However, such a perspective did not align with the interests of rural Rio's inhabitants.

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The debate over what role this area should play in the city's development sparked significant dispute and grew in intensity from the second decade of the 20th century onwards. The issue transcended mere technical considerations, thereby representing a complex socio-political challenge. It entailed engaging in profoundly political matters that implicated competing interests and ambitions. This manifested itself in the city's social geography through district boundaries, political and electoral influence zones, and fiscal collection patterns. This study analyzes the competing proposals for establishing a rural zone in the former Federal District, examining the distinct functions and envisioned potentials assigned to this territory by the various social actors engaged in the debate.

In a 1930 report to the Ministry of Agriculture concerning agricultural improvement in the Federal District between 1927 and 1928, the author expressed concern about the 'state of abandonment' of extensive cultivable lands, noting their potential contribution to Rio's food supply if properly exploited. Expanding on this observation, the author further notes that these rural lands, while possessing, had deteriorated into swamp-like states requiring reclamation (Pechman, 1985, p. 74). Consequently, the report showed the need for production incentives, positioning rural development as key to addressing urban affordability crisis through enhanced food supply systems. It is plausible that Ministry of Agriculture officials approached the issue of fallow lands through a broader lens than purely agricultural productivity. The available evidence suggests their concerns may have encompassed broader economic and territorial governance considerations. The abandoned land, in this sense, harmed both agriculture and Rio's public health. Regional sanitation was important then in two ways: it was a means to restore agricultural lands and eliminate the various outbreaks of disease that had settled there.

Figure 1

1911 map of the Federal District.



Source: Brazil's National Library Digital Archives Collection

The need to upgrade rural parishes/districts in Rio's municipality entered urban political debates as early as the 1900s. Advocates highlighted the region's needs by raising these issues and pushing for official recognition of its systemic problems. However, contemporary appeals for agricultural area improvements consistently prioritized combating insalubrity,² a pervasive problem in these peripheral zones. Intendant Fonseca Telles notably observed in press commentaries about the "suburban area" — "where the working class predominantly resided and the District's crops were cultivated" — that burial taxes ranked among its largest revenue sources. To this end, Telles proposed inviting the mayor to tour the region, asserting: "This visit would significantly benefit the area. Upon witnessing conditions firsthand, the Chief Executive would undoubtedly take prompt action—if not to beautify these areas, then at least to make them more traversable and salubrious" (*Annals of the Municipal Council*, September 22, 1909, pp. 176-177).

² Contrary to the current meaning of the word salubrity, which is associated with degrading or precarious living conditions, at the turn of the 19th century, the term was linked to the impossibility of living in certain areas due to the existence of disease outbreaks.

While widespread insalubrity was acknowledged as requiring government intervention, certain actors simultaneously perceived it as an opportunity to invest capital in an extensive area of the Federal District. The region's economic potential was heightened by evident demographic growth, making it particularly attractive to capital. Numerous private actors strategically framed sanitation infrastructure and agricultural development as mutually reinforcing initiatives to enhance the value of the Republic's agricultural region. This zone notably included the rapidly urbanizing 'suburban area'.³

Amadeu Fajardo, a civil engineer attuned to these dynamics, proposed a project to the municipal legislature in October 1911 for the "use and enjoyment of an electric tramway" that would "start from Santa Thereza hill, near the aqueduct, and end in Sepetiba, with" lateral, electrified, rail-less roads connecting the districts of Jacarepaguá, Guaratiba, Campo Grande, and Santa Cruz to the main line—along with associated privileges for this undertaking". The project's primary justification—and appeal—lay in its dual promise: simultaneous sanitation of insalubrious lands and their conversion into agricultural frontiers, explicitly framed as a public good. This transformation would occur at one go, addressing both public health crises and food production needs through integrated infrastructure:

The project targeted as well a neglected Atlantic corridor—from Gávea Peak to Sepetiba—where insalubrity and underpopulation had long hindered agricultural development. Considering also that the projected undertaking would not only complete the sanitation of a large area of marshy land but also determine the settlement of the extensive area served by the electric tramway and electrified side roads [...] transforming it into a zone enriched by small-scale farming and livestock capable of supplying urban markets through efficient transport (*Annals of the Municipal Council*, June 20, 1911, pp. 176-157).

Beyond capitalist interests, numerous legislators also pushed for regional improvements, grounding their appeals in the urgent need to combat insalubrity. Fonseca Telles, for instance, demanded

³ In Brazil, *the suburbs* or *suburban areas* (subúrbio) typically refers to lower-income, often underserved peripheral neighborhoods of major cities, frequently associated with informal settlements, limited infrastructure, and socioeconomic marginalization, closer in meaning to "urban periphery" or "working-class outskirts". The Brazilian usage reflects historical urban development patterns, where the *subúrbio* emerged along railway lines and industrial zones, distinct from the planned, affluent suburbs of North America or Europe.

immediate intervention at the Jacarepaguá lagoon, where stagnant waters had created a severe paludism (malaria) hotspot (*Annals of the Municipal Council*, June 20, 1911, p. 401).

A few years later, the existence of unsanitary hotspots would once again be highlighted by Cesario de Mello,⁴ such as the Guandú River region, further stressing how the issue surrounding "the misery of forgotten regions, misery that depresses their development" impeded agricultural progress in an area widely regarded as naturally suited for farming:

By misery, the Speaker refers to that caused by the morbus which, in these impalescent regions, decimates their already scarce populations, while those drawn there by the promise of fertile soil endure all things through commendable effort and defiance.

It is urgent, indispensable, and imperative to combat without respite, in these promising areas of the District, the decimating and terrifying morbus: such as uncinariasis, leishmaniasis, paludism (malaria), and the epizootics ravaging livestock (*Annals of the Municipal Council*, July 2, 1917, p. 75).

The sanitation pressures in the region grew so pronounced that under Mayor Amaro Cavalcanti's administration, the City Council formally proposed legislation for the "sanitation of suburban and rural areas" to the municipal legislature. A central objective included "clearing and cleaning riverbeds and banks throughout the District, elevating watercourses, and leveling and draining adjacent lands to enable cultivation" (*Annals of the Municipal Council*, July 10, 1917, p. 228).

In Message No. 362 to the City Council, Mayor Amaro Cavalcanti outlined his strategy to transform the Federal District's rural zone into a major agricultural supplier—what he explicitly termed a "breadbasket" for the capital:

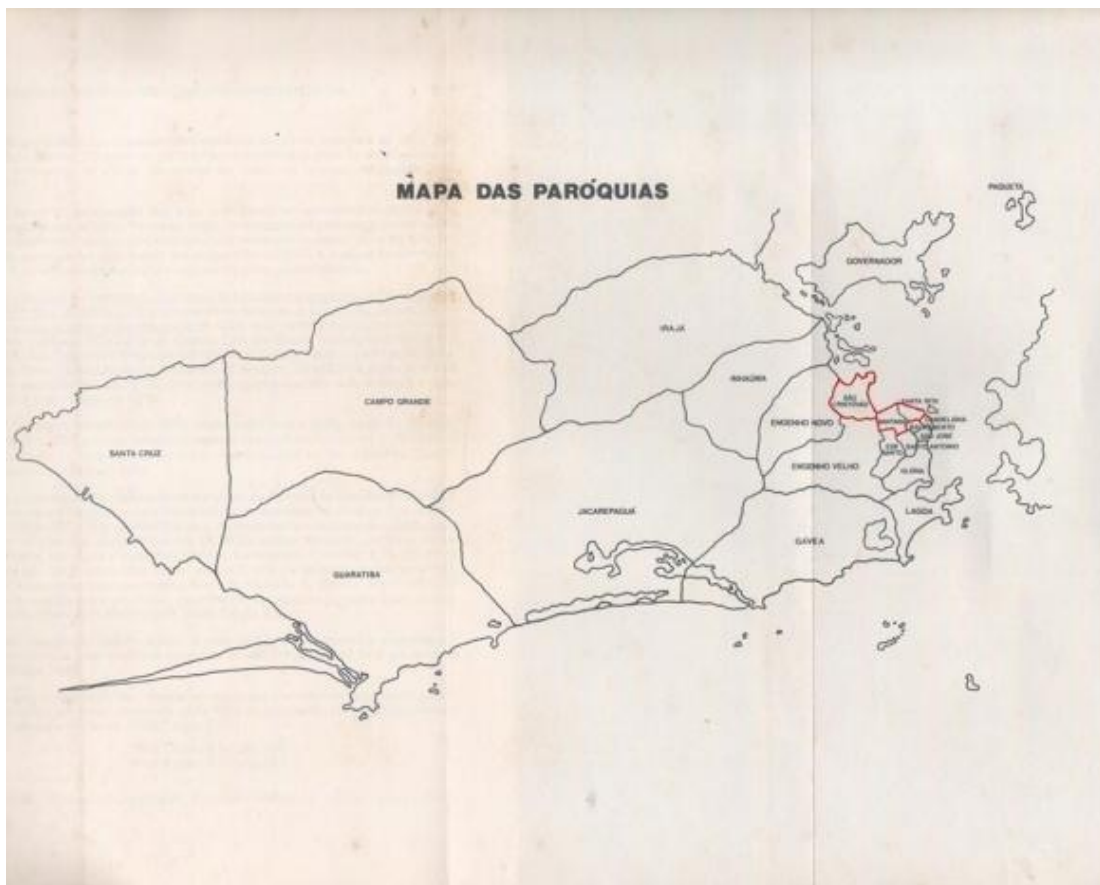
⁴ Cesário de Mello was a landowner and physician in the region, noted for his role as a political leader in the area. He was elected councilman twice (1924 and 1930) and senator for the Federal District in 1935.

To encourage, assist, and promote—without interruption—the development of agriculture in the Federal District must be recognized, by law, as one of the permanent obligations of the local government.

[...] This is not an undertaking to be accomplished all at once. No one expects to see, within just a year or two, the entire territory of the Federal District transformed into a granary of foodstuffs or into an orchard or garden yielding fruits and flowers of every kind. What is intended is to initiate, with faith and perseverance, the agricultural work of the District, sowing—where most appropriate—the good seed, so that from it may sprout select plants capable of bearing the finest fruits. Let us proceed gradually, yet with unwavering confidence in success, provided that the proper methods and tools are employed, and let us not abandon the endeavor midway through its course. If we act thus, within five or six years, the Federal District will have for its population an abundant, secure, and locally sourced food supply; its currently uncultivated lands will be greatly enhanced in value by the immense wealth they produce; and public finances, in turn, will see a progressive increase in revenue streams—streams that are now lacking and will continue to be so for as long as the fate of the District's own wealth remains neglected. (*Annals of the Municipal Council*, September 7, 1917, p. 217)

Figure 2

Map of parishes in the Federal District.



Source: LOBO, Eulália. *História do Rio de Janeiro: do Capital Comercial ao Capital Industrial e Financeiro*. Rio de Janeiro: IBMEC, 1978.

One of the obstacles to such a plan was the precarious state of agriculture in Rio itself, which, according to him, 'is meager and underdeveloped, lacking the means for its advancement.' This precariousness stemmed from the poor condition of roads in rural areas and the prevalence of unsanitary areas.

After considering that the City Government lacked the financial capacity to purchase 'large tracts of land to convert into agricultural settlements' (implying that this would have been the most advisable measure to implement), Amaro Cavalcanti proposed the following 'items for a program, albeit modest,' which would ensure 'profits and advantages' for Rio's sharecroppers:

1) A practical rural school [...] 2) Periodic agricultural workshops in various localities, where farmers would be instructed—in plain and clear language—on the best techniques and practices for diverse crops [...] 3) Small local markets [...] 4) Facilitated access to seeds, fertilizers, and machinery [...] 5) Monetary prizes (ranging from one to five contos de réis)⁵ for farmers who achieve the highest yields in specified crops [...] 6) Improvement or completion of roadworks for cart-accessible thoroughfares [...] 7) Revised transport tariffs [...] 8) Construction of a central marketplace [...] 9) Dredging of rivers—serving both as a sanitation measure and as a means to render adjacent lands suitable for farming [...] 10) Prompt drainage of coastal marshlands in Jacarepaguá, Guaratiba, and Irajá, as well as the swampy regions along the Mendanha's Rio da Prata and the Guandu do Sena [...] 11) A narrow-gauge railway, extending from Gávea through fertile coastal farmlands to Sepetiba [...] 12) Reduction of taxes or duties [...] 13) Standardized measures to streamline fruit exports [...] 14) Organized maritime or land transport to expedite the distribution of fish from coastal villages [...] 15) Land registry formalization for all Federal District properties. (**Annals of the Municipal Council**, 07/09/1917, pp. 218-220)

Amaro Cavalcanti would return to this issue nearly a year later, in June 1918, in a new message to the Municipal Council, addressing "agricultural development in the Federal District" with greater specificity. The then-mayor outlined several initiatives aimed at transforming the "modest suggestions" from the previous year into more effective measures to support municipal agricultural activities. One such initiative was the establishment of the Superintendencia dos Serviços Municipaes da Lavoura do Districto Federal (Superintendency of Municipal Agricultural Services for the Federal District) through Legislative

⁵ Contos de réis was the highest numerical unit of Brazil's first currency, the réis, used from the colonial period (1500s) until 1942.

Decree No. 1,183 of January 3, 1918. This agency, in addition to the superintendent, included four "instructor-agronomists". The primary function of this body was to provide agricultural guidance and advice to small farmers throughout "the entire rural zone of the Federal District". Initially, these instructors were assigned to four designated stations:

- Station No. 1 - Irajá, which covered Inhaúma, Engenho Novo, Meyer, and the Islands, with its headquarters at the "Demonstration Field" in Deodoro;
- Station No. 2 - Jacarepaguá, which included Tijuca and Gávea, based in Taquara;
- Station No. 3 - Campo Grande, which included part of Santa Cruz, headquartered in Campo Grande;
- Station No. 4 - Guaratiba, which encompassed another portion of Santa Cruz, based at the Sacco Farm.

Issues such as machine repairs, seed management, and problems like the 'anthill plague' ("The number of eradicated anthills is no longer small: it exceeds 400"), plant grafting, and animal training were some of the most commonly addressed topics by the instructors when assisting small-scale carioca⁶ farmers. However, the initiative faced significant operational challenges due to several compounding factors. Chief among these was the severely limited technical staff, with each agricultural station assigned just a single instructor. This meant a mere four instructors were responsible for servicing the entire rural zone of Rio, an area encompassing nearly two-thirds of the municipal territory. As Amaro Cavalcanti himself lamented: "The number of instructors is insufficient to properly address requests from various locations, often very distant". Another complaint concerned the limited supply of agricultural equipment (Annals of the Municipal Council, 18 de Junho de 1918, p. 26). The following excerpt provides a clear picture of the Agricultural Superintendence's operational challenges. The account reveals both functional aspects and grievances about inadequate working conditions:

⁶ Carioca (Portuguese: [kari'okɐ]) refers to a native or resident of the city of Rio de Janeiro, Brazil's coastal metropolis (e.g., "Carioca culture").

[...] unless by increasing the current number of instructors, it becomes necessary to provide them with a practical assistant of intermediate rank between the instructor and the laborer - one possessing slightly greater qualifications than the latter, with more competence and knowledge, so as to better assist and, in certain cases, even substitute for the instructors in their duties and supervisory tasks.

Once the stations are properly organized and adequately equipped, the instructors shall be required to conduct practical agricultural lessons at designated locations, on fixed days and hours each week, thereby enabling the surrounding population to become further skilled in the requirements of their industry.

The services currently provided at the stations have consisted principally of: Assembling agricultural machinery and instructing in its operation; Demonstrating its utility and purposes; Training animals to work with machinery; Advising on proper land selection and utilization; Plant grafting; and, most frequently, undertaking work for the eradication of anthills.

[...] It appears highly advantageous that each station maintains nurseries dedicated to cultivating useful plants for distribution to farmers - either gratuitously or at minimal cost when supplying large quantities (Ibid).

Nevertheless, the limitation most lamented by Amaro Cavalcanti, given the Agricultural Superintendency's lack of resources, concerned the works for 'draining the swamps and dredging the rivers of the Federal District'. According to the mayor:

The clearing of rivers and the drainage of fields are necessary measures, the fulfillment of which complements those just mentioned: for only then will the swampy stagnation of waters cease—a stagnation which, when it does not bring death, inflicts a slow and corrosive degradation upon the vitality of the rural worker and his descendants.

Sanitation would remain a significant problem for the region in the years to come. In July 1919, *Gazeta Suburbana* lamented the fact that Tijuca, Jacarepaguá, Campo Grande, Santa Cruz, Sepetiba, Irajá, and Inhaúma were 'localities whose progress [was] most hindered by the various diseases that debilitate or kill their populations'. The report further detailed the factors contributing to this situation:

[...] the consumption of well water, the absolute lack of sewage systems for fecal matter, the scarcity of medical assistance, the presence of numerous swamps, and, finally, the difficulty of transportation for those needing to reach the nearest prophylactic stations.

Rezult (sic): the depopulation of that locality and the loss of vital energies that could have greatly benefited the community" (*Gazeta Suburbana*, July 12, 1919, p. 2).

One of the most notorious local politicians, Cesário de Mello, described Santa Cruz as seeing 'the birth rate coefficient diminished and those of mortality and stillbirths augmented':

The influenza pandemic of past years still accounts for the burden of mortality. There is no denying that, from the State's improvidence in allowing the population to condense in an endemic environment - through permanent stagnation and pollution, lacking hygienic housing and public assistance services - stems nearly all the harmful effect to which I have just alluded (*Annals of the Municipal Council*, June 13, 1923, p. 164).

The sanitation of rural lands was increasingly becoming the greatest challenge in the region. Promoting agriculture, as a broad and mass-scale policy by public authorities, was seen as an important tool for improving the area. In the Rio de Janeiro context, agricultural activity had a sanitizing character. The project submitted by Cesário de Mello to the Municipal Council's executive board perfectly encapsulates this conception:

That measures be taken with the Honorable Ministers of Agriculture, Transportation, and Internal Affairs to establish an agreement with the Federal Government to intensify: cultivation, field development, rectification works, drainage [sic] and dredging services, and the systematization of water supply - so that, as far as possible, the desiccation and supply for hygienic treatment of household effluents may prove efficient, thereby preventing transmission to humans and animals, either directly or indirectly through insects and parasites that develop actively and incessantly in stagnant, muddy, and polluted environments, maintaining endemic conditions" (Ibid.).

RETHINKING THE RURAL ZONE'S DEVELOPMENTAL IDENTITY

'Meager resources' were not the only issue that hindered the implementation of sanitation measures. Back in 1918, Amaro Cavalcanti highlighted an issue that virtually no other political actor mentioned when discussing agricultural improvement in the rural zone of the Federal District: the question of land ownership—and, related to it, the tendency of many 'landowners' to engage in land speculation. He had observed, as early as 1918, that the improvements carried out by public authorities in the rural zone, rather than benefiting agriculture and small farmers, could instead serve very different ends:

Most of the lands through which the rivers to be cleared flow are privately owned, acquired perhaps for minimal prices, but whose owners remain waiting for the public authorities to undertake improvements, spending large sums to increase their value - with the results then being reaped by those who had no concern for the public good, nor contributed to its sanitation.

The administration must therefore be equipped with the necessary means to resolve this issue, with the general welfare in mind - that is, by productively transforming insalubrious regions into fertile and productive fields.

To this end, it must be furnished with wisely adopted laws which either: impose upon the landowners of such properties, under severe penalties, the obligation to promptly undertake their sanitation, allowing them to reap the resulting benefits themselves; or empower the public authorities with the right to expropriate them and, once sanitized, divide them into rural lots to be leased to private individuals for periods sufficient to allow them to benefit from plantings and other improvements made thereon.

I am convinced this would be one practical way to solve such an important problem, providing real compensation for the substantial expenditures that will prove indispensable" (*Annals of the Municipal Council*, July 20, 1918, p. 164).

Beyond financial resources, the Municipality needed legal instruments to prevent rural lands from serving less noble purposes. It is crucial to note that for Amaro Cavalcanti and numerous sanitarians, the measures promoting the region's salubrity carried strong moralizing undertones. They believed that the hazardous environment (especially endemic diseases) generated indolence among rural inhabitants while simultaneously being reinforced by it. The notion of sanitation was simultaneously biological and moral. In this same address, the mayor emphasized that:

Another grave ill to be vigorously combated, much like the insalubrity of the fields, is the disordered consumption of alcohol by countless individuals of the lower classes inhabiting these areas. Those who travel the various paths and roads crossing the rural zones encounter at every crossroads a small tavern. These establishments, which ought primarily to facilitate food distribution and quench travelers' thirst, are instead almost exclusively vehicles for propagating and distributing alcohol in its most harmful and repugnant form: cachaça. The field laborer, living in swampy lands and victim to the worst local endemic diseases characteristic of the region, frequently seeks recreation or pastime in conversations under the tavern's awning, where they repeatedly ingest the poison that will inevitably undermine their constitution - often already weakened by prolonged exposure to insalubrious or pestilential fields. [...] It is the habitual use of alcohol that primarily produces that characteristic indolence or lack of work dedication noted in a large portion of the rural proletariat. They earn little because they work few days, and even then, the greater part of their meager wages is invariably spent acquiring alcohol, whose consumption renders them increasingly indolent" (Ibid.).

This view of the rural population was echoed in Rio's own press. The *Gazeta Suburbana* analyzed the following on January 24, 1920:

Tillage needs hands. And the police must fulfill their duty. Why do we say this? Because we cannot tolerate so many individuals (nearly all of apparent robustness) spending entire days in taverns and suburban bars - idle and languishing through cachaça consumption - without being able to honestly account for the money funding their habits, when they could be employing their energies in agricultural work. Were the police willing, these individuals could be put to good use. This would constitute an excellent service to both the social question and the nation" (*Gazeta Suburbana*, January 24, 1920, p. 2).

Hence, from the early 20th century onward, agricultural education proposals were regularly disseminated in the press and in class association organs. The then-Federal District's primary promoter would be the Sociedade Nacional de Agricultura (National Agriculture Society) through its magazine *A Lavoura* (January 1910, p. 23). To some extent, it would ultimately succeed in establishing rural schools. The municipal education network, which had expanded since at least the administration of Sezerdelo Correa (September 1909 – November 1910), reached the rural zone by the early 1920s. This launched the Rural Schools initiative, "which aimed to provide education suited to local peculiarities". Their reconstruction began between 1922 and 1926. The first of these would be the Escola Rural Alberto Torres (Alberto Torres Rural School), located in Santíssimo, on the margin of the Santa Cruz royal road (Froes; Gelabert, 2004, p. 192). Acting just before the Municipal Government, the federal administration under Marechal Hermes established the Escola Técnica Visconde de Mauá (Visconde de Mauá Technical School) in the Vila Proletária, where agricultural courses were also taught (Oliveira, 2004, p. 2).

Moreover, the Municipal Government had already shown interest in establishing rural educational institutions in the region as early as the 1910s. On July 10, 1917, Intendant Cesário de Mello introduced Project No. 6, authorizing the mayor "to create, in the rural zone, an agricultural apprenticeship program, under the conditions it establishes, and to take other measures". In the project's introductory text, the author not only demonstrates a framework grounded in the notion of agricultural education as an instrument for redeeming the 'disadvantaged' classes (Mendonça, 1998, p. 15), but also highlights the

pressing contemporary issue of increasing the region's agricultural productivity to alleviate the city's supply crisis:

Whereas the necessary knowledge for properly directing field work must be disseminated among different social classes; Whereas through these means and knowledge - by applying rational cultivation principles and proven methods endorsed by experience - one can significantly increase production (Ibid.).

These concerns would shape subsequent government projects and actions, demonstrating that, in practice, the rural zone was not entirely a 'forgotten region' or 'devoid of meaning' for public authorities, despite this being the prevailing perception of the area. The consequences triggered by the implementation of some of these projects, particularly regarding agriculture and rural sanitation, would lead to profound transformations in the rural zone beginning in the 1930s.

Beyond improving the region's sanitary conditions, transforming the rural zone into a 'breadbasket for the capital' also addressed another crucial demand: the city's own need for food supplies.

With the First World War and the increase in the fuel price, the freight of food products imported through Rio de Janeiro increased significantly. This rise would have repercussions on the final price of the products and it would weigh on consumers' wallets, particularly the mass of urban wage earners. However, before that, supplying the city was already a problem. In her study about the implementation of the Bangu Factory at the end of the previous century, Luciana Cunha Oliveira (2006, p.49) notes that the factory's management built the Santo Antonio mill in 1900 to facilitate the supply of goods to the workers' families. The author attributes this initiative to the cost of the workers' food in Rio de Janeiro, as it was the highest during this period due to the population increase in the federal capital and the downturn in the agricultural region. This was the formula found by Bangu Factory to ease the problem (Idem). In addition to the mill, Luciana Oliveira points out that the Factory's strategy also involved creating conditions for the workers to provide their own subsistence, a point highlighted by Mr. Diocleciano Machado in a worker's article:

In Bangu they made us live together, the factory gave us a land and wood to build the house. No one in my family had ever worked in factories before. The men of the Company allowed us to farm and keep a few animals, pigs and chickens, so there were many ranches. Some planted sugar cane and sold it to the mill. (Oliveira, 2006, p. 51)

The role of the backyard in subsistence production for the 'labourers' is also recalled by Everardo Backheuser:

The backyard in workers' houses is, especially if there is no garden, one of the most important areas; it is where the household and outdoor clothes are washed, because the use of public laundries unfortunately is not widespread among us, which we wish it were; it's where the children play, because otherwise they would be out on the street; it's where the chicken coop is located. (Backheuser, 1906, p. 24)

Backheuser defends the idea that one of the few things that could lead "workers" to settle in the suburban areas at the beginning of the 20th century was the possibility to cultivate their own vegetables, as well as the "clean air" and the "more affordable" price of land, but leaving aside all the high costs of transportation (since a large part worked in urban areas). In this regard, the problem of food supply was far from being a minor issue in that Rio de Janeiro of the first decades of the 20th century⁷. Not surprisingly, the issue of high food costs would appear recurrently in many protests by workers' groups and parties in the city. However, the supply crisis was not only prejudicial to workers. An important detail comes along: workers in the former Federal District, especially in the factory sector, were the most well-paid in the country. According to the historian, "the main reason for the higher wage rate in Rio was the high cost of feeding the labor force in the region, due to the lack of local agriculture and the precarious agricultural situation in the Fluminense region" (Linhares; Teixeira, 1979, p. 20).

Other repercussions of this city characteristic were still evident in the mid-1910s. Alfredo César, in a study of the Vila Proletária (known today as Marechal Hermes), in 1914, highlights that several of the residences designed for this Vila were made for the occupation of "farmers". The author deduces that

⁷ Maria Yedda Linhares and Francisco Carlos recall that in 1918 the Public Food Commission was created, "the first body to mark the State's intervention in the supply problem". The author also mentions that this Commission emerged in the midst of "an acute social crisis, marked by popular and workers' movements that even questioned the authority of the State". (1979, p.20)

there was, on the part of the Federal Government, "a concern to make the Vila Proletária self-sufficient in necessity goods" (Oliveira, 2004, p. 2).

Aware of this problem, the municipal government, through some of its mayors, would take certain measures. In a city with a considerable degree of mobilization among the working-class, the hypothesis that this class would have to deal with the large increase in the value of food in their daily lives caused at least some concern among the public authorities. The personal notes made by Mayor Amaro Cavalcanti (1917) on the subject help to understand the extent of such concern. They were found by me during research carried out at the beginning of 2007 at the Instituto Histórico-Geográfico Brasileiro (Brazilian Historical and Geographical Institute) funds. This compilation, although not very extensive, reveals a little of the public authorities' understanding not only of the supply issue itself, but also of its political and social implications. One of the [newspaper] clippings the mayor kept contains an article on 'The cheapening of Uruguay's food supply'. The text of the article contains the following information: "the Government is studying a draft law banning this foodstuff, going so far as to requisition them in serious cases, in return for payment" (Cavalcanti, 1917).

Attached with the article is a personal note from the mayor, which appears to be a draft of a speech he was going to make. Here, rather than talking about how this type of decision would be taken in the city, Amaro comments on the political repercussions that such matter could have on the population:

There is no real cause for the population, mostly laborers and neediest classes, to be led by the malevolent suggestions of those who seek to disrupt order on the pretext of a shortage of basic foodstuffs. It's not unknown the high-cost of foodstuffs nowadays. But, the situation is being watched by the Mayor and remains the same, either in terms of quantities or prices respectively. And both Mr President of the Republic and the City Hall remain vigilant in this regard, adopting measures advised by prudence and prevention on a daily basis (Cavalcanti, 1917).

Further on, certainly inspired by the Uruguayan example, Amaro Cavalcanti signalled possible measures to re-establish an adequate supply of goods. The war situation - we were still in 1917 -, in which certain initiatives were allowed, might have justified some measures. However, another element

contributed to making the period much more tense. 1917 marked the peak of the strikes organised by the labour movement under anarchist hegemony. This reflects in Amaro Cavalcanti's considerations, as we shall see:

Unfortunately, if this hope were to be a bad omen, the public authorities would still have the extraordinary measure of either fixing the maximum retail and wholesale price of essential goods or selling them directly to the population, so that their fate would not be at the mercy of speculative greed. What is needed is for each one to be careful against insinuations of individuals, not at all well-meaning, who, with the good of the workers [the harmed party], - what they really want - is the common misfortune of all (Cavalcanti, 1917).

Azevedo Sodré's City Hall administration had already been experimenting with more concrete measures a year earlier, such as Decree No. 1,126 of 20th November 1916, which authorised the establishment of street markets in urban and suburban areas.

In fact, Amaro Cavalcanti's government⁸ introduced two new priorities onto the municipal administration's agenda: supplying the capital and improving transport as well as agricultural production, in suburban and rural areas. This is the first (and fleeting) time that a mayor has demonstrated a willingness to invest more in these regions than in urban areas. To this end, the Potiguar magistrate emphasized the attendance of the demands in suburban and rural areas, as well as addressing the problem of supplying the city, encouraging farming and craft production, and repairing roads to facilitate the outflow of this production (Pinto, 2008, p. 158). The urban planner José Reis notes Amaro's great efforts to improve the communication routes between the urban district and the rural and suburban district; and this was the main focus of his administration: “with scarce funds, large stretches of local roads were improved, bringing real benefits to residents of the northern area and, above all, those of the carioca hinterland, as the Campo Grande and Santa Cruz area was called” (Reis, 1977, p. 65).

⁸ Amaro Cavalcanti (Amaro Cavalcanti Soares de Brito, 1851-1922) was born in the municipality of Caicó, in the Seridó region (state of Rio Grande do Norte). He graduated in Law from Albany Law School in New York (USA) and was mayor of the Federal District between January 12th and November 15th 1917.

Occasionally, the idea of setting up agricultural colonies in rural areas reappeared. It was an enormously costly undertaking, but the pressure to ensure a stable food supply kept growing. Paulo de Frontin would once again signal his intention to buy 'old farms' located in the rural zones in order to establish these colonies. When commenting upon the then mayor's proposal, *Gazeta Suburbana* made it clear that the problem of food consumption for the carioca population was a fundamental issue for improvements in the region:

The existence of these colonies, which could be magnificent centers for the production of small crops, poultry and small livestock, would bring great benefits in terms of abundant supplies to the existing or future small markets in all the most populated parts of this capital, as well as the cheapening of all these products, which is the only way to remedy the crisis caused by the lack of transport, the cause of the high-cost of living. Well cultivated, these farms could be a source of income that would more than compensate for the expenses incurred by the Prefecture in transforming them into agricultural colonies, if they weren't torn up and given on a precarious basis, to those who wanted to colonise them on the condition that they would take their produce to the municipal markets and sell it at the prices set by the Prefecture. Some of these farms have seaside locations. This would mean that the pisciculture industry could be set up on these lands, which would also be of significant interest to consumers, as fish and shrimp, etc., would come at the lowest price possible. This problem is one of the most important and demands a ready solution (*Gazeta Suburbana*, July 12, 1919, p. 2).

Under Carlos Sampaio's administration, Decree no. 2,392 was issued on 12th January 1921, and in its 5th article:

To fund the meat supply services reform, as well as for other improvements and new projects, the Mayor is hereby authorised to take out an external or internal loan up to the sum of 60,000 contos de réis, which may be increased by an amount equal to the value of the current loans that have been redeemed, calculating equality by the equivalence of the interest service, with the sum of 10,000 contos destined for services and improvements in the municipal districts of Espírito Santo, São Christovão, Engenho Velho, Andarahy, Tijuca, Engenho Novo, Meyer, Inhaúma, Jacarepaguá, Campo Grande, Santa Cruz and Guaratiba (Sampaio, 1921).

In the following year, the situation takes an unexpected turn. What Amaro Cavalcanti had pointed out as a drastic but necessary possibility ended up being implemented by Carlos Sampaio through Decree No. 2,274 of 29 September 1922. On the one hand, Amaro Cavalcanti's justification lay in the hardships

caused by World War I and the 'malevolent agitation' caused - according to him - by labour leaders. On the other hand, Carlos Sampaio's support for such a measure was based on the occasion of the Centenary of Brazil's Independence celebrations, held in the national capital (Motta, 1992)⁹. In his opinion, it would be enough for him to be authorised by decree "to carry out the acts he deems necessary to ensure the regular supply of basic necessities to the population of the Federal District on the occasion of the centenary festivities and gives other measures" (ACM, September 29, 1922, p. 636).

Two very important measures to improve food production in the capital were also emphasised, both of which would have great repercussions in the effort to assert the role of the rural zone as a space for agricultural production. These measures anticipate by more than a decade the intentions contained in the urban planning regulations of 1935 and 1937.

The project No.263, for example, authorized "the Mayor to transform the Sacco de Guaratiba farm into an agricultural colony and breeding farm" (ACM, 14 December 1920, p. 149)¹⁰. With the approval of this project, the *Fazenda Modelo de Guaratiba* was born and still exists today. The City Hall's decision in 1924, through Bill 154, to 'promote the colonisation of the rural zone of the Federal District' and the 'organisation of food production cooperatives' was another important measure. Through this project, the City Hall could even create a 'Banco Hypothecario Municipal' (Municipal Hypothecary Bank) to make feasible mobilising credit for the implementation of colonisation plans, involving the purchase of machinery, tools, seeds, construction of schools and improvements, etc. (ACM, 19 December 1924, p. 274).

In fact, all the crisis surrounding the issue of supply, with all its political repercussions, was largely stimulated due to the industrial surge experienced by the country and specifically by the city of Rio de Janeiro. Furthermore, population growth itself was a key factor in this scenario. In terms of the growth that is taking place in Rio, there is a further complicating element for public authorities to

⁹ See also CAULFIELD (2000).

¹⁰ At that time, the Juliano Moreira Colony was also being created. Back then, it was known as the Jacarepaguá Psychopathic Men's Colony. The purpose of this colony was to house the São Bento Men's Colony, located on Ilha do Governador and built in 1890.

manage. The majority of the population that has been incorporated into the city since the last decade of the 19th century is made up of Portuguese immigrants¹¹. Gladys S. Ribeiro reports that the Portuguese presence in the city was significant between 1890 and 1930. In this first year, for example, there were 106,461 Portuguese in Rio, of whom 77,954 were men and 28,507 were women. Men made up 50% of the foreign population and women 18%. According to Gladys, 68% of foreigners were men and women (Ribeiro, 1994).

Growth of this kind revealed to the public authorities how important it was to consolidate reliable sources of goods to supply the population of the country's capital. Rio's countryside began to be seen as one of these sources. Significantly, from the 1920s onwards, several of the improvements planned for this region addressed the city supply issue as one of the justifications for their relevance.

Figure 3

The green spaces of Jacarepaguá in the early 1950s.



Source: Observador Econômico, April 1951, no. 183, p. 58.

¹¹ Manolo Florentino and Cacilda Machado point out that of the 5,600 foreigners who arrived in Brazil between 1820 and 1972, a third were Portuguese, compared to 29% Italian and 13% Spanish. See "Essay on Portuguese immigration and patterns of miscegenation in Brazil in the 19th and 20th centuries", In: Portuguese Studies Review, Trent-Canada, v. 10, n. 1, 2002, p. 1. Another essential read about the subject is LOBO (2001).

When justifying the project to build a bridge linking the coast to Barra de Guaratiba, the legislators emphasised the appeal of the area affected by the project:

It is a real haven, a place that can be used as one of the most attractive spots on our coast due to its mild temperature, natural beauty and other essential features, such as the modest living conditions inherent in a locality with its own resources from fishing and farming. The aim of building the bridge, moreover, is to facilitate the exploitation of the restinga, which has [...] a large contribution of an appreciable supply of farming and fishing products to the population of this capital (Annals of the Municipal Council, 4 October, 1927, p. 39).

In August 1928, one of the main justifications for the rail service planned by the City Council between Irajá and Guaratiba was the fact that it was a 'producing zone' with a 'reasonable supply coefficient' (Annaes do Conselho Municipal, 4 November 1928, p. 57).

When asked to give his opinion on the High-speed Urban Transportation Project by engineer Raymundo Pereira da Silva in 1929, the then director of the Rio de Janeiro Remodelling Plan, Alfred Agache, formulated the reasons behind his approval as follows:

- 1st- The project preliminarily solves the problem of urban and suburban transport as a whole.
- 2nd - Fits perfectly into the general plan for remodelling the city and its extension, carried out under my direction.
- 3rd - Corresponds, on the one hand, to an urgent need to relieve the traffic jams in the central part of the city and, on the other hand, provides rapid communication with the centre, the suburbs and one of the best parts of the countryside.
- 4th - Facilitates the provisioning of the city with the products of small-scale farming and, at the same time, enables the construction of workers' villas and residential buildings in better conditions of economy, hygiene and comfort (Annals of the Municipal Council, 2 December 1929, p. 1396).

BEYOND RURAL: MOVING PAST AGRICULTURAL DOMINANCE

Rural zones were not conceptualized solely as hubs for agricultural promotion. Rather, they were also envisioned as strategic targets for non-agricultural investments and as spaces conducive to the expansion of urban activities and dynamics.

Figure 4

Newspaper Report on the Fazenda Modelo in the 1940s.



Source: O Campo, July 1943, p. 17

In October 1921, a proposed project at the Municipal Council sought to incentivize the construction of "houses for private habitation in suburban and rural zones" through special concessions. Though never approved, the proposal serves as a telling indication that, much like the suburbs, the countryside had long been perceived as a viable space for residential expansion.

This does not imply, however, that rural and urban functions were viewed as mutually exclusive. Rather, the initiative reflects an underlying intent to shape the region into a hybrid territory where urban and rural land uses could coexist. Various projects to improve the countryside, advanced by both public authorities and private actors, reinforced this connection, further blurring the boundaries between urban and rural development.

The bridge to be built in 1927, linking the coast to Barra de Guaratiba, highlighted—in addition to its benefits for small-scale farming in the locality—that "due to the special conditions in which the sandbank is located, it can also, as long as there are easy communications via the bridge, be used for the installation of industrial establishments, whose location is not convenient in the populated centers of the city." The project also underscored another aspect that would later be heavily exploited by the real estate market from the late 1940s onward—the construction of summer homes:

The site is one of the most desirable for recreational or leisure retreats, particularly during the calm season, and its development—resulting from the proposed connecting route—will contribute to a broader and more valuable utilization of the Guaratiba and Campo Grande zones, owing to a foreseeable ripple effect (Annals of the Municipal Council, October 3, 1927, p. 49).

Years later, in August 1935, deputy Romero Zander submitted a request to establish bus routes connecting Campo Grande to Rio da Prata. He justified the creation of this urban public service as follows:

A prosperous and densely populated locality, this rich area with exceedingly fertile lands stands as one of the Federal District's leading zones for citrus cultivation, horticulture, and extensive papaya plantations. Served only by a branch line of the Campo Grande Streetcar Company, it bears noting that residents effectively lack proper transportation due to the company's complete breakdown into insecurity, unreliability, and discomfort. The administration's good faith in supporting the enterprise with reasonable subsidies proved utterly futile (Annals of the Municipal Council, August 26, 1935, p. 448).

A few construction projects had the clear interest of favoring small-scale farming. One example is Ernani Cardoso's project for official recognition of the Bocca do Matto and Fazenda roads:

Estrada da Fazenda is one of the oldest roads in the rural zone, it penetrates the heart of one of the most fertile regions and is connected to numerous paths that run through the entire mountainous region. Bocca do Matto road crosses the entire region of the same name. It is an area inhabited entirely by farmers, who struggle with the bad roads (Annals of the Municipal Council, September 17, 1935, p. 238).

Nevertheless, as the years progressed, one could observe the emergence of projects emphasizing the non-agricultural character of rural zone enterprises. In July 1927, for instance, Paulo da Cunha e Silva and José Joaquim Galvão petitioned the Municipal Council for authorization to operate a 'motor tramway service' for passenger and cargo transportation, to be established 'between Madureira, the parish of Irajá, and Guaratiba'. As "an extension of the concession," the petitioners of said enterprise were granted:

"The right to use and enjoy a tract measuring 5 kilometers in frontage by 1 kilometer in depth for a period of fifty years, for a Bathing Villa (Villa Balnearia) they obligated themselves to construct within three years from the concession date—via Barra de Guaratiba or at the site called Pontual—whichever location offered better adaptation and provisioning conditions according to studies and plans to be presented to the City Hall [...]" (Annals of the Municipal Council, July 22, 1927, pp. 579-580).

Further on, the specified constructions are detailed in a way that underscores the urban character of this enterprise:

- A proper bathing establishment containing Suites for couples and single guests, a hotel, music hall, library, barbershop, cigar store, café and bar, stationery shop, telegraph and post office compartment, medical office, pharmacy, infirmary, hydrotherapeutic and thermal treatment room, swimming pool, and all amenities inherent to an establishment of this nature, as per the corresponding blueprint.
- Rustic and country-style houses lining avenues, built within the grounds of the Villa Balnearia, intended for rent; with one public school (under the City Hall's jurisdiction), a police station and a building for the post office, telegraph and public health services—all exempt from rent or taxes, as shown in the respective plans.
- Modern and fully secure equipment for open-sea bathing, to be installed by the concessionaires within a designated zone, following approved designs.
- Roadways, amusement parks, and landscaped gardens (Ibid.).

On August 20, 1935, Project No. 118 was introduced, aiming to legalize "owner-occupied residences built in suburban and rural zones," provided that the owner applied "within 90 days, submitting sketches of the building and land, along with receipts for territorial or property taxes, upon payment of a 30,000-réis permit fee" (Annals of the Municipal Council, August 20, 1935, pp. 349-350).

During this period - the 1920s and 1930s - the rural zone remained a kind of agricultural frontier. But not exclusively so. Even then, the region was already being conceived as capable of accommodating other types of developments.

FINAL CONSIDERATIONS

The formulation of rural sanitation policies emerges on the horizon as a proposed solution to the prevailing unsanitary conditions in the region. At this point, sanitation and the creation of a "green belt" began to be strategically linked, as one component reinforced the other. Then the Green Belt - seen almost as a synonym for the Rural Zone - became the target of another objective: meeting the food demand, particularly for vegetables, of the urban population of the then Federal District.

That demand provided another reason to convince the public authorities of the need to preserve the countryside. Initiatives that had been underway since the 1920s seemed to attest to the fact that this notion was well-established: the federal and municipal governments were carrying out major improvements in the region, which pointed to a policy aimed at fostering the city's green belt. We can highlight the creation of rural schools, the inauguration of the Guaratiba Model Farm and tax exemptions for small farmers. The very purpose of the work to clean up the Sepetiba and Jacarepaguá lowlands in the 1930s was to gain unhealthy land for farming.

However, the Rural district was also thought for non-agricultural purposes. In the case of Rio de Janeiro, plans for the agricultural use of the region have always gone hand in hand with plans that reserved the expansion of urban activities for the same region. Once more, the federal government's sanitation works were an emblematic example: the land gained for agriculture was also excellent for urban subdivisions.

Such urban expansion would jeopardize the very existence of the city's countryside. This expansion could be supported by land grabbing, contributing to the expulsion of small farming families from their land, among other things. This process showed that, while it was necessary to promote

agriculture to supply the Federal District, it was also necessary to establish a policy that would ensure land ownership for its small sharecroppers.

The 1940s and 1950s showed that agricultural policies were not enough. In order to guarantee the preservation of Rio's green belt (then already called Sertão Carioca), it was necessary to stop land grabbing and land theft. A "land policy" was needed to ensure an agricultural policy. That, however, is a story to be told at another time.

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COMPARATIVE ANALYSIS OF EXPANSIVE SOIL STABILIZATION: NATURAL VS. INDUSTRIALIZED MATERIALS AND RECYCLED WASTE IN THE MCT METHOD

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Abstract

Expansive soils pose geotechnical challenges due to volumetric changes in the presence of water, being common in the region of Pelotas/RS. This study evaluates the efficiency of different stabilizing agents — lime, Construction and Demolition Waste (CDW), and natural Butia fibers — in mitigating the expansiveness of a clayey soil. The methodology is based on the MCT (Miniature Compacted Tropical) method, analyzing water penetration and diametrical shrinkage of specimens molded with different additive contents. Previous results indicate that lime shows superior performance in delaying the wet front, while CDW acts as a filler material with limitations as a primary stabilizer. The inclusion of Butia fibers (BF) proposes a sustainable mechanical reinforcement mechanism, aiming to reduce cracking and improve dimensional stability. This work contributes to the development of low-environmental impact solutions by comparing traditional methods and innovations based on regional biodiversity.

Keywords: Butia fiber, Construction waste, Expansive soils, Lime, Soil stabilization.

INTRODUCTION

Expansive soils represent one of the greatest challenges for global geotechnical engineering, being characterized by high volumetric instability in response to variations in moisture content. According to Calegari et al. (2024), this expansive behavior stems from the mineralogical constitution of the soil, wherein the presence of clay minerals from the smectite group — which possess a 2:1 crystalline structure — allows the intercalation of water molecules between their layers, leading to pronounced swelling and shrinkage processes during wetting and drying cycles. In the region of Pelotas/RS, the occurrence of these soils is significant, demanding stabilization methods that ensure the structural integrity of pavements and foundations.

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Historically, chemical stabilization using lime has been the predominant technical solution, particularly in tropical and subtropical soils. According to Nogami and Villibor (2024), the application of lime promotes immediate microstructural modifications, such as flocculation and cation exchange, followed by long-term pozzolanic reactions that increase cohesion and reduce the plasticity of the soil-additive system. However, although the effectiveness of lime in controlling expansive soils is widely documented in the literature (Al-Rawas et al., 2023), the environmental impact associated with its industrial production and the growing demand for circular economy practices have driven the investigation of alternative materials.

In this context, the utilization of Construction and Demolition Waste (CDW) emerges as an alternative for managing urban environmental liabilities, with studies indicating its viability in geotechnical applications (Farias et al., 2023). Nevertheless, its effectiveness as a primary stabilizing agent in fine-grained soils still presents limitations due to its predominantly inert nature and strong grain-size dependency (Kianimehr et al., 2019).

Concurrently, soil reinforcement using natural fibers presents an innovative and sustainable frontier. Studies such as those by Hejazi et al. (2012) and Gowthaman et al. (2018) suggest that the inclusion of fibers significantly improves shear strength and controls desiccation cracking propagation, acting as a mechanical anchoring network that restricts the movement of clay particles. Within the local scenario, the use of *Butia* fiber arises as a proposal to enhance regional biodiversity, seeking to align technical performance with the availability of natural biopolymers, as preliminarily explored by Tins et al. (2025).

This chapter proposes a novel comparative analysis, utilizing the MCT (Miniature Compacted Tropical) method to evaluate the efficiency of three distinct approaches: the established industrial method (lime), the reuse of CDW, and the application of natural biopolymers (*Butia* fiber). The objective is to

quantify water penetration and diametrical shrinkage parameters, discussing the potential for replacing or complementing conventional materials with low-environmental-impact alternatives.

LITERATURE REVIEW

NATURE AND BEHAVIOR OF EXPANSIVE SOILS

The problematic nature of expansive soils is intrinsically linked to their mineralogical composition, specifically the presence of clay minerals from the smectite group. These minerals are characterized by a 2:1 crystalline structure, composed of two silica tetrahedral sheets sandwiching an aluminum octahedral sheet. According to Grim (1968) and Mitchell & Soga (2005), this configuration results in weak interlaminar bonds held by Van der Waals forces and a deficient charge balance. This allows water molecules to easily enter the interlayer spaces, causing significant volumetric expansion (swelling).

Geotechnically, this behavior translates into high susceptibility to volume change in response to fluctuations in moisture content. When saturated, these soils exhibit a drastic reduction in shear strength and a significant increase in erosivity (Das, 2014). Conversely, the desiccation process leads to severe material shrinkage, resulting in macro-cracks that propagate structural failures and compromise the stability of civil works, such as shallow foundations and pavements (Al-Rawas & Goosen, 2006).

In the region of Pelotas/RS, particularly in areas such as the Quartier neighborhood, these soils are classified as solodic and present a predominantly non-lateritic clayey texture. The analysis of these materials via the MCT method and specimen testing confirms a highly expansive behavior, making stabilization a mandatory step to enable their engineering application. According to Calegaro et al. (2024), the use of reinforcement agents alongside chemical or physical stabilizers has been explored in the region as a viable solution to mitigate structural damage caused by these local geological formations.

CHEMICAL (LIME) AND PHYSICAL (CDW) STABILIZATION

The utilization of additives for expansive soil improvement primarily aims to alter the clay mineral's affinity for water or modify the porous matrix structure to enhance its mechanical strength.

Stabilization through chemical methods is historically well-established, with lime being recognized as one of the most effective chemical agents for smectite-rich soils. As detailed by Sherwood (1993), the process occurs in two consecutive stages: initially, rapid cation exchange and flocculation reduce the thickness of the diffuse double layer, immediately decreasing soil plasticity and improving workability. Subsequently, long-term pozzolanic reactions take place, where the high pH induces the dissolution of amorphous silica and alumina from the soil, which react with free calcium to form hydrated calcium silicates and aluminates (C-S-H and C-A-H). These cementitious compounds bind the clay particles together, ensuring long-term dimensional stability (Nogami & Villibor, 2024).

Unlike lime, Construction and Demolition Waste (CDW) acts predominantly through physical mechanisms of grain-size stabilization. When incorporated into the soil, CDW functions as a rigid granular skeleton that aids in void filling and proportionally reduces the active (expansive) fine content within the total mixture (Arulrajah et al., 2014). However, its isolated technical effectiveness is highly dependent on the particle size distribution and mineralogical composition of the waste, presenting severe limitations as a primary stabilizer when unaccompanied by complementary chemical reactions or a compaction effort that effectively seals preferential water percolation paths (Mohammadinia et al., 2016). The comparative analysis of these methods allows an understanding of the balance between the superior technical performance of lime and the ecological potential of CDW within a circular economy framework.

MECHANICAL REINFORCEMENT WITH NATURAL FIBERS

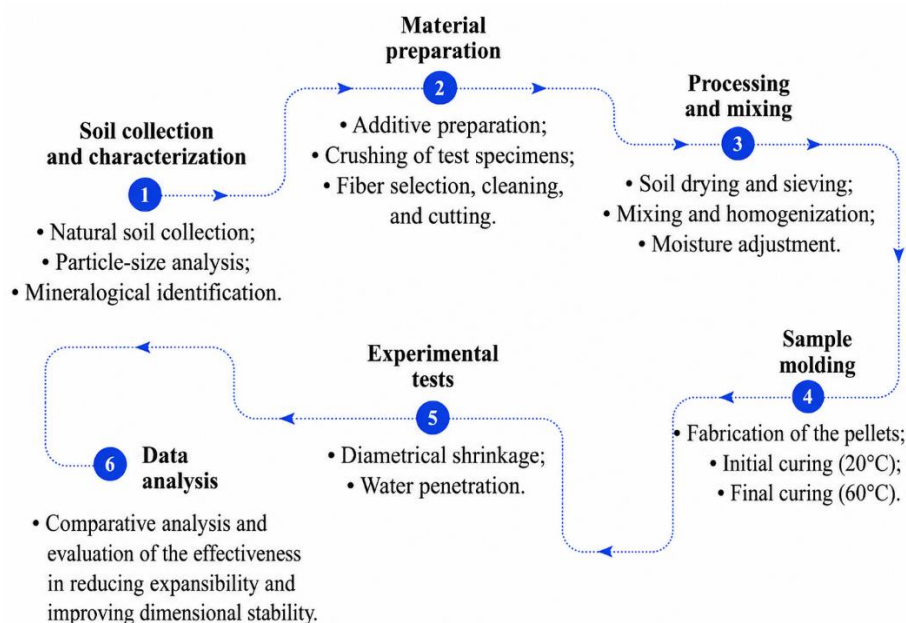
The inclusion of natural fibers in expansive soils introduces an essentially physical-mechanical stabilization mechanism, frequently described in the literature as a tension-transfer bridge (Tang et al., 2007). When randomly distributed throughout the soil mass, the fibers act as three-dimensional reinforcement elements that intercept failure planes and volumetric expansion fronts. The efficiency of this system relies heavily on the quality of the soil-fiber interface, where surface friction, filament roughness, and mechanical adhesion between components govern the transfer of stresses from the clay matrix to the reinforcement element (Gowthaman et al., 2018).

Consequently, when the soil initiates the swelling process due to water absorption, the fibers are subjected to tensile stress, generating a local confining pressure that restricts the movement of smectite particles and reduces the overall magnitude of expansion. Complementarily, during moisture loss, these fibers act as clamps or bridges that stitch together the edges of forming micro-cracks. This mechanism prevents tensile stresses generated by desiccation from evolving into macroscopic fissures, thereby preserving the continuity and structural integrity of the soil mass. As highlighted by Hejazi et al. (2012), the primary advantage of this method lies in the fibers' capacity to convert the brittle and unstable behavior of clayey soil into a markedly ductile behavior, considerably increasing shear strength and dimensional stability without relying exclusively on chemical reactions.

METHODOLOGY

Figure 1

Experimental methodology flowchart



Source: Author (2026)

The experimental design of this study was structured to allow a direct comparison between different stabilization methods, based on the MCT method for the evaluation of tropical and subtropical soils. The research followed a logical sequence that included everything from the granulometric and mineralogical characterization of the natural soil to the performance testing of the mixtures with industrial, recycled, and natural additives, as previously presented in Figure 1.

MATERIALS AND CHARACTERIZATION

The soil used was collected in the Quartier neighborhood, in Pelotas/RS, and was identified as a solodic soil with a clayey texture and highly expansive behavior due to the presence of smectites. To modify its geotechnical behavior, three agents with distinct natures were selected:

- a) Hydrated Lime: Representing the consolidated industrial method, applied at 3% and 6% contents.
- b) Construction and Demolition Waste (CDW): Material originating from concrete and mortar crushing, also tested at 3% and 6% proportions.
- c) Butia Fibers (BF): Representing the natural and sustainable alternative. The fibers, passing through the 1.19 mm sieve, were processed and incorporated into the soil matrix at contents of 1.0%, 2.5%, and 5.0% relative to the dry soil mass.

For mixtures containing fibers, the experimental schedule provided for curing periods of 7 and 28 days, allowing for the observation of the influence of time on the interaction between the natural filaments and the clayey matrix, especially regarding dimensional stability and resistance to water penetration.

EXPERIMENTAL PROCEDURE AND SAMPLE PREPARATION

The experimental rigor followed a chronological sequence divided into six fundamental stages, based on adaptations of the MCT (Miniature Compacted Tropical) method for expedited tests on pellets. Initially, the natural soil was collected from the surface layer (0.00 to 0.50 m) in the Quartier neighborhood, in Pelotas/RS. The soil was subjected to initial geotechnical characterization, including grain-size analysis by sedimentation and sieving (according to current technical standards) and qualitative mineralogical identification, confirming the predominance of active smectite clay minerals.

In the material preparation phase, residual laboratory specimens (concrete and mortar) were crushed in a jaw crusher and quartered to obtain Construction and Demolition Waste (CDW) in fine fractions. In parallel, Butia fibers (BF) were washed in distilled water to remove superficial organic impurities, air-dried, and cut uniformly with the aid of blades, being subsequently selected by passing entirely through a 1.19mm sieve (No. 16 mesh).

Subsequent processing consisted of pre-drying the natural soil in a thermostatically controlled oven at 60°C until constant mass, followed by crushing and complete sieving through the No. 200 (0.075mm) mesh. Subsequently, the additives were weighed and manually dosed in relation to the dry mass of the soil, homogenizing the mixtures dry. The adjustment of the optimum moisture content was performed gradually with distilled water until the matrix reached a standardized plastic consistency, the homogeneity of which was controlled via an adapted penetration test, using the free fall of a standard 1mm needle under constant weight.

The molding of the samples was executed through static compaction of the wet mass inside rigid PVC rings with nominal dimensions of 21mm in diameter and 5mm in thickness, ensuring the repeatability of the dry apparent specific mass of the specimens. The structured curing process occurred on two fronts: all samples were subjected to an initial curing in a wet chamber for 24 hours at a controlled temperature of 20°C ($\pm 2^\circ\text{C}$), followed by induced desiccation in an oven at 60°C for a period of 4 hours to promote initial water stabilization. For the series additivated with Butia fibers, the curing periods in a protected environment were extended to 7 and 28 days before the terminal desiccation process, allowing for the temporal monitoring of the adhesion at the soil-fiber interface.

The definitive experimental tests evaluated two macroscopic degradation parameters: diametrical shrinkage and resistance to water penetration. Diametrical shrinkage was quantified immediately after leaving the oven, using a manual mechanical caliper (0.05mm precision) adjusted to perform readings on three orthogonal axes previously marked on the pellets, obtaining the arithmetic mean of the deformations. Finally, the water penetration test consisted of partially immersing the dry pellets in cuvettes filled with distilled water. The resistance to penetration and the evolution of the material's softening were quantified using a manual penetrometer equipped with a dial gauge. The equipment was positioned perpendicularly on the upper surface of each pellet, applying the stroke of the standard needle to record the penetration depth (in millimeters) at strict time intervals of 5, 15, and 30 minutes, followed

by control readings at 2 and 24 hours. The collected data were tabulated for the consolidation of a comparative statistical analysis focused on the efficiency of each stabilizing agent.

DISCUSSION AND RESULTS

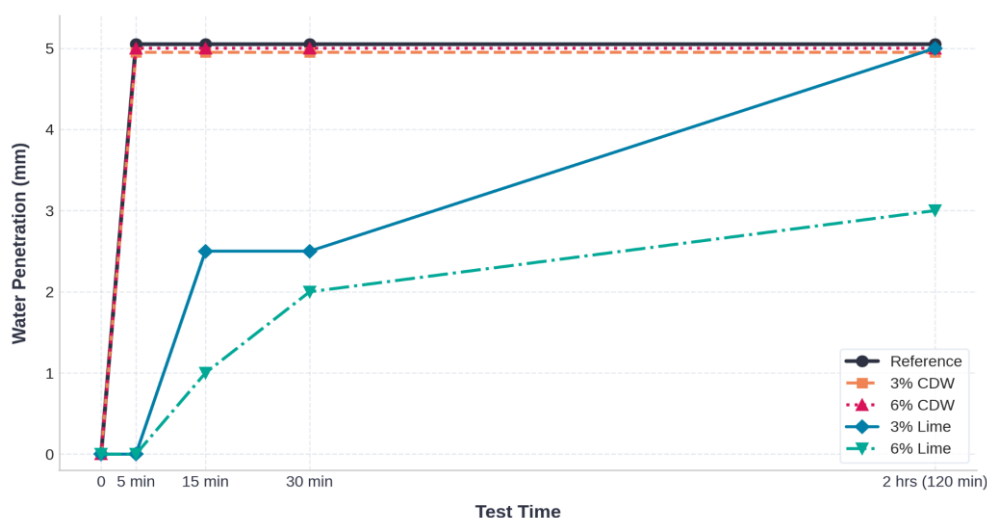
EFFICIENCY IN WATER PENETRATION RESISTANCE

Water penetration analysis allows for the evaluation of the stabilizing agents' capacity to modify the soil pore network and reduce its affinity for water, a critical factor in controlling expansiveness. The obtained results reveal significant contrasts among the chemical, physical, and mechanical approaches.

Regarding conventional and recycling methods, the specimens treated with Construction and Demolition Waste (CDW) showed a low capacity to delay the advancement of the wetting front, reaching the maximum penetration of 5mm within the first 5 minutes of the test. This behavior highlights that CDW, in its inert form, did not promote effective pore sealing. Conversely, as observed in Figure 2, the consolidated efficiency of lime is evident in delaying full saturation up to the 2 hours interval, especially at the 6% content, where softening and penetration depth progressed gradually due to pozzolanic reactions and structural modification of the clay matrix.

Figure 2

Water penetration as a function of time for reference soil, lime, and CDW.

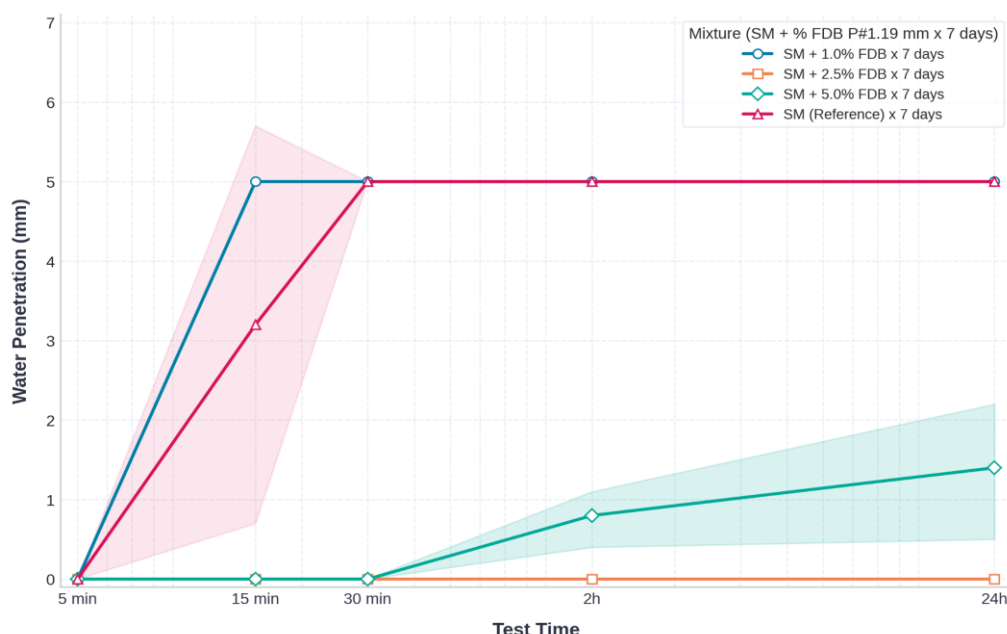


Source: Author (2026)

The introduction of Butia fibers (BF) showed results that vary substantially according to the content and curing time, as shown in Figure 3. At 7 days of curing, the mixtures with 1.0% and 2.5% BF showed rapid saturation, reaching 5 mm between 15 and 30 minutes, a performance similar to the reference soil. However, the 5.0% BF content at 7 days already demonstrated a notable improvement, keeping penetration below 2 mm even after 24 hours of immersion.

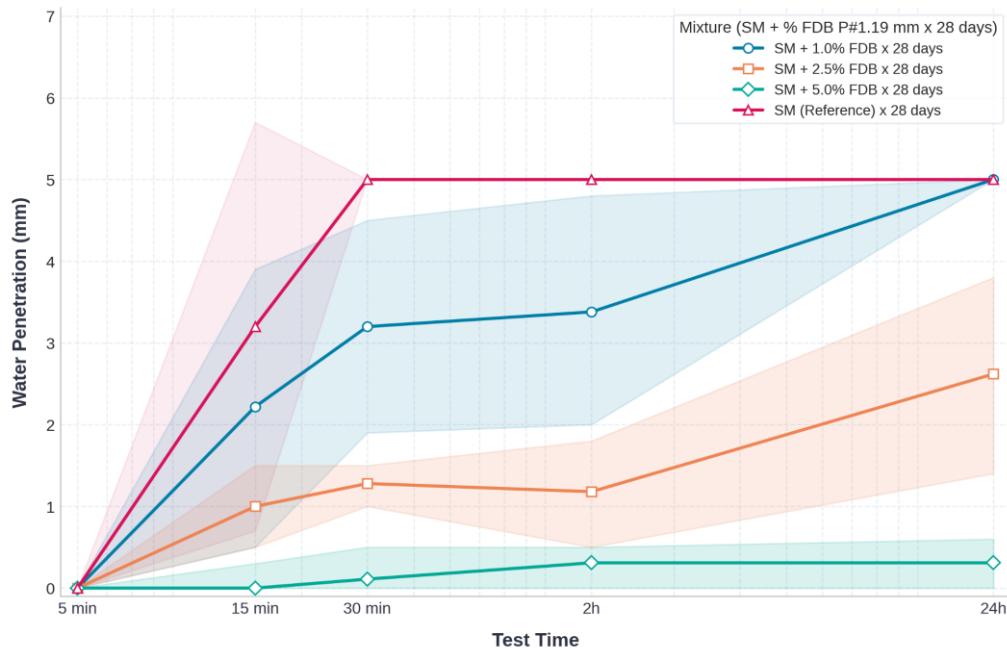
Figure 3

Water penetration as a function of time for soil + BF (7 days)



Source: Author (2026)

The most significant development occurred at 28 days of curing. At this stage, it was observed that the 5.0% BF network practically prevented severe water infiltration, maintaining penetration close to zero throughout the entire test (Figure 4).

Figure 4*Water penetration as a function of time for soil + BF (28 days)*

Source: Author (2026)

Even the lower contents (1.0% and 2.5%) showed better retardation than that observed at 7 days, suggesting that the interaction time between the fibers and the soil matrix favors the system's stability. This indicates that the stress transfer bridge mechanism of the fibers not only provides mechanical reinforcement but also assists in maintaining the integrity of the specimens, hindering preferential water flow paths.

DIMENSIONAL STABILITY AND DIAMETRICAL SHRINKAGE

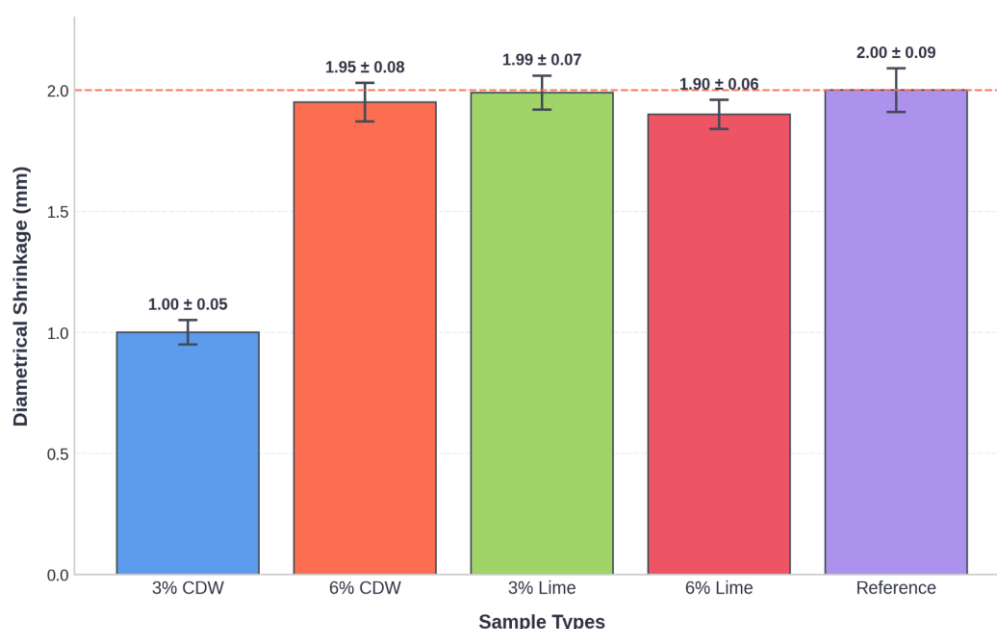
Diametrical shrinkage is a direct indicator of soil sensitivity to desiccation. While water penetration measures resistance to water entry, shrinkage assesses structural integrity when the soil loses moisture, allowing for the expeditious differentiation of the effectiveness of each stabilizing agent.

When analyzing conventional and recycled methods, it is observed that the reference soil presents an average shrinkage of 2.00 mm. The addition of 6% lime resulted in a discrete reduction to 1.90 mm, a value which, although indicating an improvement, demonstrates that chemical stabilization alone still

allows for significant volumetric movement under severe drying conditions. Interestingly, the use of 3% CDW presented the lowest shrinkage value among the mineral methods (Figure 5), which suggests that the presence of recycled coarse aggregates can act as a physical skeleton that restricts the shrinkage of the clay mass, although, as seen previously, it does not prevent water infiltration.

Figure 5

Diametrical shrinkage graph for reference soil, lime, and CDW

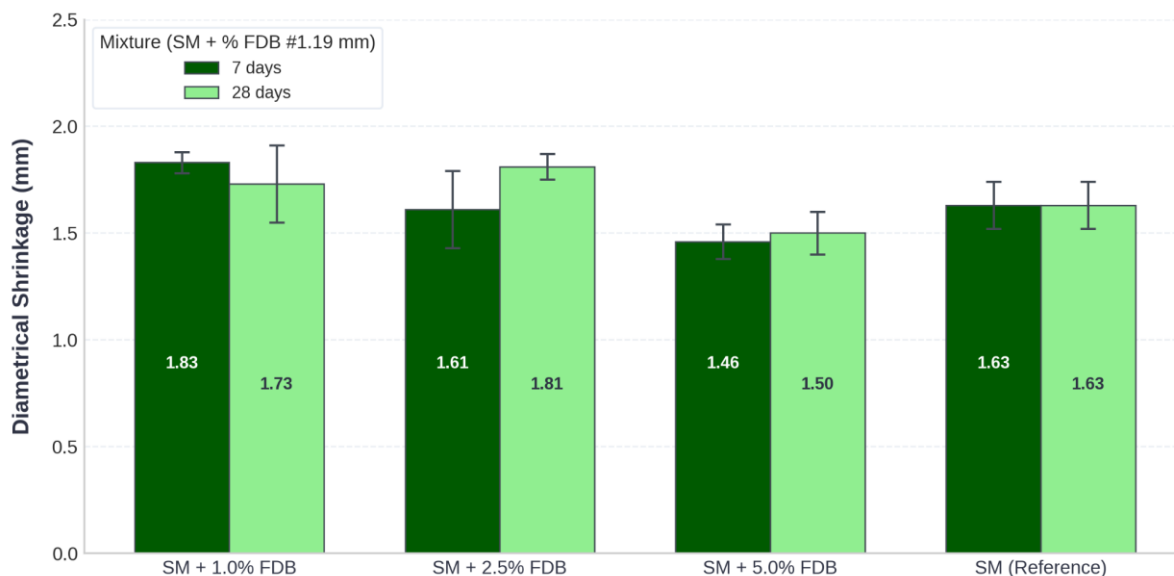


Source: Author (2026)

The introduction of Butia fiber brought a new dynamic to the dimensional stability of the system. Unlike lime, which acts on the mineral chemistry, the fibers act through mechanical anchoring. For the samples with BF, the shrinkage results ranged between 1.46 mm and 1.83 mm (Figure 6).

Figure 6

Diametrical shrinkage of mixtures with Butia fiber (7 and 28 days).



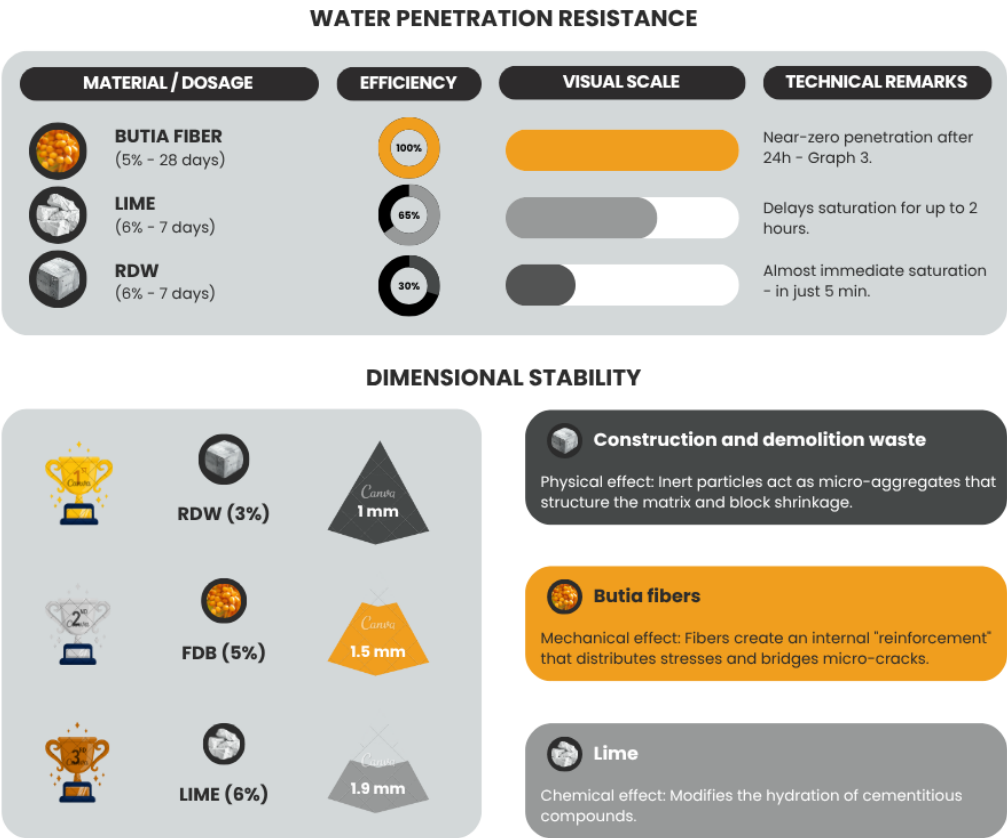
Source: Author (2026)

The best performance was observed at the 5.0% content at 7 days of curing (1.46 mm), indicating that a higher density of fibers in the matrix is capable of 'stitching' the soil more efficiently, reducing overall shrinkage compared to the natural soil.

A highlight is the maintenance of this stability at 28 days. Even with the expected natural variation in organic materials, the values remained consistent (around 1.50 mm for the 5.0% content), confirming that the Butia fiber network offers permanent physical restriction against tensile stresses generated by water loss. This capacity to keep the pellet intact, with less reduction in diameter, complements the excellent hydraulic performance observed previously, positioning the natural fiber as a multidimensional reinforcement agent.

To synthesize the findings of this study, Figure 7 presents a comparative analysis of the relative efficiency of each additive.

Figure 7
Relative Performance Infographic



Source: Author (2026)

It is evident that while lime and Butia fibers dominate in protecting against the advancement of the wetting front, CDW and fibers share the leading role in the physical restriction of diametrical shrinkage. This integrated view reinforces that Butia fiber acts as a hybrid agent, offering benefits that combine the best of chemical and physical stabilization.

DISCUSSION AND RESULTS

The comparative investigation between different stabilizing agents allowed for a clear overview of the technical efficiency and sustainable potential of each approach in mitigating the soil expansiveness in the region of Pelotas/RS. The results obtained consolidate the understanding that the choice of stabilizing

material must balance mechanical performance, water resistance, and the environmental impact of the project.

Chemical stabilization with lime confirmed its historical efficacy, presenting a significant retardation of the wetting front and an improvement in dimensional stability, resulting from profound microstructural modifications. In contrast, the isolated use of CDW demonstrated severe limitations as a primary stabilizer, especially in controlling water infiltration, although it showed interesting behavior in restricting physical contraction due to its granular filling effect.

The major innovation of this study, the use of Butia fiber, positioned natural materials as a high-performance and low-impact alternative. Experimental data revealed that, with a content of 5.0% and a 28-day curing period, the natural fiber network was able to surpass the performance of lime regarding the blocking of water penetration, maintaining the integrity of the specimens for periods exceeding 24 hours. This behavior demonstrates that the stress transfer bridge, a mechanical effect of the fibers, not only reinforces the soil matrix against shrinkage cracks but also creates an efficient physical barrier against the advancement of the wetting front.

In summary, this chapter highlights that the transition from industrialized methods to solutions based on regional biodiversity, such as Butia fibers, is technically feasible and promising. For future large-scale applications, it is recommended to study the long-term biological durability of these fibers in the soil, consolidating the use of sustainable materials as a strategic pillar for contemporary geotechnical infrastructure.

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PRODUCTIVE, SANITARY, AND WELFARE INDICATORS IN NON-CONVENTIONAL LAYING HEN SYSTEMS

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Abstract

The laying poultry sector has undergone a significant transition from conventional systems to non-conventional production models, driven by demands related to animal welfare, sustainability, and product quality. This study aimed to critically analyze the scientific evidence regarding the effects of non-conventional laying hen rearing systems on productive, sanitary, and animal welfare indicators. This is an integrative literature review conducted in the PubMed database, covering studies published between 2015 and 2025. A total of 52 studies were selected after applying previously defined inclusion and exclusion criteria. Data were systematically extracted and analyzed through qualitative synthesis, addressing productive, sanitary, and welfare outcomes. The results indicated that non-conventional systems have variable effects on productivity, with performance being maintained in some cases, although with greater variability compared with conventional systems. Greater expression of natural behaviors and improvements in welfare indicators were also observed, although these were accompanied by sanitary challenges, such as increased exposure to environmental pathogens. It is concluded that non-conventional egg production systems involve a complex balance among productivity, health, and animal welfare, being strongly influenced by the management practices adopted. This study contributes by critically integrating these three axes, offering a comprehensive view of the available evidence and highlighting the need for more sustainable and integrated production strategies.

Keywords: Agricultural economics, Biosecurity, Laying hens, Production chain, Zootechnical management.

INTRODUCTION

Laying hen farming constitutes one of the main activities in animal production, playing a strategic role in supplying protein of high biological value to the world population and contributing significantly to food security and to the economy of the agricultural sector. The growth in demand for eggs has been accompanied by the search for production systems capable of reconciling zootechnical efficiency,

sustainability, and compliance with society's increasing demands regarding animal-rearing conditions. In this context, in addition to productivity, aspects related to product quality, flock health, and bird welfare have come to occupy a central position in scientific research and in the decisions of producers, consumers, and public policy makers (Yunes; Von Keyserlingk; Hötzel, 2017; Yang et al., 2024).

Historically, commercial egg production was consolidated in conventional cage-rearing systems, characterized by high environmental control, space optimization, and productive efficiency. However, in recent decades, concerns related to the behavioral limitations imposed by these systems have driven the adoption of alternative rearing models, especially in countries where consumers, retail chains, and regulatory bodies have begun to value attributes related to animal welfare. This transition has favored the expansion of systems such as free-range, cage-free, aviaries, organic systems, barn systems, systems with access to the outdoor environment, and other non-conventional production modalities, each presenting specific characteristics of management, infrastructure, and interaction between the birds and the environment (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022; Yang et al., 2025).

Non-conventional systems are distinguished mainly by providing greater freedom of movement, the possibility of expressing natural behaviors, and environmental enrichment, factors recognized as important components of animal welfare. Resources such as perches, nests, substrates for dust bathing, outdoor areas, and environmental enrichments stimulate behaviors inherent to the species, potentially reducing stress indicators and favoring better physical and behavioral conditions for laying hens. Recent reviews demonstrate that enrichment of the rearing environment has a positive influence on several welfare indicators from the early stages of bird development, while systems with access to the outdoor environment expand opportunities for environmental exploration and behavioral expression (Xu et al., 2022; Yan et al., 2022).

Although these systems have the potential to improve birds' living conditions, their adoption also introduces new challenges related to management, biosecurity, and productive performance. Greater exposure to the outdoor environment may increase contact with infectious agents, parasites, and wild

fauna, raising the risk of occurrence and dissemination of pathogens such as *Salmonella spp.*, *Campylobacter spp.*, and avian influenza virus. Studies conducted in different countries have reported the prevalence of these microorganisms in alternative systems, demonstrating the need for effective sanitary monitoring and biosecurity strategies to minimize risks to animal health and public health (Zhao et al., 2016; Xu et al., 2021; Worku et al., 2025; Zhu et al., 2018).

In addition to sanitary aspects, the literature shows that the effects of different rearing systems on productive indicators remain controversial. While some studies describe improvements in egg quality, greater expression of natural behaviors, and better welfare conditions in alternative systems, others report increased mortality, higher incidence of keel bone lesions, feather pecking, productive losses, and greater variability in zootechnical performance. Likewise, factors such as genetic line, nutritional management, quality of facilities, use of the outdoor environment, and environmental enrichment can significantly modify the results obtained, making direct comparison between studies difficult (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022; Winter; Toscano; Stratmann, 2022; Wolc et al., 2021).

In recent years, technological advances have also expanded the possibilities for monitoring non-conventional systems through the use of sensors, computer vision, and artificial intelligence techniques capable of tracking bird behavior, detecting locomotor alterations, monitoring space use, and identifying early changes related to welfare and productive performance. In parallel, studies involving environmental quality, intestinal microbiota, egg quality, and physiological responses have contributed to a broader understanding of the interaction among rearing environment, health, and productivity in laying hens (Zaninelli et al., 2016; Zaninelli et al., 2017; Yang et al., 2024; Yang et al., 2025).

Despite the substantial growth in scientific production on alternative rearing systems, studies often address productive, sanitary, or welfare indicators in isolation, and there is a scarcity of syntheses that integrate these three axes critically and comprehensively. In addition, methodological differences among experimental designs, the indicators used, environmental conditions, and the systems evaluated themselves hinder the consolidation of consistent evidence regarding the advantages, limitations, and

challenges associated with non-conventional laying hen systems. Thus, an integrative review is necessary to gather and critically analyze the knowledge produced, identifying convergences, divergences, and remaining gaps in the scientific literature.

Considering this context, the present integrative review is innovative in synthesizing, within a single analysis, evidence simultaneously related to productive, sanitary, and welfare indicators in non-conventional laying hen rearing systems. Thus, the study aims to critically analyze the available scientific evidence on these indicators, identifying the main factors associated with productive performance, sanitary conditions, and animal welfare, as well as characterizing different alternative rearing systems, comparing their effects on production and bird health, identifying management and infrastructure factors related to observed outcomes, synthesizing the advantages and limitations described in the literature, and indicating gaps that may support future research aimed at improving alternative egg production systems.

THEORETICAL FRAMEWORK

NON-CONVENTIONAL LAYING HEN SYSTEMS

Non-conventional laying hen systems comprise different rearing models developed with the purpose of providing better conditions for the expression of natural behaviors in laying hens, in contrast to conventional cage systems. Among the main models described in the literature are cage-free, free-range, aviary systems, barn systems, organic production systems, pasture-raised systems, and other systems with access to the outdoor environment. Although they differ in degree of freedom, facilities, and management practices, these models share the objective of expanding the space available to birds, favoring their movement, and enabling behaviors such as perching, scratching, dust bathing, using nests, and exploring the environment, aspects considered fundamental for promoting animal welfare (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022; Yan et al., 2022).

The main differences among these systems are related to infrastructure, access to the outdoor environment, and the level of management intervention. In cage-free systems, birds remain loose inside

poultry houses, with access to perches, nests, and litter areas, but without mandatory outdoor access. In free-range systems, in addition to these internal structures, hens have periodic access to outdoor areas intended for grazing and environmental exploration. Organic systems, in turn, incorporate additional requirements related to feeding, sanitary management, stocking density, and the use of inputs permitted by specific certifications. Aviary systems are characterized by the use of multi-tier vertical structures, expanding the usable area available and allowing greater three-dimensional exploration of the environment by the birds. These structural differences directly influence behavior, productivity, health, and welfare indicators, making individualized assessment of each system necessary (Zhao et al., 2015; Wurtz et al., 2022; Yang et al., 2025).

The expansion of alternative rearing systems is associated with changes in society's expectations regarding animal production, the strengthening of welfare policies, and the growing consumer demand for foods produced under standards considered more ethical and sustainable. Studies involving the perceptions of producers and consumers demonstrate that animal welfare has become an important decision-making factor both in the adoption of new production technologies and in egg purchasing preferences. However, implementation of these systems still faces challenges related to the cost of adapting facilities, management requirements, workforce training, and the need to reconcile productive performance, economic viability, and compliance with current certification and regulatory standards. These difficulties partly explain the differences observed among countries and regions in the speed of adoption of non-conventional systems (Yunes; Von Keyserlingk; Hötzel, 2017; Yang et al., 2024; Yang et al., 2025).

Although non-conventional systems are often associated with improved welfare of laying hens, the literature shows that their effects depend on several factors, including genetics, management, environmental enrichment, facility quality, climatic conditions, and effective use of outdoor areas. Studies demonstrate that birds kept in organic and free-range systems tend to show a higher frequency of natural behaviors and greater use of available resources, but may also be more exposed to environmental and

sanitary factors that influence productive performance and flock health. Thus, the mere adoption of an alternative system does not guarantee better outcomes; appropriate planning of facilities, biosecurity, nutritional management, and monitoring practices is indispensable so that the expected benefits are effectively achieved (Wurtz et al., 2022; Yan et al., 2022; Xu et al., 2022).

PRODUCTIVE INDICATORS IN LAYING HENS

Productive indicators constitute one of the main parameters used to evaluate the performance of laying hens in different rearing systems, allowing measurement of both productive efficiency and the possible impacts of management conditions on egg production. Among the indicators most frequently used are laying rate, cumulative egg production, egg mass, egg weight, shell quality and internal component quality, as well as productive viability of the flock. In non-conventional systems, these parameters assume even greater importance, as they make it possible to compare the performance of birds kept under different housing conditions and to identify possible relationships among productivity, rearing environment, and animal welfare. Comparative studies indicate that the effects of alternative systems on egg production are not uniform, being influenced by factors such as genetic line, bird age, management, nutrition, and environmental conditions (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022).

Egg quality represents another important productive indicator, since it directly influences the commercial value of the product and its acceptance by consumers. Evaluations usually include external characteristics, such as shell thickness, strength, and integrity, as well as internal attributes related to albumen and yolk quality and the nutritional composition of eggs. Several studies demonstrate that nutritional factors, especially supplementation with minerals and organic trace minerals, can significantly improve shell formation, increase its mechanical resistance, and favor oxidative stability in eggs. In addition, studies involving organic and free-range systems suggest that rearing conditions can modify the physicochemical and nutritional characteristics of eggs, although these effects depend on feeding,

management, and the interaction among environmental and genetic factors (Xiao et al., 2015; Zhang et al., 2021; Yang et al., 2024; Zita et al., 2022).

Feed efficiency is also an essential parameter in the evaluation of alternative production systems. Indicators such as feed intake, feed conversion, and nutrient utilization make it possible to estimate the birds' ability to transform ingested feed into egg production. However, in systems with access to the outdoor environment, the higher level of physical activity and the possibility of consuming forage, insects, and other natural resources may modify nutritional requirements and influence feed efficiency. Nutritional strategies involving probiotics, prebiotics, alternative protein sources, and mineral supplementation have been investigated with the aim of improving nutrient utilization, strengthening the intestinal microbiota, and maintaining high levels of productive performance even in more complex rearing systems (Yadav; Jha, 2019; Zhao et al., 2022; Zhou et al., 2025).

In addition to egg production and feed efficiency, indicators such as body weight, flock uniformity, survival, and productive viability are widely used to evaluate the overall performance of laying hens. These parameters reflect the interaction among genetics, nutrition, health, environment, and management, providing important information about the adaptation of birds to different rearing systems. In non-conventional systems, greater freedom of movement may contribute to better muscular and skeletal development, but may also increase energy expenditure and individual variability in performance. Thus, interpretation of productive indicators should simultaneously consider aspects related to the rearing environment, sanitary conditions, and animal welfare indicators, allowing a more comprehensive assessment of the efficiency and sustainability of different alternative egg production systems (Wurtz et al., 2022; Xiang et al., 2018; Yin et al., 2018).

SANITARY INDICATORS

Sanitary indicators represent a fundamental component in evaluating non-conventional laying hen systems, since they reflect the health conditions of birds and the effectiveness of the management and

biosecurity practices adopted on farms. Among the main parameters used are disease occurrence, mortality, morbidity, immune response, presence of infectious agents, and prevalence of parasites. Although alternative systems are recognized for favoring the expression of natural behaviors and promoting improvements in aspects related to animal welfare, the greater interaction of birds with the outdoor environment may also increase exposure to microorganisms, wild fauna, and environmental reservoirs of pathogenic agents. Thus, sanitary assessment of these systems requires an integrated approach, simultaneously considering environmental factors, management practices, stocking density, and disease prevention measures (Xu et al., 2020; Wurtz et al., 2022).

Among the main agents of sanitary importance in alternative systems are the genera *Salmonella* and *Campylobacter*, both widely recognized for their impact on animal health and public health. Studies conducted with hens raised in free-range systems have shown the occurrence of *Salmonella* in different producing regions, indicating that contact with the outdoor environment may favor the circulation of these microorganisms when adequate biosecurity measures are not implemented (Zhao et al., 2016). Similarly, recent studies have identified a high prevalence of *Campylobacter jejuni* and *Campylobacter coli* in birds raised in alternative systems, including the detection of antimicrobial-resistant strains, a factor that heightens concern regarding the dissemination of these pathogens throughout the production chain (Xu et al., 2021; Worku et al., 2025). In addition to bacterial infections, studies also report the occurrence of avian influenza virus in farm birds with outdoor access, as well as a higher frequency of gastrointestinal helminths, reinforcing the need for continuous epidemiological surveillance in these systems (Zhu et al., 2018; Zloch et al., 2021).

Given these challenges, biosecurity plays a strategic role in maintaining flock health and the sustainability of non-conventional egg production systems. Measures such as controlling the access of people and animals to facilities, sanitizing equipment, microbiological monitoring, appropriate litter management, water quality control, vaccination programs, and disinfection of facilities contribute to reducing the risk of introduction and dissemination of infectious agents. In addition, monitoring

environmental conditions and air quality, combined with the use of technologies for sanitary surveillance and early detection of changes in bird behavior, may assist in the rapid identification of health problems and the adoption of corrective measures. Thus, maintaining high sanitary standards depends on the integration of adequate infrastructure, efficient management, and consistent biosecurity programs, making it possible to reduce mortality, preserve productivity, and promote better welfare conditions for laying hens raised in alternative systems (Zhao et al., 2016; Zang et al., 2019; Yang et al., 2025; Yi et al., 2025).

ANIMAL WELFARE IN LAYING HENS

Animal welfare constitutes one of the main pillars for evaluating non-conventional laying hen rearing systems, representing a multidimensional concept that encompasses physical, physiological, behavioral, and sanitary aspects. In laying poultry, this concept is directly related to the birds' ability to maintain an adequate state of health, express natural behaviors, adapt to the environment, and respond to management challenges without significant impairment of their biological functions. The growing societal interest in more sustainable and ethically responsible production systems has driven research aimed at identifying indicators capable of objectively measuring bird welfare, supporting both the development of technologies and the formulation of standards and certifications for different rearing systems (Yunes; Von Keyserlingk; Hötzel, 2017; Yang et al., 2024).

Welfare assessment is based on the use of behavioral, physical, and physiological indicators, which make it possible to identify alterations in the birds' adaptation to the rearing environment. Among the behavioral indicators are the use of perches and nests, dust bathing, foraging, environmental exploration, locomotion, resting, and the occurrence of abnormal behaviors, such as feather pecking and cannibalism. Studies demonstrate that cage-free, free-range, and organic systems favor greater expression of these natural behaviors compared with conventional systems, although factors such as genetics, environmental enrichment, stocking density, and management may significantly influence the frequency of these activities. In addition, recent studies show that automated monitoring through sensors, computer

vision, and artificial intelligence has expanded the capacity to continuously track bird behavior, enabling early identification of changes related to welfare (Winter; Toscano; Stratmann, 2022; Xu et al., 2022; Yang et al., 2024; Yang et al., 2025).

Among the physical indicators of welfare, plumage integrity, occurrence of keel bone damage, footpad dermatitis, and body condition of the birds are among the parameters most frequently used in the scientific literature. Feather loss and excessive pecking may indicate problems related to the environment, management, or social interactions, while keel bone lesions are mainly associated with the use of perches, the structure of facilities, and bird movement in multi-tier systems. Likewise, the occurrence of footpad dermatitis may reflect inadequacies in litter quality, environmental humidity, and hygiene conditions within facilities. Although alternative systems provide greater freedom of movement and stimulate natural behaviors, they may also increase the risk of certain types of lesions if they are not adequately planned and managed (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022; Xu et al., 2022).

Physiological indicators complement welfare assessment by providing information on birds' organic responses to environmental and management challenges. Among these indicators are corticosterone concentration, parameters related to oxidative stress, immune response, and hormonal changes associated with reproductive performance. Situations of prolonged stress may compromise immunocompetence, reduce productivity, and negatively affect egg quality, whereas enriched environments and adequate management conditions tend to favor greater physiological stability. Studies involving transcriptomic and hormonal analyses also demonstrate that different rearing systems may modify gene expression related to metabolism, immune response, and mechanisms involved in birds' adaptation to the environment, showing that welfare results from the interaction among genetic, nutritional, and environmental factors (Xiang et al., 2018; Yin et al., 2018; Xu et al., 2020).

Thus, welfare assessment in non-conventional systems should be conducted in an integrated manner, simultaneously considering behavioral, physical, physiological, and productive indicators. The literature demonstrates that the mere adoption of alternative systems does not, by itself, guarantee better

welfare conditions, since outcomes depend on the quality of management, infrastructure, environmental enrichment, biosecurity, stocking density, and the genetic characteristics of the birds. Accordingly, the joint use of different indicators enables a more comprehensive assessment of rearing conditions, contributing to the development of production systems capable of reconciling productive efficiency, animal health, and the expression of natural behaviors in laying hens (Wurtz et al., 2022; Yan et al., 2022; Xu et al., 2022).

METHODOLOGY

The present study consisted of an integrative literature review of a descriptive, analytical, and interpretive nature, developed with the objective of gathering, evaluating, synthesizing, and critically analyzing the available scientific evidence regarding productive, sanitary, and welfare indicators in non-conventional laying hen systems. The choice of this method was justified by its ability to integrate results from different methodological designs, allowing a comprehensive understanding of the knowledge produced on the subject and the identification of convergences, divergences, and gaps in the scientific literature.

The review followed previously defined methodological stages, comprising formulation of the research question, definition of the search strategy, selection of databases, application of inclusion and exclusion criteria, identification and selection of eligible studies, extraction of relevant information, critical analysis of the evidence, and qualitative synthesis of the results. This methodological procedure enabled the systematic organization of the available information and favored an integrated analysis of the different indicators related to productive performance, sanitary conditions, and welfare of laying hens raised in alternative production systems.

The development of the guiding review question was based on the PIO strategy (Population, Interest, and Outcome), widely used to structure literature reviews in health and agricultural sciences research. The population (P) consisted of laying hens raised in egg production systems. The interest

component (I) comprised non-conventional laying hen systems, including free-range, cage-free, aviary systems, organic systems, pasture-raised, barn systems, systems with outdoor access, and other alternative rearing systems. The outcomes (O) covered the main productive, sanitary, and animal welfare indicators described in the scientific literature, including egg production and quality, feed conversion, feed intake, body weight, mortality, productive viability, disease occurrence, presence of pathogens, biosecurity, morbidity, behavior, stress, plumage integrity, feather pecking, bone quality, keel bone lesions, footpad dermatitis, comfort, and expression of natural behaviors. Based on this strategy, the following research question was formulated: **what scientific evidence is available on productive, sanitary, and welfare indicators in laying hens raised in non-conventional egg production systems, and which factors are associated with productive performance, sanitary conditions, and animal welfare in these systems?**

The bibliographic search was conducted in the PubMed database (National Library of Medicine), selected because of its broad coverage of scientific journals in the fields of Veterinary Medicine, Animal Production, Animal Science, Animal Health, and Biological Sciences. The search strategy was prepared in advance based on the research question structured according to the PIO strategy, using controlled descriptors from the Medical Subject Headings (MeSH) and free terms searched in title and abstract fields (Title/Abstract). The combination of these terms aimed to maximize search sensitivity, allowing retrieval of the largest possible number of potentially relevant studies on non-conventional laying hen systems and their productive, sanitary, and welfare indicators.

The search strategy was constructed using the Boolean operators “AND” and “OR,” grouping the terms into three major blocks corresponding to the components of the PIO strategy. The first block covered the population of interest, including descriptors and keywords related to laying hens, such as “Chickens”[Mesh], laying hens, layer hens, egg-laying hens, poultry, and chicken. The second block brought together the different non-conventional rearing systems, including terms such as free-range, cage-free, aviary, barn system, floor system, deep litter, outdoor systems, pasture-raised, organic production, alternative housing, alternative systems, alternative poultry production, non-conventional systems, and

backyard poultry. The third block comprised the outcomes of interest, including MeSH descriptors related to animal welfare, diseases, health status, and animal management, as well as terms referring to productive, sanitary, and welfare indicators, such as egg production and quality, feed conversion, feed intake, body weight, mortality, pathogenic agents, biosecurity, behavior, stress, plumage integrity, keel bone lesions, bone quality, footpad dermatitis, and corticosterone.

Execution of the search strategy resulted in the initial identification of 2,931 records in the PubMed database. After screening stages, reading titles and abstracts, evaluating eligibility, and applying previously established inclusion and exclusion criteria, studies directly aligned with the objective of the integrative review were selected. The search strategy was developed to ensure broad coverage, reproducibility, and methodological transparency, enabling identification of the main scientific evidence published on productive, sanitary, and welfare indicators in laying hens raised in non-conventional egg production systems.

The review included studies addressing laying hens raised in egg production systems, with a focus on non-conventional rearing systems such as free-range, cage-free, aviary systems, organic systems, pasture-raised, barn systems, systems with outdoor access, and other alternative systems. Studies that evaluated one or more outcomes of interest in the present review were also considered eligible, including productive indicators (egg production and quality, feed conversion, feed intake, body weight, mortality, and productive viability), sanitary indicators (sanitary status, disease occurrence, presence of pathogens, morbidity, mortality, and biosecurity measures), and animal welfare indicators (behavior, stress, plumage integrity, feather pecking, bone quality, keel bone lesions, footpad dermatitis, comfort, and expression of natural behaviors).

Regarding methodological design, experimental trials, cohort studies, case-control studies, cross-sectional studies, observational studies, and comparative studies were included, as well as systematic reviews, meta-analyses, integrative reviews with clearly described methodology, and theses or dissertations presenting explicit methodological rigor. The selection was restricted to full-text

publications published between 2015 and 2025 in Portuguese, English, or Spanish. In addition, only studies with direct adherence to the research question structured according to the PIO strategy and to the objectives established for the integrative review were considered.

Studies conducted exclusively with broilers, ornamental birds, or other avian species other than laying hens were excluded, as were studies directed only at conventional cage-rearing systems without comparison or discussion involving alternative systems. Studies focused exclusively on economic, market, or commercialization aspects, without evaluation of productive, sanitary, or animal welfare indicators, were also excluded, as were exclusively laboratory or molecular studies that did not establish a direct relationship with rearing systems. Editorials, letters to the editor, opinion articles, comments, simple abstracts, publications without original scientific data, studies with insufficiently described methodology, duplicate studies during the selection stages, publications outside the previously defined period, studies without full-text availability, and research not aligned with the objective of the review were also excluded from the final sample.

The study selection process was conducted in sequential stages, following an adapted PRISMA flow diagram model (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), with the objective of ensuring transparency, reproducibility, and methodological rigor in identifying the final sample. Initially, all records identified in the PubMed database were compiled and organized in an electronic spreadsheet, with duplicate removal and standardization of records carried out for subsequent analysis.

In the identification stage, 2,931 records were retrieved and submitted to initial screening through reading of titles and abstracts, with the purpose of verifying adherence to the review topic. Next, potentially relevant studies were selected for full-text reading, during which the previously defined inclusion and exclusion criteria were applied. At this stage, aspects such as type of rearing system, species studied, outcomes analyzed, and methodological adequacy were evaluated.

After screening and eligibility assessment, studies that fully met the established criteria were included in the final sample of the integrative review, totaling 52 selected studies after evaluation of 74 full-text articles. The selection process was conducted independently and rigorously, ensuring that only studies directly aligned with the research question were included in the final synthesis and ensuring consistency between the proposed objectives and the evidence analyzed.

Data extraction from the included studies was carried out systematically, with the objective of standardizing and organizing the information relevant to the synthesis of the integrative review. A structured spreadsheet was used to record the variables of interest, ensuring uniformity in collection and facilitating comparison among the selected studies. The extracted information included general study characteristics (author, year of publication, country, and methodological design), type of rearing system evaluated, population studied, and the main outcomes related to productive, sanitary, and animal welfare indicators.

The data were subsequently grouped into thematic categories according to the objectives of the review, allowing descriptive, interpretive, and comparative analysis of the evidence found in the literature. Meta-analysis or inferential statistical analysis techniques were not applied because of the methodological heterogeneity and different approaches used in the included studies. Thus, a qualitative synthesis of results was adopted, with critical interpretation of the scientific evidence, highlighting convergences, divergences, and knowledge gaps related to non-conventional laying hen systems.

RESULTS AND DISCUSSION

CHARACTERIZATION OF THE INCLUDED STUDIES

The present integrative review included a total of 52 studies, selected from the PubMed database after application of the previously established eligibility criteria. The studies analyzed were published between 2015 and 2025, encompassing different methodological designs, including experimental trials, observational studies, comparative studies, systematic reviews, and integrative analyses. This

methodological diversity reflects the complexity of the topic investigated and the multiplicity of approaches used to evaluate productive, sanitary, and welfare indicators in non-conventional laying hen systems.

Regarding geographic distribution, there was a predominance of studies conducted in countries in Europe, Asia, and North America, especially research carried out in intensive production contexts undergoing transition to alternative systems, such as cage-free and free-range systems. Studies from countries with extensive or small-scale production systems were also identified, in which the use of systems with outdoor access and organic models is more frequent. This distribution demonstrates the global interest in the topic, driven by demands related to animal welfare, food safety, and sustainability of egg production systems.

In relation to the rearing systems evaluated, there was a predominance of comparative studies between conventional cage systems and non-conventional systems, especially cage-free, free-range, and aviary systems. Organic systems and pasture-access systems were also widely represented, although in smaller proportion. Some studies also included evaluations of enriched or modified systems, in which additional environmental resources, such as perches, nests, and substrates, were introduced with the objective of improving bird welfare and reducing undesirable behaviors.

With regard to the outcomes analyzed, most studies addressed more than one evaluation axis simultaneously, combining productive, sanitary, and animal welfare indicators. The most frequent productive indicators included laying rate, egg quality, feed conversion, and body weight. Sanitary indicators involved the occurrence of pathogens, such as *Salmonella spp* and *Campylobacter spp.*, in addition to flock mortality and morbidity. In the field of animal welfare, behavioral assessments, plumage integrity, keel bone lesions, footpad dermatitis, and levels of physiological stress stood out.

In general, the included studies showed significant heterogeneity in relation to experimental designs, management conditions, and indicators used, which limits direct comparison among results. Even so, it was possible to identify consistent patterns in the literature, especially regarding the

relationships among rearing systems, productive performance, exposure to sanitary agents, and welfare indicators. This heterogeneity reinforces the need for integrative syntheses capable of critically organizing the available evidence and providing a comprehensive view of the impacts of non-conventional egg production systems.

EFFECTS OF NON-CONVENTIONAL SYSTEMS ON PRODUCTIVE INDICATORS

The productive indicators evaluated in the included studies demonstrated consistent variation among different laying hen rearing systems, especially when conventional cage systems were compared with non-conventional systems such as free-range, cage-free, and aviaries. In general, egg production was one of the most frequently analyzed parameters, showing that although some alternative systems may maintain productive levels similar to those of conventional systems, others show reductions in laying rate due to factors related to the environment, management, and the birds' level of activity (Yilmaz Dikmen et al., 2016; Wurtz et al., 2022).

Regarding egg production, systems with greater freedom of movement, such as free-range systems and systems with outdoor access, tended to show greater variability in laying rate. This variation may be associated with exposure to adverse environmental conditions, greater energy expenditure by birds, and differences in feeding behavior. On the other hand, cage-free systems and aviaries, when well managed, demonstrated the capacity to maintain productive performance close to that observed in conventional systems, suggesting that internal infrastructure and adequate management are determining factors for production stability (Wurtz et al., 2022; Yan et al., 2022).

Feed conversion and feed intake were also influenced by rearing systems, with a tendency toward increased feed intake in non-conventional systems. This increase may be related to the greater physical activity of birds and the need for energy compensation resulting from environmental exploration. In some studies, feed efficiency was reduced in systems with outdoor access, whereas enriched systems and well-structured aviaries showed a better balance between intake and production, indicating that nutritional and

environmental management plays a central role in maintaining productive efficiency (Yadav; Jha, 2019; Zhao et al., 2022).

Regarding egg quality, several studies indicated that non-conventional systems may positively influence characteristics such as nutritional composition, shell quality, and lipid profile, especially in organic and outdoor production systems. Mineral supplementation and nutritional management were identified as important factors in improving shell strength and egg oxidative stability. However, some studies also reported a higher incidence of dirty eggs or eggs with external defects in systems with access to the ground or outdoor environment, which may affect the commercial quality of the final product (Xiao et al., 2015; Zhang et al., 2021; Zita et al., 2022).

Comparisons among systems indicated that there is no single pattern of productive superiority among the models evaluated, with results being highly dependent on factors such as bird genetics, stocking density, facility quality, and management level. In some cases, conventional systems showed greater productive stability, while non-conventional systems demonstrated advantages in terms of product quality and behavioral expression of birds, albeit with greater variability in productive results (Wurtz et al., 2022; Xiang et al., 2018).

Overall, the findings suggest that non-conventional egg production systems present a set of productive trade-offs, in which possible gains in welfare aspects and product quality may be associated with variations in productive efficiency. This relationship reinforces the importance of integrated management, nutrition, and infrastructure strategies capable of minimizing productive losses while maintaining the benefits associated with alternative laying hen rearing systems.

SANITARY IMPACTS OF ALTERNATIVE SYSTEMS

The studies included in the review indicated that non-conventional laying hen systems present relevant sanitary impacts, especially in relation to the greater exposure of birds to pathogenic agents present in the environment. Among the microorganisms most frequently investigated are *Salmonella spp.*

and *Campylobacter spp.*, whose prevalence tends to be influenced by the type of rearing system and the biosecurity conditions adopted. In systems with outdoor access, a higher risk of contact with environmental reservoirs of these pathogens was observed, which may contribute to variations in the occurrence of infections (Xu et al., 2021; Worku et al., 2025).

With regard to diseases and infections, it was found that free-range and outdoor production systems may present a greater diversity of infectious agents, due to the birds' greater interaction with soil, wild fauna, and environmental organic matter. Studies have reported the presence of gastrointestinal parasites and greater exposure to environmental fungi and bacteria in less confined systems, which may affect intestinal health and immune performance in birds (Zloch et al., 2021; Yang et al., 2025). However, some studies also indicated that adequate management and biosecurity practices can significantly reduce these risks.

Mortality and morbidity varied among the systems evaluated, being influenced by factors such as stocking density, ventilation quality, sanitary management, and facility structure. In certain studies, alternative systems showed slightly higher mortality rates, possibly associated with greater incidence of lesions, environmental stress, and sanitary challenges. On the other hand, well-managed systems with adequate environmental enrichment demonstrated the capacity to maintain health indices comparable to those of conventional systems, evidencing the central role of management in risk mitigation (Zhao et al., 2021; Yi et al., 2025).

The risk of environmental exposure was widely highlighted as one of the main factors associated with sanitary variability among systems. The presence of organic dust, microbial aerosols, and contact with contaminated surfaces may increase the pathogen load in the rearing environment, especially in systems with greater outdoor access or less environmental control. In addition, factors such as inadequate ventilation and accumulation of waste were associated with increased sanitary pressure inside facilities, favoring the dissemination of infectious agents (Zhao et al., 2015; Yi et al., 2025).

Overall, the findings indicate that non-conventional egg production systems present a complex balance between benefits related to animal welfare and additional sanitary challenges. Although they may offer more natural environments favorable to bird behavior, these systems require greater rigor in biosecurity strategies, sanitary monitoring, and preventive management in order to reduce disease incidence and ensure the productive and sanitary sustainability of flocks.

ANIMAL WELFARE INDICATORS

The animal welfare indicators analyzed in the included studies showed consistent differences between conventional and non-conventional egg production systems. In general, free-range, cage-free, and aviary systems were associated with greater expression of natural behaviors in laying hens, such as foraging, dust bathing, and environmental exploration. However, these behavioral benefits often coexisted with challenges related to birds' physical integrity, indicating the multifactorial nature of animal welfare in these systems (Yan et al., 2022; Wurtz et al., 2022).

Regarding plumage integrity, several studies reported greater variability in feather condition scores in non-conventional systems. In some cases, improved plumage was observed as a result of reduced social stress and greater opportunities to escape aggressive interactions. On the other hand, poorer plumage scores were also recorded in systems with higher density or inadequate management, suggesting that system structure and management quality directly influence this indicator (Xu et al., 2022; Yilmaz Dikmen et al., 2016).

Keel bone lesions and pododermatitis were widely reported as important indicators of physical welfare. Studies indicated that systems with inadequate surfaces, high density, or deficient litter management may increase the occurrence of these lesions, especially in cage-free systems and aviaries. However, when compared with conventional cage systems, some alternative systems with better environmental conditions showed reductions in certain types of lesions, demonstrating that housing type

alone does not independently determine the level of welfare (Zhao et al., 2015; Yilmaz Dikmen et al., 2016).

Natural bird behavior was consistently more expressed in non-conventional systems, especially those with access to the outdoor environment. The possibility of movement, exploration, and interaction with natural substrates was associated with greater behavioral diversity and reduced stereotyped behaviors. However, use of outdoor space varied significantly among studies, being influenced by factors such as climate, predators, density, and facility structure, which directly affects the consistency of observed results (Yan et al., 2022; Wurtz et al., 2022).

Indicators of physiological stress, frequently evaluated through corticosterone levels and immune responses, also varied among rearing systems. Some studies indicated lower stress levels in enriched systems or systems with greater behavioral freedom, while others pointed to increased stress in environments with greater exposure to adverse environmental factors. This divergence suggests that stress in laying hens is more closely related to management and environmental conditions than exclusively to the type of production system (Xiang et al., 2018; Xu et al., 2020).

In general, feather pecking and aggressiveness were identified as important welfare challenges in non-conventional systems, especially in situations of inadequate management or high population density. Although greater freedom of movement may reduce conflicts in some contexts, the social complexity of birds in collective systems may favor the occurrence of aggressive behaviors. Thus, the results indicate that animal welfare in alternative systems depends on a balance among physical environment, management, and the social structure of the birds, and is not determined exclusively by the type of rearing system.

CRITICAL INTEGRATION OF FINDINGS

The integrated analysis of the included studies shows the existence of a consistent set of trade-offs among productivity, health, and animal welfare in non-conventional laying hen systems. While systems

such as free-range, cage-free, and aviaries tend to promote improvements in behavioral indicators and aspects related to welfare, these gains do not always translate into greater productive or sanitary stability. Conversely, more confined systems present greater productive predictability, but with important limitations regarding the expression of natural behaviors and freedom of movement for birds.

The influence of management emerged as a determining factor in mediating these outcomes. The findings indicate that differences in environmental quality, stocking density, nutrition, ventilation, and biosecurity may be more relevant than the type of rearing system itself. Thus, well-managed non-conventional systems may present productive and sanitary performance similar to that of conventional systems, whereas poorly managed alternative systems may intensify health problems, stress, and reduced productive efficiency (Zhao et al., 2021; Yi et al., 2025).

Significant inconsistency was also observed among studies regarding the magnitude of the effects of rearing systems on the indicators evaluated. This variability may be attributed to methodological heterogeneity, genetic differences among laying hen strains, climatic conditions, and different levels of implementation of alternative systems. In addition, the lack of standardization of welfare indicators and sanitary protocols makes direct comparison among results difficult, limiting the generalization of conclusions.

Finally, the methodological limitations identified in the literature include the predominance of cross-sectional or short-term studies, variability in criteria for outcome assessment, and scarcity of integrated approaches that simultaneously consider the three axes analyzed. These limitations reinforce the need for cautious interpretation and highlight the importance of more robust studies capable of incorporating multiple dimensions of poultry production in non-conventional systems.

KNOWLEDGE GAPS

The studies included in this integrative review were distributed over the period from 2015 to 2025. The body of evidence showed a greater concentration of publications from 2018 onward. This pattern

indicated increased scientific interest in non-conventional laying hen systems. The studies analyzed covered different countries and production contexts. The literature included research conducted in intensive, semi-intensive, and extensive systems. The authors mainly investigated free-range, cage-free, aviary, and organic systems. Studies involving pasture-raised systems, barn systems, and systems with access to the outdoor environment were also identified (Zhao et al., 2015; Wurtz et al., 2022; Yan et al., 2022).

Analysis of the literature reveals important gaps in scientific knowledge related to non-conventional laying hen systems, especially regarding the absence of standardization of the indicators used to assess productivity, health, and animal welfare. It is observed that different studies employ distinct metrics for the same outcomes, which makes direct comparison of results difficult and limits the consolidation of more robust evidence on the real impact of these systems.

Another relevant gap concerns the scarcity of longitudinal studies capable of monitoring bird performance throughout the entire production cycle. Most of the available investigations have cross-sectional or short-term experimental designs, which restricts understanding of the cumulative effects of rearing systems on the health, behavior, and productivity of laying hens. This limitation compromises the evaluation of long-term impacts, especially in systems with high environmental variability, such as free-range and organic systems.

Finally, the need for greater integration among the three axes analyzed in this review—productivity, health, and animal welfare—stands out, since a large proportion of studies still address these aspects in isolation. The literature points to the importance of multidimensional and interdisciplinary approaches that allow a more comprehensive understanding of the effects of non-conventional egg production systems, contributing to the development of more sustainable, balanced, and scientifically grounded systems.

CONCLUSION

The present integrative review showed that non-conventional laying hen systems, such as free-range, cage-free, aviary, and organic systems, exert simultaneous and interdependent effects on productive, sanitary, and welfare indicators in laying hens. In general, these systems present greater complexity of outcomes when compared with conventional systems, reflecting significant performance variations associated with management conditions, environmental quality, and production structure.

Regarding productive indicators, it is concluded that there is no absolute superiority among the systems evaluated, with both gains and losses in performance being observed depending on implementation conditions. Non-conventional systems can maintain acceptable levels of egg production and quality, but frequently present greater variability in productive efficiency, especially due to increased bird activity and more exposed environmental conditions.

With respect to sanitary aspects and animal welfare, it is concluded that non-conventional systems tend to favor the expression of natural behaviors and certain welfare indicators, although they may be associated with a greater risk of exposure to pathogenic agents and additional sanitary challenges. Thus, a scenario of delicate balance is observed between behavioral benefits and potential sanitary vulnerabilities, strongly mediated by the management and biosecurity practices adopted.

Thus, the general objective of the research was achieved by critically synthesizing the available evidence on the effects of non-conventional egg production systems, identifying important interactions among productivity, health, and animal welfare. The main contribution of this study lies in the integration of these three analytical axes, which are frequently addressed in isolation in the literature, allowing a broader and more systemic understanding of the impacts of these production models.

Finally, it is recommended that future research adopt longitudinal designs, greater standardization of indicators, and integrated approaches that simultaneously consider productivity, health, and animal welfare. In addition, the need for studies evaluating management strategies capable of mitigating negative

impacts and enhancing the benefits of non-conventional systems is emphasized, contributing to the development of more sustainable and balanced egg production systems.

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TAMBOR DE CRIOULO: THE IMPORTANCE OF AFRO-BRAZILIAN CULTURE, AN APPROACH IN THE MUNICIPALITY OF SÃO JOÃO DO ARRAIAL, PIAUÍ

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Abstract

This study addresses Tambor de Crioulo as an important manifestation of Afro-Brazilian culture in the municipality of São João do Arraial, in the state of Piauí. The research aims to analyze the relevance of this cultural expression for the preservation of memory, identity, and traditions of African origin present in the local community. Methodologically, the study is based on a bibliographic review and on the analysis of historical, social, and cultural aspects related to Tambor de Crioulo, highlighting its contribution to strengthening community relations and valuing intangible cultural heritage. The results show that this manifestation goes beyond its festive and religious character, constituting an important instrument of cultural resistance, transmission of knowledge, and identity affirmation among Afro-descendant populations. It is concluded that Tambor de Crioulo plays a fundamental role in maintaining local cultural traditions, contributing to the appreciation of cultural diversity and to the recognition of African heritage in the formation of Brazilian society.

Keywords: Afro-Brazilian culture, Cultural identity, Intangible heritage, São João do Arraial, Tambor de Crioulo.

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INTRODUCTION

The present project aims to address the need to recover the history of Tambor de Crioulo in the Chapada da Sindá community. Knowing the history of local culture means recovering and preserving its tradition and memory.

The importance of preserving the popular culture of our city lies in the fact that it is a way of valuing our origin or the place where we live. Knowledge of local culture strengthens appreciation, as well as encourages the development of the region through popular manifestations and expressions that embody the regional context as a factor of Afro-Brazilian cultural identity.

Thus, there is a need to disseminate Afro-Brazilian culture through the “Tambor de Crioulo of the Chapada da Sindá community” as a recovery of the local culture of São João do Arraial. It is important to value the history of Tambor de Crioulo and the local culture of the Chapada da Sindá community because, through it, future generations may come to know its importance in their lives, their beliefs, their customs, and their artistic and religious festivities.

The objective of this project is to know and value the history of Tambor de Crioulo in order to recover and disseminate its culture, beliefs, customs, and artistic and religious festivities, by encouraging Afro-Brazilian culture in different places within the municipality and even across the country, as well as by reaching various social strata, making it possible for popular culture to cease being the privilege of a few people and become more accessible to everyone.

It is necessary, above all, to know our history, our cultures, our people, and to value our roots, and from there to begin the search for knowledge, for new histories, cultures, peoples, and worlds.

In this way, the implementation of a History project is necessary, one that seeks to broaden knowledge of Tambor de Crioulo in the Chapada da Sindá community, in addition to providing new instruments of understanding and critical thinking, thereby contributing directly and indirectly to a better learning experience regarding our local culture.

This research seeks to present popular culture and Afro-Brazilian culture through Tambor de Crioulo in the cultural, social, and personal spheres, fostering a new perspective on the local culture of São João do Arraial and the Chapada da Sindá community, with its way of life. For it is necessary, above all, to know and value our own local history so that we may appreciate and understand other histories, peoples, and cultures.

The study was developed through an analytical and descriptive methodology, by means of bibliographic and documentary research, using both printed books and data collection about the Chapada da Sindá community through the internet.

The structure of the work, that is, how it is divided, is as follows: in the first chapter, we will discuss Popular Culture, understood as cultural elements belonging to a society or region, which the population practices constantly and actively through different manifestations such as dance, theater, art, literature, folklore, gastronomy, music, and so forth. In the second chapter, Afro-Brazilian culture will be discussed, defined as the set of cultural manifestations in Brazil that have undergone some degree of influence from African culture from the period of Colonial Brazil to the present day. In the third chapter, Tambor de Crioulo will be addressed as a cultural group that emerged in the 1950s through the families of João Luzia and Sindá, in the Chapada da Sindá community, under a sapucaia tree, as a form of understanding and integration within the community, where they would gather to play.

Valuing culture is not merely showing how it is present in our daily lives, but seeing it as an essential component and participant in the social and educational formation of every individual.

POPULAR CULTURE

Before discussing popular culture, it is important to address what culture is, or what may constitute a culture. As may be seen below, it is composed of various elements developed by a society over time. Thus:

Culture is constituted by the set of knowledge, practices, rules, norms, prohibitions, strategies, beliefs, ideas, values, and myths that are transmitted from generation to generation, reproduced in each individual, control the existence of society, and maintain psychological and social complexity. There is no human society, archaic or modern, devoid of culture, but each culture is unique. Thus, culture always exists within cultures, but culture exists only through cultures. (Morin, 2002, p. 56)

Popular culture, in turn, is a form of cultural manifestation intrinsically related to the anonymous, the collective, the spontaneous, tradition, and orality. In general terms, we may say that popular culture is:

the set of knowledge and practices experienced by the people, although they may also be experienced and instrumentalized by elites. Consider *candomblé*, carnival, *feijoada*, folkloric practices, *jogo do bicho*, and *capoeira*. (...) Popular culture simply [is] what is spontaneous, free from canons and laws, such as dances, beliefs, and traditional sayings. (...) Everything that happens in the country by tradition and deserves to be maintained and preserved unchanged. (...) Everything that is knowledge of the people, of anonymous or collective production. (Vannucchi, 1999, p. 98).

As one can perceive, defining popular culture is not simple, because it is necessary to establish a relationship with the word people. The term “people” has various meanings, as it may be related to ideological, political, social, and economic conceptions.

It must be said that popular culture also involves public space, cultural policy projects, and June festivals, all contributing to local development. According to Ana Maria Ochoa Gautier, in her text *Indicadores Culturais para Tempos de Desencanto* [Cultural Indicators for Times of Disenchantment], she states that:

one of the pillars of the notion of public space—its distinction from the private—collapses in this sphere and, behind the new walls, the media replace the public square as a political forum and as a meeting space (Martin Barbero, 2000 apud Gautier; 2003:65)

Culture governs all aspects of the formation of a society, such as behaviors, thoughts, expectations, and even the formal or informal education present in the daily life of every human being. At

the same time that cultures preserve traditions, they also integrate traditions from other cultures and other peoples, forming an exchange of practices, customs, traditions, foods, and so forth.

These ways in which we observe the world generate different representations and valuations of cultures. There is no culture superior to another; however, there are different perspectives and values presented. Societies change, evolve, and undergo crises of values and economics, yet culture remains present in our daily lives. Each people has its identity guided by its local culture, and this does not dissolve either with the evolution of machines or with the evolution of technology, which today is globalized.

According to Benedict (1972, p. 16 apud Laraia, 2009 p. 67), “culture is like a lens through which man sees the world”; thus, different cultures possess different lenses. The way we see the world and react to situations is part of the cultural heritage we receive throughout our lives. We are not born knowing how we will behave; rather, we learn as time passes, and this behavior may generate, through cultural heritage, various types of prejudice toward already existing cultures and practices. “Our cultural heritage, developed over countless generations, has always conditioned us to react depreciatively toward the behavior of those who act outside the standards accepted by the majority of the community.”

Humble people who have had little schooling and who live in communities far from large cities nevertheless contribute to passing down stories across generations, transmitting the beliefs, dances, customs, values, and rituals that belong to their people.

AFRO-BRAZILIAN CULTURE

Afro-Brazilian culture is the set of predominant cultural manifestations in Brazil, formed from the combination of elements of the cultures of African peoples who were brought as enslaved people to the country during the colonial period.

During Colonial Brazil, every type of cultural manifestation of African origin was discouraged and marginalized in society. At that time, the customs and traditions of African peoples were considered primitive and savage by Europeans.

With the end of slavery in Brazil (1888), a slow process of reinterpretation of African culture began. In the mid-twentieth century, the Brazilian elite began to view certain African cultural aspects as legitimate artistic expressions that represented national identity.

In Brazil, African culture was also influenced by European cultures, especially Portuguese culture, and Indigenous cultures, so that characteristics of African origin in Brazilian culture are generally mixed with other cultural references. Strong traces of African culture can be found today in various aspects of Brazilian culture, such as popular music, religion, cuisine, folklore, and popular festivities. The states of Maranhão, Pernambuco, Alagoas, Bahia, Minas Gerais, Espírito Santo, Rio de Janeiro, São Paulo, and Rio Grande do Sul were the most influenced by culture of African origin, both because of the number of enslaved people received during the period of the slave trade and because of the internal migration of enslaved people after the end of the sugarcane cycle in the Northeast region.

The website *A Participação dos Negros na Construção do Brasil* [The Participation of Black People in the Construction of Brazil] (2014) adds:

It is necessary to stress that Black people did not come from their place of origin without culture. Upon entering Brazil, they encountered a reality completely different from the one in which they had lived, since, for the European colonizer, they were considered merely labor; however, on the African continent, Black people lived in tribes, and there they were princes. The cultural heterogeneity of African ethnic groups was immense; in other words, there was a differentiated cultural practice depending on the region to which each group belonged. (Black Influence in Brazil, 2014, n.p.)

Once present in the country, among so many other difficulties experienced by Black people, as history tells us, one of them was precisely keeping their culture alive. Many factors interfered, such as distance from their “land,” their “families,” and the “loss” of their culture, imposed by those who held power in their hands: the Empire and the Church.

During slavery, alongside the Empire, the Catholic Church held the reins of power. European culture, considered white, predominated in the country and allowed no room for African customs, which were discriminated against by white society, then the majority. In this regard, Abdias do Nascimento writes:

Among the instruments used by the enslaving power is the Catholic Church, which, absolutely, is not responsible for the persistence of religions of African origin in the so-called Latin America: Haiti, Cuba, and Brazil, among others. This Church owned slaves for profit and constantly persecuted and attacked African religious beliefs for centuries, up to the present day (Nascimento, 1978, p. 101).

In order to preserve their culture and beliefs, Black people were forced to seek two paths: the “acceptance” of what was imposed by the Catholic Church, mixing it with what was compatible with their own culture, and also, for those who managed to flee, the maintenance of their rites in clandestine societies formed by them, known as quilombos.

In the quilombos, in a hidden manner and on the margins of power, Black people possessed a certain freedom to express themselves, especially in accordance with the customs of their homelands.

In short, despite all the difficulties encountered and despite the fact that much was lost, the contribution of African peoples to Brazilian formation was essential both in the physical composition of the population and in the shaping of what would become culture. This includes several dimensions, such as cuisine, language, music, religion, aesthetics, social values, and mental structures.

TAMBOR DE CRIOULA AND ITS MANIFESTATION IN SÃO JOÃO DO ARRAIAL

Tambor de Crioula is a form of Afro-Brazilian expression involving circular dance, singing, and drum percussion. Brought to Brazil between the eighteenth and nineteenth centuries by enslaved people from various regions of Africa, Tambor de Crioula is a form of entertainment or of fulfilling a vow to

Saint Benedict (a Black saint), as well as to other saints associated with traditional Catholicism and to entities worshipped in terreiros.

Tambor de Crioula groups are formed by the coreiras, the name given to the female dancers, by the drummers, and by the singers, guided by the uninterrupted rhythm of the drums and by the influence of the singing, culminating in the punga or umbigada. The punga or umbigada, the main part of the dance, is a choreographic movement in which the coreiras, in a gesture understood as both greeting and invitation, touch one another's abdomen. Its place of origin and occurrence is the state of Maranhão, in the Northeast region of Brazil, with groups existing in municipalities along the coast and in the interior.

According to Ferretti (2002), the oldest known information about Tambor de Crioula is that these dances were used to conceal fighting exercises. After the end of slavery, since the use of force was no longer necessary, this practice began to be performed as a dance in which women could now participate in the circle, displaying all their sensuality.

The oldest information I have about Tambor de Crioula is that it was performed to conceal fighting exercises: while farther south this was done hidden under the sound of the berimbau, in Maranhão it was done under the sound of drums. Thus, the leg movements—according to the oldest information I gathered—were practiced to the sound of drums; it was not exactly dance; it was like capoeira in Bahia. Américo deduces that with the abolition of slavery, since Black people no longer needed to train for combat against the white oppressor, “the custom remained, and little by little it was transformed into a dance.” For him, therefore, the introduction of women into Tambor de Crioula occurred after Abolition, that is, when its basic connotation as combat gave way to a typically festive choreography (Ferreti, apud Azevedo, 2002, p. 51).

Tambor de Crioula is performed with three drums, played by hand by men who position themselves alongside a group of singers. The participants organize themselves in a circle, and the dance is performed by women, each entering the circle in her own time to develop the choreography, whose high point is the punga. The three drums that make up the instrumental ensemble are made of wood, tapered and hollowed out, and covered with leather at one end, fastened with pegs and tied with rope or leather. The singing begins with a soloist who improvises words that are repeated for hours on end. The

melody is built upon the words, pronounced with a distinctive accent full of regionalisms and old terms, often difficult for outsiders to understand.

Another assertion is that Tambor de Crioula was also a way of training blows in preparation for confrontation. The anthropologist Sergio Ferretti, based on a statement by playwright Américo Azevedo Neto, in his book *Tambor de Crioula – ritual and spectacle*, tells us that:

The oldest information I have about Tambor de Criola is that it was performed to conceal fighting exercises: while farther south this was done hidden under the sound of the berimbau, in Maranhão it was done under the sound of drums. Thus, the leg movements—according to the oldest information I gathered—were practiced to the sound of drums; it was not exactly dance; it was like capoeira in Bahia.” Américo deduces that with the abolition of slavery, since Black people no longer needed to train for combat against the white oppressor, “the custom remained, and little by little it was transformed into a dance.” For him, therefore, the introduction of women into Tambor de Crioula occurred after Abolition, that is, when its basic connotation as combat gave way to a typically festive choreography. (Ferretti, 1995a, p. 51)

Its recognition as an important cultural expression began in the 1960s, leading the groups to become more organized. Today, Tambor de Crioula groups must have legal registration and a headquarters, which usually operates in the home of the “owner” of the tambor.

The Tambor de Crioula of São João do Arraial, in Piauí, emerged in the 1960s through the João Luzia and Sindá families, in the Chapada da Sindá community, under a sapucaia tree, where they gathered to play the drum. At that time, the families used the drum to signal when a group that had gone hunting in the woods had arrived back in the community, and the other group used the sound of the drum to give notice. The dance is marked by rhythmic movements, the accelerated beating of the drums, and the strong stamping of feet. According to the documentary produced by the group *Oppressed Cultures of Chapada da Sindá* (2007), directed by Erinaldo Carvalho, we observe this fact:

The Tambor de Crioula of the Chapada da Sindá Community Settlement in São João do Arraial, Piauí, began around the 1950s as a form of entertainment and integration for the local community. Women and men, adults, adolescents, and children dance in strong rhythmic movements, marked by the beating of the drums and the strong stamping of feet. (Carvalho, 2007, n.p.)

Master João Luzia, as he is known, lives in the Chapada da Sindá community, in the municipality of São João do Arraial, located in the northern region of Piauí. He leads the Tambor de Crioula group, which brings together different generations. The farmer João Luzia, seventy years old, who did not have the opportunity to attend school, composes the lyrics of the songs of an amusement that he learned from his father and passes on to his children and grandchildren. The hard labor of the fields is accompanied by the music of Master João Luzia. Married and the father of seven children, João Luzia has danced Tambor de Crioula since childhood. While still young, he took charge of the group, becoming responsible for the tunes, rhythms, and lyrics that portray, in a simple way, the daily life of the rural worker.

The group is composed of approximately forty-five people, divided among drummers, singers, chorus members, and coreiras (women, men, and children who dance and sing in the tambor). It is coordinated by Master João Luzia, a self-taught farmer who composes songs, rhythms, and tunes drawn from the sounds of the environment in which he lives and works.

According to Ferretti (1995),

as in samba de roda, Tambor de Crioula is generally danced outdoors; its choreography, free and varied, is developed within a circle formed by the dancers, singers, drummers, and participants. [...] The circle forms naturally. The drummers arrive, place the drums, and begin to play (testing whether they are properly tuned); then the singers arrive, as do the dancers, coreiras, crioulas, or “baianas,” who, positioning themselves side by side, form the circle and begin the dance. [...] One dancer at a time enters the circle, while the others continue exchanging small steps to the right and left or making small movements while waiting for the punça in order to enter. [...] Each dancer defines her individual way of dancing; nevertheless, a choreographic unity can be observed in the ensemble as a whole. Normally, there is no break in rhythm, and all the dancers follow the same beat as the drummers. (Ferretti, 1995a, p. 65–66).

The rhythm is dictated by three drums. The songs address stories from everyday life. The dance has no defined steps. Each person participates in the way they prefer. It is an action implemented in São João do Arraial to encourage art and culture.

The municipality recovered local culture through the dance of the traditional cultural group Tambor de Crioula of the Chapada da Sindá community. Ten years ago, the group became organized. They created costumes, recorded a CD, and participated in several festivals in other states. It is during the June festival period that they perform most often, recovering an important cultural manifestation of the people of the Northeast. According to Carvalho (2007):

In January of this year, they managed—with the support of the Municipal Government, the State Government, and private initiative—to record their first CD with ten tracks, the last of which is a compilation of images from the group's performances. (Carvalho, 2007, n.p.)

For the Chapada da Sindá community, Tambor de Crioula underwent adaptations and became an expression of the creative capacity of a population that suffered from poverty, oppression, and hunger. Dancing Tambor de Crioula was a way of driving away sadness and bringing joy to their lives.

“I could not fail to honor João Luzia at this very important moment of recognition. Recognition of the farmer, of the municipality's culture, and of the Tambor group, which has been carrying forward this typical dance as a true treasure. This is proof of yet another achievement by the people of São João do Arraial and by Piauí culture,” stated the current state deputy and former mayor Francisco Limma, who attended the event.

CONCLUSION

Popular culture generally refers to the traditions and material culture of a particular society. In the modern West, pop culture refers to cultural products such as music, art, literature, fashion, dance, cinema, cyberculture, television, and radio consumed by the majority of society's population. In other words, the manifestations of a people, such as Tambor de Crioulo, are a strong example of the culture of a people that has been built and transformed over time according to the environment in which these peoples live, which has also undergone transformations.

“Brazil is the country that, for the longest time and in the greatest number, received enslaved people from Africa” (Lima, Mônica apud Figueiredo, Luciano, 2009, p. 12). Thus, it is undeniable that one cannot ignore the magnitude of the contribution of Black culture to Brazilian popular culture. The Tambor de Crioula presented in this work is an example of how a dance underwent changes according to the way it was introduced into Brazilian culture.

Tambor de Crioula is considered a ritual dance of São João do Arraial. Tambor de Crioula, Bumba-meu-boi, and reisado have become cultural expressions of the population of Chapada and the region. It became an instrument for bringing the community together and for confronting poverty, as well as for strengthening its organization and its struggle for land.

Based on the research, it can be observed that the dissemination of this dance in the municipality of São João do Arraial has led to certain changes and to the loss of its ritualistic character, transforming the ritual into a mere spectacle, especially when performed outside the context in which it is normally produced, thereby causing it to lose some of its character as a cultural manifestation.

The discussion of the theme of Tambor de Crioula is broad and has considerable potential to be explored in future works, particularly regarding the dissemination of this ritual in other states, beyond São João do Arraial in Piauí, as well as regarding the issue of its spectacularization, which has been occurring alongside this dissemination.

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PRODUCTIVITY OF FERTIGATED CORIANDER AS A FUNCTION OF NITROGEN RATES AND BIOSTIMULANT APPLICATION

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Abstract

Coriander (*Coriandrum sativum* L.) is widely used as a culinary seasoning and is an important income-generating crop, particularly for small-scale farmers. However, its cultivation requires appropriate management and the rational use of fertilizers, together with the adoption of technologies such as biofertilizers. Accordingly, this study evaluated the yield of coriander subjected to different nitrogen rates applied through fertigation and to foliar biofertilizers. The experiment was conducted under field conditions in the experimental area of the Federal University of Alagoas (UFAL), Arapiraca Campus, between August and October 2022. A randomized block design was used in a factorial arrangement with split plots, comprising four blocks and 16 treatments consisting of four nitrogen rates (0, 40, 80, and 120 kg ha⁻¹) and four biofertilizer treatments (control, Arbolin, Bioative, and Organo Top Grap). Six fertigation applications and three foliar applications were performed. The variables analyzed were chlorophyll B, yield per hectare, total fresh weight, root fresh weight, stem dry weight, root length, and

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number of plants per linear meter. The data were subjected to analysis of variance, with means compared using Tukey's test at the 5% significance level and regression analysis performed for the nitrogen rates. Chlorophyll B, total fresh weight, and stem dry weight reached their highest values at the nitrogen rate of 120 kg ha⁻¹. Maximum yield was obtained at a rate of 89.07 kg ha⁻¹, at approximately 17,000 kg ha⁻¹. The biofertilizers did not affect the agronomic characteristics evaluated.

Keywords: *Coriandrum sativum* L., Fertigation, Leafy vegetable, Nitrogen fertilization.

INTRODUCTION

Coriander (*Coriandrum sativum* L.) is an annual leafy vegetable belonging to the Apiaceae family (Msaada, 2007). It is adapted to warm-climate conditions and has low tolerance to cool temperatures. It is also highly tolerant of soil acidity and has relatively low fertility requirements, which facilitates its cultivation under different soil and climatic conditions (Oliveira, 2018).

In Brazil, coriander is grown predominantly by small- and medium-scale farmers, primarily for the production of fresh biomass, which is widely used as a seasoning in dishes, sauces, and salads. In addition to its culinary importance, the crop is notable for its medicinal properties, including anticancer, anti-inflammatory, antidiabetic, and analgesic effects attributed to the presence of phytochemical compounds such as polyphenols, vitamins, and phytosterols (Mahleyuddin et al., 2021).

Regarding its regional distribution, much of the coriander grown in Northeastern Brazil is cultivated in household gardens using family labor. In this context, the city of Arapiraca, formerly known for tobacco production, underwent a process of agricultural restructuring following the decline of that crop. Consequently, greenbelts gained prominence and stimulated vegetable production, with coriander emerging as a crop of considerable economic importance (Oliveira, 2018).

Given the crop's growing importance, appropriate management is essential, particularly concerning fertilization. The soil's natural fertility is not always sufficient to meet coriander's nutritional requirements, making supplemental nutrient application necessary. Among these nutrients, nitrogen (N) is

one of the elements most required by leafy vegetables. It plays a fundamental role in plant growth and development and influences the source-sink relationship and the distribution of assimilates within the plant (Filgueira, 2008).

For this reason, nitrogen fertilization has been extensively studied in coriander because it promotes vegetative development and increases leaf biomass, directly contributing to higher yields and improved final product quality (Cerqueira et al., 2016; Pinto et al., 2018). Furthermore, strategies such as fertigation, particularly when combined with localized drip irrigation systems, contribute to more efficient nutrient use (Cunha et al., 2023). When coupled with appropriate cultivar selection and proper plant spatial arrangement, these practices enhance crop productivity (Martins et al., 2018).

Consistent with this approach, experimental studies have demonstrated coriander's positive response to nitrogen application. Silva (2022) observed linear increases in yield per square meter, number of bunches, and plant height as N rates increased from 30 to 60, 90, and 120 kg ha⁻¹. Similarly, Oliveira (2003) found a positive linear response in plant height and fresh biomass yield at N rates ranging from 0 to 80 kg ha⁻¹, with the highest values obtained at the highest rate.

In addition to mineral fertilization, other technologies have been incorporated into crop management to optimize production. These include biostimulants, substances capable of promoting plant development through different physiological mechanisms (Du Jardin, 2015). More recently, advances in nanotechnology have enabled the development of nanoparticle-based biostimulants that are more efficient than conventional formulations. These products may enhance nutrient uptake, improve plant tolerance to stress, and increase photosynthetic rates, resulting in greater growth and productivity (Lemos, 2021).

Therefore, considering the importance of nutrient management and the potential of emerging technologies, this study evaluated coriander yield as a function of different nitrogen rates associated with biostimulant sources.

METHODOLOGY

RESEARCH TYPE

This was a quantitative experimental field study conducted under actual cultivation conditions to evaluate the yield of coriander subjected to different nitrogen rates applied through fertigation in combination with foliar biostimulants. The study sought to identify the crop's agronomic response by comparing previously established treatments.

STUDY SITE AND PERIOD

The experiment was conducted in the experimental area of the Federal University of Alagoas (UFAL), Arapiraca Campus, located in the Agreste region of Alagoas State (9°45'09" S, 36°39'40" W, at an elevation of 325 m), from August 31 to October 2, 2022.

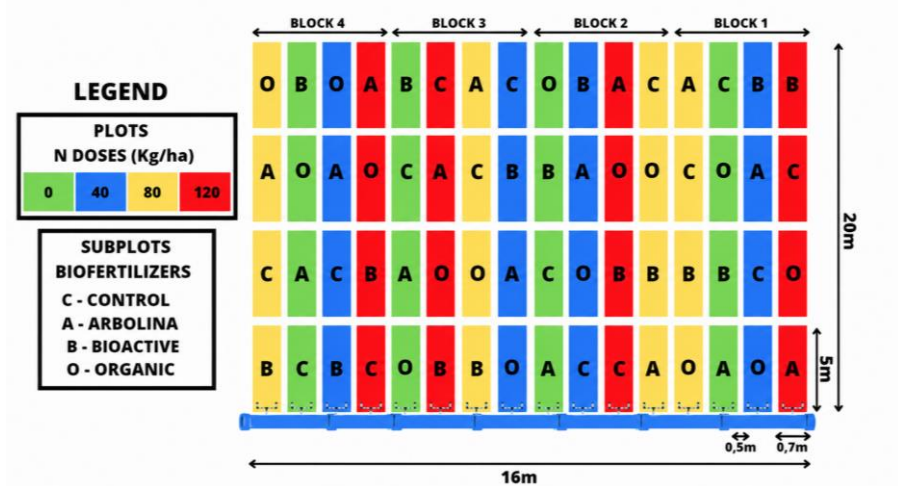
The soil in the region is classified as a nonsaline and nonsodic dystrophic Red-Yellow Latosol, with a medium-to-clayey texture and bulk density (Ds) of 1.48 g cm⁻³. The local climate is classified as tropical "As," with a characteristically dry, hot summer season extending from September to March. December is the driest and hottest month of the year, with an average temperature of approximately 25 °C, although the location has a considerable temperature range. According to Xavier and Dornellas (2012), the region's rainy season generally extends from April to early August, with an average annual precipitation of approximately 854.27 mm year⁻¹.

EXPERIMENTAL DESIGN

The experiment was established using a randomized block design (RBD) in a factorial split-plot arrangement with four blocks, distributed over an area of 320 m². It consisted of 16 beds measuring 0.7 × 5 m in width and length, respectively. Each bed represented one plot and was divided into four subplots. Each bed consisted of two sets of paired rows, totaling four plant rows. The spacing used was 10 cm between individual rows and 20 cm between paired rows (Figure 1). The usable area of each subplot

consisted of the plants in the central paired rows, corresponding to 50 cm of each central individual row, with the plants at the ends excluded to avoid possible border effects.

Figure 1
Layout of the experimental area.



Source: Authors, 2023.

The treatments consisted of four nitrogen rates (0, 40, 80, and 120 kg ha⁻¹), using urea as the source and applying it as topdressing. According to the recommendation manual of the Agronomic Institute of Pernambuco (Instituto Agrônômico de Pernambuco—IPA), the recommended N rate for the crop is 40 kg ha⁻¹. Three foliar biofertilizers, Arbolin, Bioative, and Organo Top Grap, as well as a control treatment, were also used, totaling 16 treatments.

EXPERIMENTAL TECHNIQUES AND PROCEDURES

The area was cleared and demarcated, after which the beds were prepared using string, wooden stakes, measuring tapes, hoes, and rakes.

Localized drip irrigation was used. The system consisted of an 18-m-long, 32-mm mainline supplying 16 lateral lines spaced 0.70 m apart. Each lateral line was subdivided into two 20-m-long drip tapes spaced 0.30 m apart, with 0.20 m between emitters and an average flow rate of 2.1 L h⁻¹. A distribution uniformity coefficient (DUC) test was performed, yielding a value of 92.27%, which was

considered excellent. Irrigation was performed daily, and the net irrigation depth was determined according to crop evapotranspiration (ETc), calculated using Equation 1:

$$Etc = Eto \times Kc \quad (1)$$

Where:

ETc = crop evapotranspiration;

ETo = reference evapotranspiration;

Kc = crop coefficient.

Reference evapotranspiration was estimated using the Hargreaves-Samani method. A Kc value of 1 was used because no specific value had been established for coriander; therefore, the tabulated value for lettuce, another leafy vegetable, was adopted. The climatic data used to determine the daily net irrigation depth were obtained from a small weather station installed beside the experimental area.

Soil fertility in the experimental area was analyzed to guide the fertilization recommendation. The results are presented in Table 1.

Table 1

Soil fertility analysis results for the experimental area, Arapiraca, Alagoas, 2023.

Parameters						
	pH	P	K	Sum of bases (SB)	H+Al	Cation-exchange capacity (CEC)
	H ₂ O	ppm	ppm	mmol/dm ³	meq/100mL	mmol/dm ³
Results	6.7	53	167	4.75	1.87	4.87
						Base saturati on (V) %
						73.6

Source: Authors, 2023.

Basal fertilization consisted of an N-P-K formulation in the proportions 20-00-20 plus 19% single superphosphate. Accordingly, 150 kg ha⁻¹ of urea, 150 kg ha⁻¹ of KCl, and 315.78 kg ha⁻¹ of single superphosphate were applied in accordance with the IPA fertilization recommendation for coriander. The

fertilizer was manually distributed per linear meter of bed and then incorporated and mixed into the soil using rakes.

For sowing, two planting furrows 4 cm deep were opened 5 cm from each drip tape, totaling four furrows per bed and thereby forming paired rows. Seeds of the Verdão cultivar were manually distributed in the furrows. Planting density was determined according to the weight of the diachenes, corresponding to 1.5 g m^{-1} , which were distributed uniformly across the plots.

Nitrogen was applied as topdressing through fertigation, using urea containing 46% N and a Venturi injector. Applications began 12 days after sowing. For each application, the urea was dissolved in 5 L of water according to the following fertigation quantities: control, $0 \text{ kg ha}^{-1} \text{ N}$; 118.3 g, $40 \text{ kg ha}^{-1} \text{ N}$; 236 g, $80 \text{ kg ha}^{-1} \text{ N}$; and 355 g, $120 \text{ kg ha}^{-1} \text{ N}$. Six applications were performed during the crop cycle, with each quantity applied twice weekly until harvest at 32 days after sowing (DAS).

Foliar products were applied one day after the first weekly fertigation application. A manual sprayer with a flow rate of 2.67 mL s^{-1} and a capacity of up to 12 L was used. However, only 2 L of spray solution was used to treat 80 m^2 . The respective rate of each product was added separately in accordance with its label instructions, resulting in the following quantities per application: 0.82 mL of Arbolin, 2 mL of Bioative, and 4 mL of Organo Top Grap.

Weeds were controlled manually whenever necessary to prevent competition for water, light, and nutrients, which could impair the development of the main crop, coriander.

DATA-COLLECTION TECHNIQUES AND INSTRUMENTS

The crop was harvested at 32 DAS, when the plants had visibly reached their maximum vegetative development and exhibited desirable commercial characteristics, such as appropriate height and intense color.

After harvesting, the plants selected for evaluation were placed in polyethylene trays and taken for agronomic assessment. Evaluations were performed immediately after harvest, always following

chronological order within the blocks and plots. The variables evaluated were chlorophyll B (CLOB), yield per hectare (YIELDha), total fresh weight (TFW), root fresh weight (RFW), stem dry weight (SDW), root length (RL), and number of plants per linear meter (NPLANT). A precision balance accurate to 0.001 g was used for all variables requiring the weighing of fresh or dry matter.

The variables were measured as follows:

- CLOB: Measured using a ClorofiLOG electronic chlorophyll content meter. The mean was calculated from 20 measurements taken in each subplot.
- YIELDha: Estimated from the weight of all whole fresh plants, including leaves, roots, and stems, harvested from one linear meter.
- TFW: From all plants harvested within one linear meter, 20 plants were randomly selected and weighed fresh and whole, including leaves, stems, and roots, using a digital balance accurate to two decimal places.
- RFW: The roots of the 20 selected plants were detached and weighed fresh using a digital balance accurate to two decimal places.
- SDW: The stems of the 20 selected plants were separated from the leaflets and roots, weighed, oven-dried at 62 °C for 48 hours, and weighed again using a digital balance.
- RL: After the roots had been detached from the 20 selected plants, the length of each root was measured with a measuring tape positioned from the root tip to the root collar.
- NPLANT: All plants within the harvested linear meter were counted.

STATISTICAL DATA ANALYSIS

The data were subjected to analysis of variance, and significance was assessed using the F-test. For significant variables, means were compared using Tukey's test at the 5% probability level, while the quantitative factor was subjected to regression analysis using Sisvar software.

During the preparation of this study, ChatGPT was used as an auxiliary tool to support the translation of passages and identify possible spelling errors. Its use was limited to linguistic matters and did not interfere with data analysis, interpretation of the results, or the study's conclusions. The authors assume full responsibility for all scientific content.

RESULTS AND DISCUSSION

There was no significant interaction between nitrogen rates and foliar biofertilizers for the variables analyzed. Nitrogen rates had a significant effect at the 1% probability level on chlorophyll B, yield per hectare, and total fresh weight, and at the 5% level on stem dry weight. Root fresh weight, root length, and number of plants per linear meter did not differ significantly. The isolated application of foliar biofertilizers did not significantly affect any of the variables analyzed in the experiment (Table 2).

Table 2

Analysis of variance for chlorophyll B (CLOB), yield per hectare (YIELDha⁻¹), total fresh weight (TFW), root fresh weight (RFW), stem dry weight (SDW), root length (RL), and number of plants per linear meter (NPLANT) in coriander grown under different nitrogen rates and foliar biofertilizer treatments.

Source of variation	d f	MS						
		CLOB	YIELDha ⁻¹	TFW	RFW	SDW	RL	NPLANT
Nitrogen (N)	3	12,323**	238686666,6**	21,866**	0,068 ^{ns}	0,02*	4,622 ^{ns}	2014,43 ^{ns}
Block	3	0,018 ^{ns}	27866666,6 ^{ns}	2,233 ^{ns}	0,039 ^{ns}	0,002 ^{ns}	6,615 ^{ns}	912,68 ^{ns}
Residual 1	9	0,28	10011111,1	2,541	0,021	0,004	1,363	1434,62
Foliar biofertilizers (F)	3	0,281 ^{ns}	7653333,3 ^{ns}	0,886 ^{ns}	0,004 ^{ns}	0,001 ^{ns}	1,644 ^{ns}	197,93 ^{ns}
N x F	9	0,193 ^{ns}	6722222,2 ^{ns}	0,268 ^{ns}	0,003 ^{ns}	0,0006 ^{ns}	0,698 ^{ns}	472,87 ^{ns}
Residual 2	3	0,181	5837222,2	0,613	0,003	0,001	0,837	705,68
	6							
CV 1 (%)		8,15	22,44	43,3	50,02	43,58	12,43	35,27
CV 2 (%)		6,56	17,13	21,14	20,31	23,77	9,74	24,74

Note: ** Significant at 1%; * significant at 5%; ns, not significant. Source: Authors, 2023.

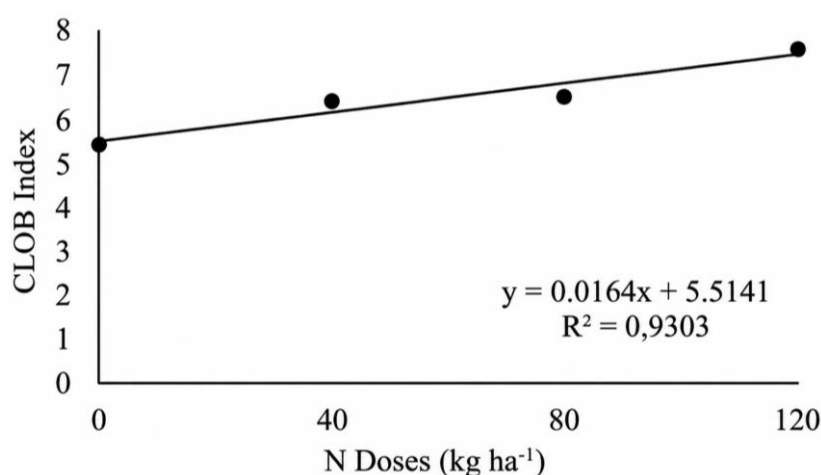
Chlorophyll B content increased as N rates increased. Consequently, chlorophyll B indices increased linearly up to the rate of 120 kg ha⁻¹ N (Figure 2). The index increased by 0.0163 for each

kilogram of nitrogen added to the soil and reached 7.5 at the maximum application rate, representing an increase of 26.1% relative to the control treatment without topdressing, which had a value of 5.53.

The effect of nitrogen fertilization on chlorophyll content can be explained by the fact that, under soil N deficiency, plants degrade chlorophyll molecules to translocate N to areas of active growth (Furlani Júnior et al., 1996). Nitrogen is one of the elements used in chlorophyll synthesis. Chlorophyll content is positively correlated with plant N content and crop yield. This relationship is primarily attributed to the fact that 50% to 70% of total leaf N is found in enzymes associated with chloroplasts (Singh et al., 2010; Reinbothe et al., 2010).

Figure 2

Chlorophyll B indices as a function of different nitrogen rates.



Source: Authors, 2023.

In contrast to the present findings, Silva (2022), when evaluating coriander performance under different nitrogen rates, found no significant effect on chlorophyll content. That study evaluated total chlorophyll using a Delta Vista portable spectrophotometer, whereas the present study used the ClorofiLOG instrument, which can measure chlorophyll A and B contents separately.

According to Muhammad (2022), nitrogen is a structural component of the chlorophyll molecule. An adequate supply of this nutrient therefore significantly increases the crop's chlorophyll index, enhancing its photosynthetic capacity and, consequently, its productivity.

In support of the present findings, Palavicini et al. (2021) evaluated another leafy vegetable, lettuce, under different N rates of 0, 50, 100, 150, and 200 kg ha⁻¹, using urea as the source under greenhouse conditions. For the Mimosa cultivar, the authors observed an increase up to 150 kg ha⁻¹, at which total chlorophyll content reached approximately 16.3 and remained constant at higher rates.

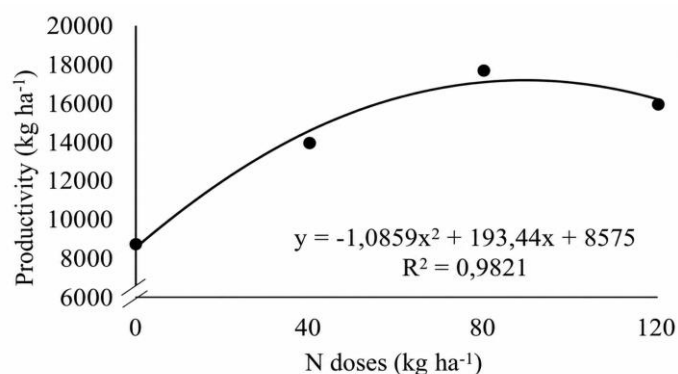
Silva (2016) also evaluated coriander under different N rates of 0, 60, 120, and 180 kg ha⁻¹, with and without thinning, and observed a linear response in the total chlorophyll index. The highest value, 34.4, occurred at the highest rate evaluated, 180 kg ha⁻¹, without thinning. This response was similar to that found in the present study.

Coriander yield per hectare was significantly affected by changes in N rates and exhibited a quadratic response. The highest yield, 17,189.75 kg ha⁻¹, or approximately 17 metric tons, was obtained with the application of 89.07 kg ha⁻¹ N. This indicates that higher rates do not produce additional yield gains, as demonstrated by the rate of 120 kg ha⁻¹ evaluated in this study, which produced a yield of 16,150.84 kg ha⁻¹. This represented a 1.72% decrease relative to the maximum point, corresponding to 33.59 kg ha⁻¹ of coriander for each kilogram of nitrogen applied to the soil (Figure 3).

Thus, coriander yield increased by 94.5 kg ha⁻¹ for each kilogram of N added to the soil until the rate of 89.07 kg ha⁻¹ was reached. This rate produced the maximum yield and represented a 49% increase compared with the control treatment without topdressing, which yielded 8,767.35 kg ha⁻¹.

Figure 3

Coriander yield in kg ha⁻¹ as a function of different nitrogen rates.



Source: Authors, 2023.

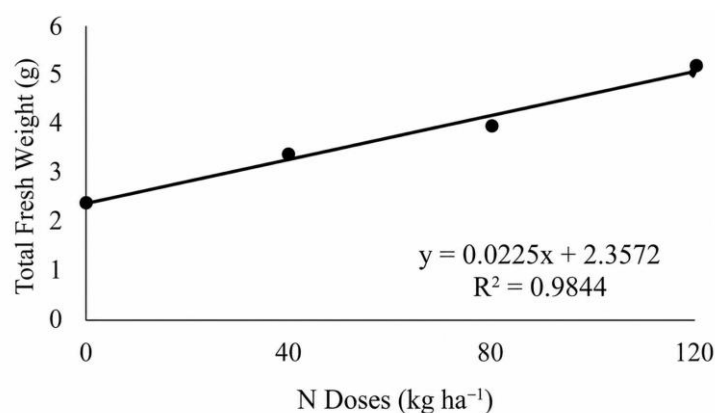
Oliveira et al. (2003), when evaluating coriander yield under increasing N rates, obtained a similar result. Coriander showed its best response at 80 kg ha⁻¹, with a yield of approximately 40,500 kg ha⁻¹, which exceeded the yield obtained in the present study. However, 80 kg ha⁻¹ was the highest rate evaluated by Oliveira et al. (2003); single rows were used, the spacing was wider at 0.25 m between furrows, and cattle manure was the nitrogen source.

Alves et al. (2020) obtained a contrasting result when evaluating different N rates of 0, 75, 150, 225, and 300 kg ha⁻¹ and two N sources, urea and ammonium sulfate, in coriander cultivation. With urea as the source, the maximum response occurred at 166 kg ha⁻¹ N, producing a fresh biomass yield of 9,800 kg ha⁻¹ with 0.25 m between furrows.

Total fresh weight increased as N rates rose. The values therefore increased linearly up to 120 kg ha⁻¹ N, the highest rate evaluated, a response that differed from that of the preceding variable. Fresh weight increased by 0.0223 g for each kilogram of nitrogen added to the soil and reached 5.06 g at the highest rate. This represented a 53% increase compared with the control treatment without topdressing and indicates that rates higher than those evaluated in this study might produce even greater fresh-weight values (Figure 4).

Figure 4

Total fresh weight per plant as a function of different nitrogen rates.



Source: Authors, 2023.

In support of this result, Santos (2021) also found a linear increase in total fresh weight as the nitrogen rate increased. At 120 kg ha⁻¹, total fresh weight reached 2.53 g per plant, representing a 28% increase over the lowest value of 1.81 g per plant. In that study, however, the lowest nitrogen rate evaluated was 30 kg ha⁻¹.

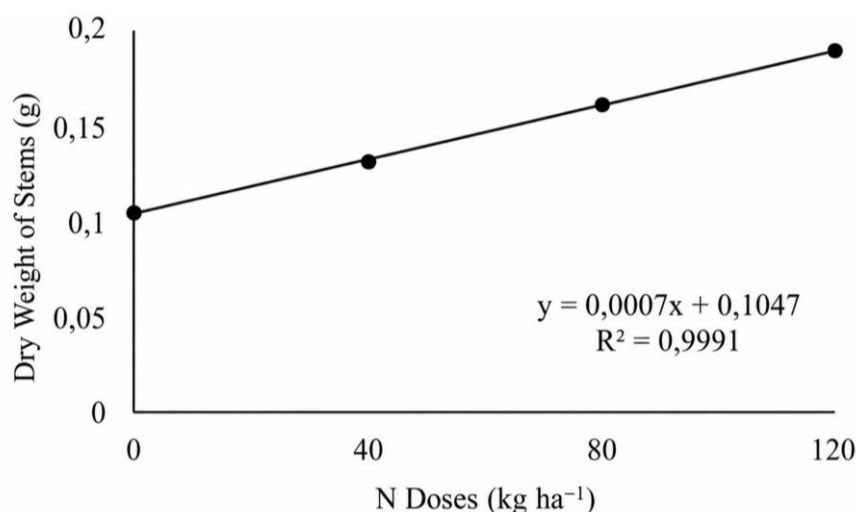
Alves et al. (2020) stated that nitrogen alters the source-sink relationship in plants. In other words, it influences crop growth and development processes and thereby favors the distribution of assimilates between vegetative and reproductive organs. In coriander specifically, nitrogen fertilization has a direct positive effect on leaf volume. Yield potential therefore increases, improving product quality, adding value, and raising the market price.

Silva (2016), when evaluating coriander productivity under N rates of 0, 60, 120, and 180 kg ha⁻¹, with and without thinning, observed that the treatment without thinning and with an optimal N rate of 69.5 kg ha⁻¹ produced a maximum fresh biomass weight of 800 g within the usable experimental area.

Like the preceding variable, stem dry weight increased as N rates rose. Its values increased linearly up to 120 kg ha⁻¹ N, the highest rate evaluated. Stem dry weight increased by 0.00067 g for each kilogram of nitrogen added to the soil and reached 0.19 g at the highest rate. This represented a 42.2% increase compared with the control treatment without topdressing, which produced 0.11 g, indicating that rates higher than those evaluated in this study might produce even higher stem dry-weight values (Figure 5).

Figure 5

Stem dry weight per coriander plant as a function of different nitrogen rates.



Source: Authors, 2023.

Silva (2016) also observed a linear response in stem dry weight when evaluating coriander under N rates of 0, 60, 120, and 180 kg ha⁻¹, with and without thinning. At the highest rate analyzed, 180 kg ha⁻¹ N, the maximum observed value was 9.22 g for 20 plants.

Ferro (2016), when evaluating coriander under different nitrogen fertilization and seeding levels, found the highest stem dry-weight value, 6.6541 g, at the highest fertilizer rate evaluated, 80 kg ha⁻¹, using urea as the N source. This finding supports the results obtained in the present study. Coriander remains severely underexplored in scientific studies and research, making comparisons with a larger body of data difficult.

CONCLUSION

Nitrogen fertilization increases coriander yield. For chlorophyll B, total fresh weight, and stem dry weight, the best-performing N rate was 120 kg ha⁻¹. A topdressing rate of 89.07 kg ha⁻¹ N is the most strongly recommended rate for fertigated coriander because it produces a satisfactory increase in yield per hectare. The use of biostimulants did not affect the agronomic characteristics studied under the soil and climatic conditions in which the experiment was conducted. The results therefore contribute to nitrogen

fertilization management in fertigated coriander by providing information that may support future management recommendations and further research on interactions between nitrogen rates and biostimulants.

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ANALYSIS OF MANAGEMENT AND CONTROL IN SWINE FEED PRODUCTION AT A MILL LOCATED IN THE SOUTH-CENTRAL REGION OF PARANÁ¹

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Abstract

This study addresses the importance of management accounting and benchmarking in the management of a swine feed mill located in the South-Central region of Paraná, an industry of considerable importance to Brazilian agribusiness. Its primary objective is to identify and analyze the accounting techniques used to control the mill and its production, thereby promoting operational efficiency and effective inventory control. Using a descriptive methodology, the study involved a literature review and field data collection through interviews and direct observation. The results indicate that management accounting supports strategic planning and inventory control, while benchmarking enables the assessment and introduction of process improvements. The study identified deficiencies in input traceability and control processes that affect efficiency and costs, and recommended automation measures to streamline the production flow. Implementing these accounting practices has the potential to reduce resource waste, thereby increasing the mill's competitiveness. The study concludes that management focused on the early identification of

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problems, based on management accounting and benchmarking, is indispensable for continuous improvement in the swine feed production industry.

Keywords: Benchmarking, Inventory control, Management accounting, Operational efficiency, Production management.

INTRODUCTION

Agribusiness plays a prominent role in the global economy and is one of the pillars of food security and economic development. In Brazil, its relevance is even greater, as the country is the world's third-largest exporter of agricultural products (CNA, 2023).

Among the various agribusiness segments, swine farming stands out for its significant contribution to the domestic market and its substantial presence internationally. Following the records achieved in 2023, Brazil consolidated its position as the world's fourth-largest pork producer, demonstrating the strength of the country's agribusiness in the global market (ABPA, 2024).

Paraná plays a major role in agribusiness. It is one of Brazil's leading producing states and the country's largest producer of poultry and pork, as well as its second-largest producer of soybeans and corn, which are essential feed ingredients (AEN, 2023).

Industrial feed production is increasing steadily due to the annual growth in demand from swine farming. According to the Brazilian Animal Protein Association (Associação Brasileira de Proteína Animal—ABPA), national pork production reached a record 5.16 million metric tons in 2023, corresponding to 4% of global production and positioning Brazil as the world's fourth-largest producer, behind China, the European Union, and the United States. In September 2024, 120,400 metric tons of pork were exported, exceeding expectations and favorably positioning the country for continued growth in the ranking.

Of the total produced in Brazil, 75% is consumed domestically, while the remainder is exported. The continued growth in demand from swine farming generates a greater need to produce feed for these

animals. From this perspective, management accounting and benchmarking are important tools for controlling and managing these production facilities (Agência Estadual de Notícias, 2023).

According to Garrison (2013), management accounting is related to activities such as control, planning, and decision-making. Planning involves establishing specific objectives to be achieved, whereas control involves ensuring that actions are properly implemented and positively adjusted as circumstances change.

Within this context of constant advancement, feed mills must continually seek to improve their control and management methods, particularly to increase production and maintain adequate control over the areas involved.

It is essential to emphasize the importance of inventory measurement, considering that the investment involved is significant and represents a substantial portion of costs. Adequate planning is therefore necessary to make purchases efficiently and assess whether inventory is appropriate for effective management (Martins, 2000).

The examples above demonstrate that this business segment has undergone major changes, including significant adjustments to its internal processes, whether in planning, management, measurement, or the interpretation of results.

Against this background, the following research question was adopted: How can management accounting and the accounting practice of benchmarking be used in the management of a feed mill, and what are the positive effects of their implementation?

This study is justified by the growing need to develop effective control and management methods that can be adopted by a medium-sized swine feed mill. Such facilities face considerable challenges arising from the pursuit of higher financial returns and the need to prevent avoidable losses during the production process.

From this perspective, the investigation is also justified by the growing need for effective management control capable of enabling a more detailed analysis and specifying the costs and expenses

incurred during the period analyzed. Such control is essential to financial and operational efficiency and, consequently, to success in the market. Moreover, more effective management provides a solid basis for strategic decision-making, minimizing waste and maximizing the use of resources. This study provides information on improvements that may be applied to enhance management, particularly in swine feed production, while addressing the challenges facing this industry.

Based on the general objective of this study, the principal management accounting techniques and practices used in the management and production processes of a swine feed mill located in the South-Central region of Paraná were identified and analyzed.

More specifically, the study identified the accounting tools and practices employed in managing the mill, highlighted the use of benchmarking in management accounting to provide more relevant and accessible information, and examined, from the manager's perspective, whether these practices were being properly applied to the mill's control and management.

To achieve these objectives, methods and procedures were applied to analyze the management and control of swine feed production at a mill located in the South-Central region of Paraná.

This research was classified as descriptive because it sought to observe, record, and analyze the data in depth, thereby contributing to a clearer understanding of the subject. Regarding its procedures, the study was bibliographic and drew on renowned and reliable sources to provide an appropriate perspective (Marconi; Lakatos, 2017).

The study population encompassed all swine feed mills located in the South-Central region of Paraná. The selected sample consisted of one specific swine feed mill in this region, chosen because of the availability of information and the application of management accounting techniques in its processes.

Data were collected through semi-structured interviews, observations in the production and inventory areas, and an analysis of the mill's inventory control tools.

DEVELOPMENT

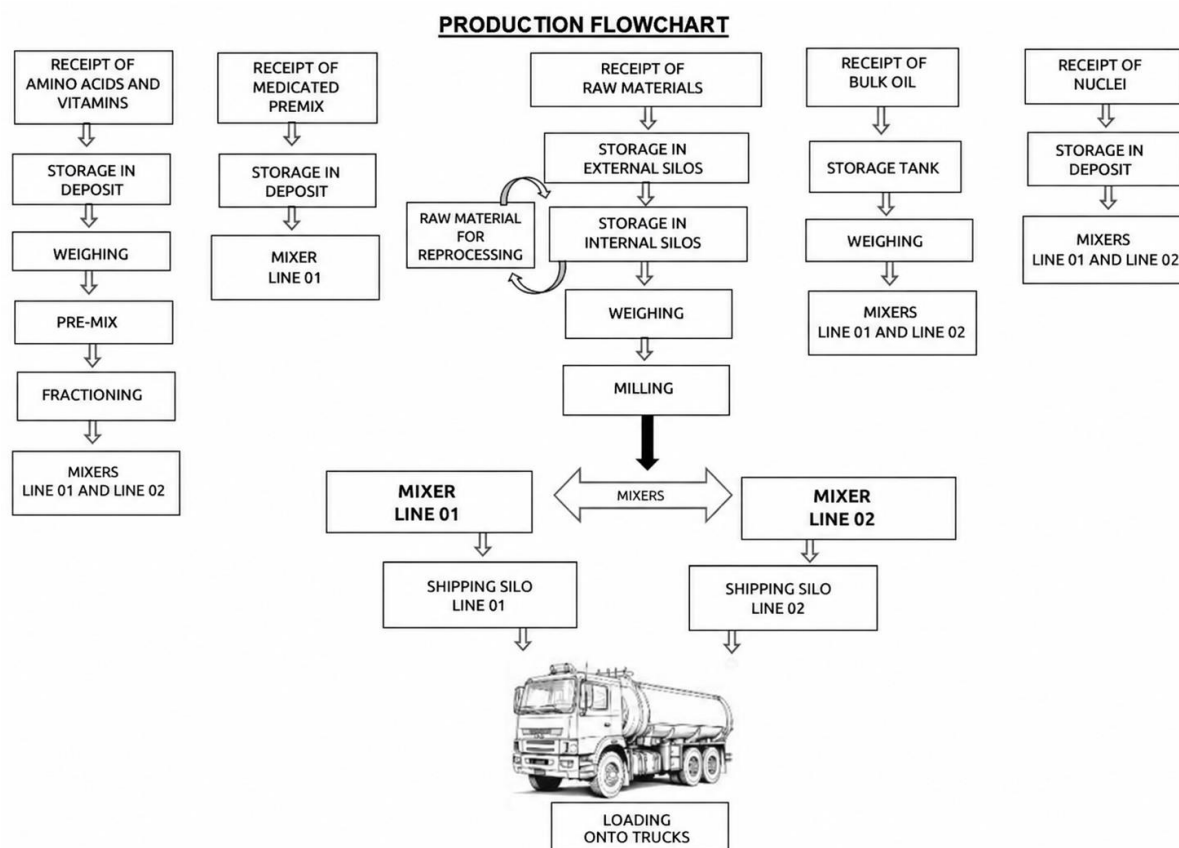
This section seeks to present and examine the methods and procedures used to analyze the management and control of swine feed production at the mill located in the South-Central region of Paraná. It reviews the literature related to the subject of the study and describes the methodology and the data collected. The results are then analyzed, focusing on the principal techniques and practices identified in the research. Finally, the findings are critically examined in relation to the study objectives, and recommendations are proposed for future management practices at the mill.

To obtain the data, particular attention was given to how the mill organizes its internal processes. It should be noted that the mill has been undergoing major changes since July 2024 as a result of improvements suggested by the Ministry of Agriculture and Livestock (Ministério da Agricultura e Pecuária—MAPA), which have contributed to a significant reorganization (Ministério da Agricultura e Pecuária, 2024).

The production flowchart illustrates the current state of the processes and incorporates the changes implemented to make them easier for employees to locate and understand. These processes are continuously updated, and new methods are being implemented to improve efficiency and performance. Figure 01 therefore presents the processes from the receipt of materials through the loading of the finished product for delivery to its destination.

Figure 01

Current Flowchart of the Production Process at the Mill Analyzed.



Source: Authors (2024).

Based on this process mapping, the study revealed the difficulty of maintaining effective inventory control because of the multiple interactions and changes involving order logistics, receipt, and production. Inadequate inventory measurement may result in high and unnecessary expenditures.

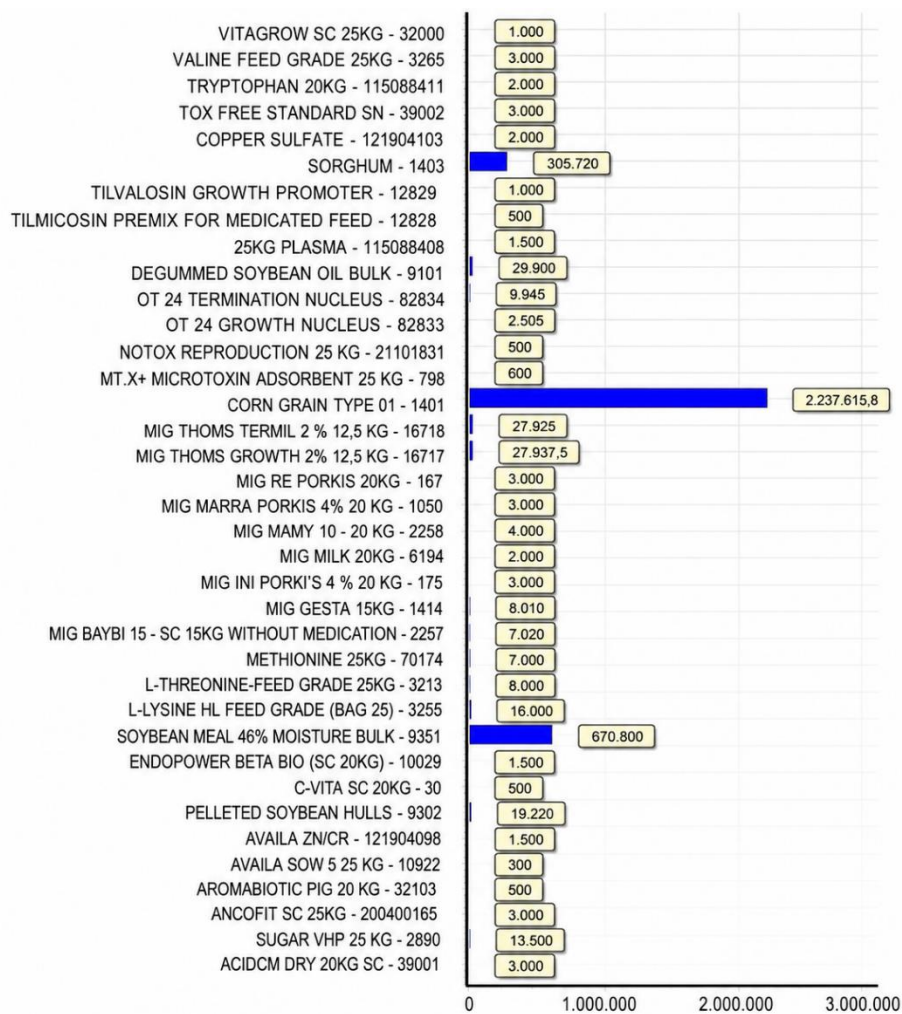
These problems initially arise in the internal control software, where unrecorded physical errors may cause discrepancies between system-recorded and physical inventory. It should also be noted that, in several situations, products are received and sent directly to production, resulting in errors that compromise the quality of the final product.

Management accounting is essential to the control and management of companies in various industries, including, in this case, a feed mill. It provides detailed and relevant information that allows managers to make decisions aimed at optimizing production processes.

The use of accounting tools can help identify and eliminate inefficiencies, improve inventory control, and ensure the quality of the final products. More effective traceability and production-batch monitoring can be incorporated into the existing system, enabling discrepancies between system-recorded and physical inventory to be corrected.

Because of the intense flow involved in receiving various raw materials, as shown in Figure 02, most of which are microingredients, particular attention is given to vegetable oil, soybean meal, corn, and other items whose availability varies according to the seasons and crop cycles. Components such as sorghum may improve feed efficiency.

Figure 02
Quality of Raw Materials Received, October 2024.



Source: Adapted from Siga Fran (2024); translated for clarity.

Benchmarking is a technique used in the marketplace to compare an organization's practices with the practices and trends of more advanced companies. This comparison makes it possible to identify areas that can be reviewed to improve performance across all departments. According to Belo (2022), by learning from industry best practices, companies can increase their competitiveness and capacity for innovation through benchmarking.

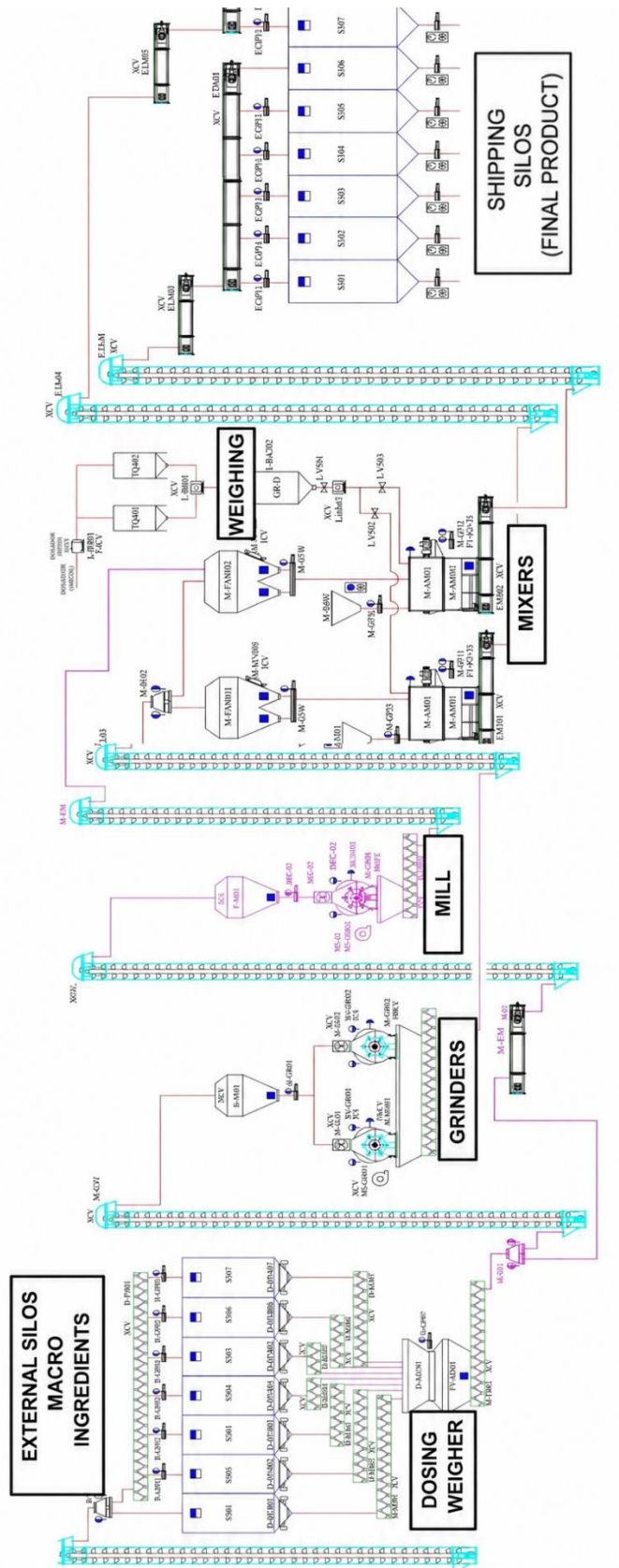
Bulk feed involves a set of specifications and differences. Before loading, it undergoes several processes, many of which are slow, resulting in less effective production that is insufficient to meet the requirements of a full day. Production operates with a minimum safety margin equivalent to half a day, and the schedule is adjusted according to the needs of the main producers.

The slowest stages of the process are micronutrient separation and weighing, which are currently performed manually. Silos and automated scales could be integrated into the same system, which would accelerate the process, reduce the margin of error, and improve working conditions for employees.

In addition to the suggested changes, the dosing of the macronutrients and liquids included in the final product should also be highlighted. The mill currently has automated scales that perform dosing for two production lines. Based on estimation studies already conducted, increasing the number of scales so that each line has its own dosing system could optimize production and increase output by more than 50%.

Figure 03 shows that the two lines remain separate only after grinding, although they are interconnected at the liquid-dosing scale before the process is completed. The figure provides an understanding of the entire process through the functions offered by the system.

Figure 03
Internal System.



Source: Adapted from Siga Fran (2024); translated for clarity.

Controlling feed-quality criteria is difficult because traceability is ineffective without the necessary supervision. Owing to inventory discrepancies, the batches used in the processes are not properly monitored.

The continued failure to update prices also makes feed pricing difficult. Although the costs of energy, labor, and other processes are established, the prices of amino acids, premixes, supplements, and vitamins are not updated. Despite representing only a small proportion of the feed composition, these are the most expensive components and may cost as much as one hundred Brazilian reais per kilogram.

The study found that some functions of the system used by the mill are underutilized, resulting in inefficiencies in processes that could otherwise be simpler and more agile. Production deficiencies that could be addressed were also identified, which would lead to greater efficiency and better use of the available resources.

The limited management accounting practices already in use have helped maximize the use of existing functions, while benchmarking has supported the effective analysis and introduction of new functions within the current system. The objective is to identify and address production deficiencies, thereby increasing efficiency and improving the use of available resources.

From the manager's perspective, management accounting and benchmarking are essential to optimizing processes and identifying areas for improvement. From this standpoint, the mill faces challenges in inventory control and in the operational area of bulk-feed production because the system's functions are used only superficially, contributing to outdated input prices.

FINAL CONSIDERATIONS

This study demonstrated the importance of management accounting and benchmarking in improving the internal processes of a swine feed mill. The analyses showed that properly applying these practices can lead to significant production optimization and effective inventory control.

Management accounting proved essential to providing accurate and relevant information, thereby enabling managers to make sound decisions and implement significant strategic improvements. Its integration with the system enhanced the use of production-batch traceability techniques and supported the correction of inventory discrepancies.

Benchmarking practices are essential to the continuous improvement of organizations because they enable improvements to be identified and implemented on the basis of systematic and rigorous comparisons. The principal benchmarking practices and their descriptions include the following:

- **Performance Indicators:** involve measuring and comparing internal processes to assess operational effectiveness and identify areas for improvement;
- **Process Analysis:** consists of reviewing and comparing operational processes to identify potential improvements and optimizations that may be adopted;
- **Market Research:** refers to analyzing competitors and market trends while continually seeking new methods and improvements to existing methods in order to remain competitive;
- **Best-Practice Mapping:** involves identifying the most effective practices used by other companies so that they may be adapted and implemented within the organization;
- **Balanced Scorecard:** involves using a balanced set of indicators to assess organizational performance, providing a broad and balanced view of results;
- **Functional Benchmarking:** focuses on comparing processes and functions within the company itself in pursuit of continuous improvement and operational efficiency.

Benchmarking stood out as an essential methodology for identifying and implementing the best practices suited to each department, revealing areas for improvement that increased competitiveness and operational efficiency.

Challenges involving inventory control and production were addressed through internal improvements and process reviews, resulting in more efficient production and better use of existing resources.

This study confirms the need for proactive and well-informed management that uses management accounting and benchmarking as pillars of growth and operational excellence at this swine feed mill located in the South-Central region of Paraná.

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ENERGY TRANSITION AND RARE EARTH ELEMENTS: CHALLENGES, OPPORTUNITIES, AND PROSPECTS

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Abstract

The global energy transition requires significant advances in the efficiency, power density, and reliability of electromechanical systems. In this context, rare earth metals play a strategic role in the manufacture of high-performance electrical machines, such as permanent magnet synchronous motors (PMSMs) and wind generators. This study aims to analyze the influence of these materials on the electromagnetic performance of modern electrical machines. The methodology is based on a systematic literature review involving the analysis of publications issued between 2018 and 2025 and indexed in databases such as Scopus, ScienceDirect, and IEEE Xplore, complemented by mathematical modeling. Recent data indicate that global demand for rare earth elements increased from approximately 78 kt in 2021 to about 93 kt in 2023 and is projected to reach 134 kt by 2030 (IEA, 2024). The results show that NdFeB magnets can increase torque density by up to twofold and reduce electrical losses by approximately 40%. It is concluded that these materials are essential to the energy transition, although they pose challenges related to the geographic concentration of production and supply-chain risks.

Keywords: Energy efficiency, Energy transition, Electrical machines, Power density, Rare earth elements.

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INTRODUCTION

The global energy transition has driven changes in electricity generation and use systems, requiring technologies that are more efficient, compact, and sustainable. In this context, Electrical Engineering plays a fundamental role in the development of high-performance electrical machines, renewable generation systems, and advanced electromagnetic devices (Alves; Silva, 2022).

Among these technological advances, particular attention should be given to the use of magnetic materials such as neodymium and dysprosium in highly efficient electric motors and wind generators. These materials provide greater power density, reduced losses, and improved energy efficiency in these systems (Barbosa; Souza, 2022; Ferreira; Lima, 2022).

However, the growing dependence on these metals poses challenges related to their availability, geographic concentration, and the environmental impacts of their extraction. These elements are regarded as critical and strategic minerals for technological development and the energy security of several countries (Costa; Pereira, 2021; Silva; Almeida, 2023). International reports also indicate that demand is likely to grow over the coming decades, driven by the expansion of electric vehicles and renewable energy generation systems (IEA, 2023; USGS, 2024).

In Brazil, its mineral and energy potential places the country in a strategic position within the global supply chain for these resources. Official documents emphasize the need to integrate mineral and energy policies in order to promote sustainable development and national technological competitiveness (Brazil, 2020; EPE, 2023; IBRAM, 2022).

Against this background, there is a need for a deeper understanding of the role these minerals play in Electrical Engineering, particularly with regard to the performance and efficiency of modern electrical machines. Accordingly, this study seeks to answer the following research question: **What is the impact of using rare earth materials on the performance and efficiency of electromechanical systems employed in the energy transition?**

The general objective is to analyze the importance of rare earth mineral elements in the development of highly efficient electrical technologies, with an emphasis on electrical machines and energy conversion systems. To this end, technical, economic, and strategic aspects related to the use of these materials will be examined on the basis of a structured literature review.

In this context, integrating technological analysis and mathematical modeling is essential to understanding their contribution to the optimization of energy conversion systems and the development of sustainable energy solutions.

THEORETICAL FRAMEWORK

The global energy transition has driven structural changes in energy generation, conversion, and consumption systems, requiring solutions that offer greater efficiency, reliability, and sustainability. In this context, electrical engineering plays a strategic role in the development of efficient electrical machines, renewable energy systems, and high-performance electromagnetic devices, all of which are essential to the decarbonization of the global energy mix (Alves; Silva, 2022).

According to the International Energy Agency (IEA, 2023), the expansion of electric vehicles, wind turbines, photovoltaic systems, and energy storage has increased demand for critical minerals. These materials are highly strategic because of their superior magnetic, thermal, and electrochemical properties, which make them indispensable in advanced technological applications.

These elements, particularly neodymium (Nd), praseodymium (Pr), dysprosium (Dy), and terbium (Tb), are widely used in the manufacture of high-performance permanent magnets, such as neodymium-iron-boron (NdFeB) magnets, which are employed in permanent magnet synchronous motors (PMSMs) and highly efficient wind generators (Barbosa; Souza, 2022; Ferreira; Lima, 2022).

According to Li, Zhao, and Wang (2021), rare earth permanent magnets increase magnetic flux density, enabling the construction of more compact electrical machines without compromising

performance. This results in greater torque density, reduced copper and iron losses, and higher overall efficiency, with power density potentially reaching twice that of conventional induction machines.

The performance of these machines can be analyzed using the dq model, which is widely employed to represent permanent magnet synchronous machines. This model makes it possible to evaluate magnetic flux, electromagnetic torque, armature current, and electrical losses and serves as a basis for comparing different machine technologies (Ferreira; Lima, 2022).

The mathematical model of the electromagnetic torque of a synchronous machine, particularly a PMSM, in the dq reference frame is used to calculate and control motor torque on the basis of the d- and q-axis currents. One of the most important equations in modern motor control is Equation (1):

$$T_e = \frac{3}{2}p[\lambda_f i_q + (L_d - L_q)i_d \cdot i_q] \quad (1)$$

In electrical machines with permanent magnets, the $\frac{T_e}{I} \propto \lambda_f$ term increases torque per ampere and reduces the operating current, thereby decreasing Joule-effect losses and increasing the machine's energy efficiency (Santos; Oliveira; Ferreira, 2021; Almeida; Souza; Barbosa, 2023). Thus, the permanent magnetic flux generated by the magnets contributes to greater torque and operating efficiency, which is particularly important in renewable energy generation applications.

According to Martins and Oliveira (2021), the energy efficiency of electric motors is one of the pillars of the industrial energy transition, as these devices account for a significant share of global electricity consumption. In this context, replacing conventional motors with permanent magnet machines reduces energy losses and improves the power factor, thereby contributing to greater operational sustainability.

Permanent magnet synchronous machines (PMSMs) exhibit higher torque density than induction machines (IMs) across the entire speed range. At low rotational speeds, PMSMs reach approximately 50

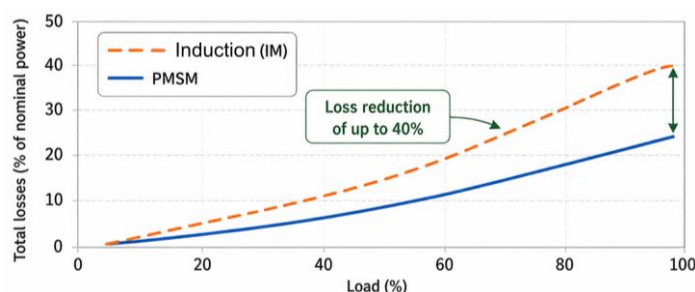
N·m/kg, whereas induction machines remain close to 20 N·m/kg, demonstrating performance up to twice as high. This is possible only because of the use of rare earth permanent magnets (Zhu; Howe, 2023).

The technical superiority of permanent magnet synchronous motors (PMSMs) over induction motors (IMs) is demonstrated by their high efficiency under different load conditions. According to Silva and Silva (2021), whereas induction motors frequently operate at efficiencies below 90%, PMSM technology reaches approximately 95%, providing a substantial performance advantage.

This operational advantage primarily results from the elimination of Joule-effect losses in the rotor and the optimization of magnetic flux provided by the magnets (Almeida; Santos, 2023). In addition, comparative studies indicate that total losses in PMSMs may be up to 40% lower than in induction motors, resulting in significantly better power utilization and greater energy sustainability (Oliveira, 2022), as shown in Figure 1.

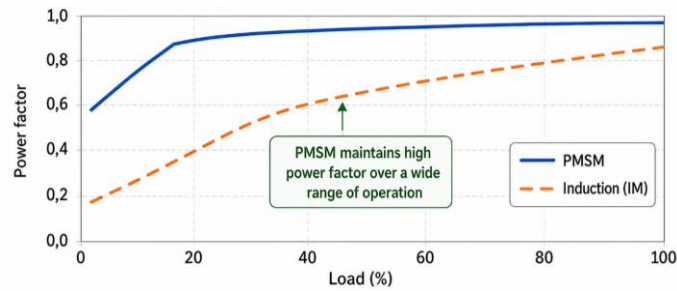
Figure 1

Total losses versus load



Source: Zhu, Z. Q.; Howe, D. 2023.

With regard to lower losses, PMSMs exhibit lower total losses than induction machines (IMs) across the entire load range. Whereas losses in an induction machine may reach approximately 40%, those of a PMSM remain close to 25%, representing a reduction of up to 40% and greater energy efficiency, as shown in Figure 2.

Figure 2*Power factor versus load*

Source: Zhu, Z. Q.; Howe, D. 2023.

According to the comparison, PMSMs offer up to twice the torque density for the same weight and volume and are three to seven percentage points more efficient over most of the load range. Their losses are reduced by up to 40%, resulting in less heating and a longer service life. In terms of power factor, they maintain a high power factor, greater than 0.9, even under partial loads.

In addition to their technical benefits, the use of rare earth elements has a significant geopolitical and economic dimension. Costa and Pereira (2021) emphasize that these elements are classified as strategic minerals because their production is highly concentrated in a small number of countries, particularly China, which dominates much of the global extraction, processing, and refining chain. This concentration creates vulnerabilities in the international supply system and risks associated with energy security.

Silva and Almeida (2023) further maintain that technological dependence on these minerals requires integrated public policies across the mineral, energy, and industrial sectors, particularly in countries with significant geological potential, such as Brazil. The country possesses substantial rare earth reserves and may assume a strategic position in global supply, provided that investments are made in research, mineral processing, and technological value addition.

Brazilian energy planning, through the National Energy Plan 2050 (*Plano Nacional de Energia 2050*), classifies critical minerals as fundamental to industrial competitiveness and the energy transition (Brazil, 2020). According to Rocha, Mendes, and Farias (2024), sectors such as electric mobility and offshore wind power are increasing demand for magnetic materials, requiring the strengthening of the

national production chain. In addition, magnet recycling has emerged as a strategic solution for mitigating external dependence and reducing environmental damage (Oliveira; Santos, 2025).

From an environmental perspective, the extraction and processing of rare earth elements also present significant challenges. The United States Geological Survey (2024) emphasizes that mining these elements can produce substantial impacts related to water consumption, waste generation, and chemical contamination, requiring more sustainable practices and stringent regulation. Technological progress must therefore be accompanied by environmental responsibility and the development of cleaner production processes.

Santos and Carvalho (2022) emphasize that advanced magnetic materials will continue to shape the future of electrical engineering, particularly in intelligent energy conversion systems, more efficient power grids, and new distributed-generation architectures. Rare earth elements have therefore become established not only as strategic mineral resources but also as central components of technological innovation in the electricity sector.

It can therefore be observed that the relationship among rare earth elements, electrical machines, and the energy transition extends beyond a purely technical dimension and encompasses economic, geopolitical, environmental, and industrial considerations. An integrated understanding of these factors is essential to the development of sustainable solutions and the strengthening of Brazil's technological competitiveness in the international arena.

The growing integration of intermittent renewable sources, such as wind and solar power, requires more robust and stable electromechanical conversion systems. In this context, permanent magnet synchronous generators stand out because they offer greater reliability, efficiency at variable speeds, and lower maintenance requirements. According to Barbosa and Souza (2022), these advantages result from the use of rare earth magnets, which provide superior magnetic flux density and a more effective dynamic system response.

Another relevant aspect concerns the advancement of electric mobility, particularly in the automotive sector, in which energy efficiency and reductions in the mass of propulsion systems are decisive factors in determining the range of electric vehicles. According to the International Energy Agency, growth in the global electric vehicle fleet directly increases demand for rare earth elements, thereby reinforcing the strategic importance of these elements to the industrial and energy sectors (IEA, 2023).

In academic research, efforts are being made to reduce dependence on critical materials and mitigate price volatility through the development of alternative materials. Recent studies have explored hybrid alloys, advanced ferrites, and electromagnetic optimization to maintain efficiency while reducing the use of rare earth elements. Despite these advances, however, NdFeB magnets remain the benchmark for high-power and technically demanding applications, particularly in the industrial and renewable energy sectors (Santos; Carvalho, 2022).

The selection of materials for magnetic circuits is based on an analysis of energy density, in which rare earth magnets, particularly NdFeB magnets, significantly outperform traditional materials. Whereas ferrite has a low energy product, technological developments in NdFeB have made it possible to achieve high levels of remanence and coercivity (Nunes, 2023). This technical superiority is the determining factor in motor miniaturization and the feasibility of highly efficient generators.

Table 1
Typical magnetic properties of materials used in electrical machines

Magnetic material	Remanence Br (T)	Coercivity Hc (kA/m)	(BH)max (kJ/m³)
Ferrite	0,38 – 0,42	200 - 300	26 - 40
AlNiCo	0,6 – 1,2	50 - 100	40 - 88
SmCo	0,9 – 1,1	600 - 2000	120 - 200
NdFeB	1,1 – 1,4	800 - 3000	200 - 440

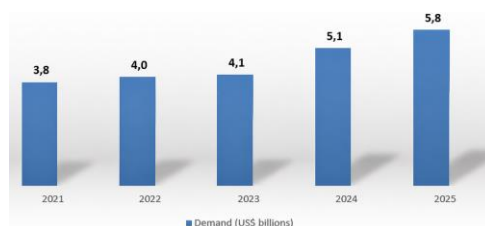
Source: Nunes, 2023.

Figure 3 illustrates the projected growth, in billions of US dollars (US\$), of demand for rare earth elements in the context of the energy transition, demonstrating the strong correlation between the

advancement of clean technologies and the increasing use of these mineral resources. A trend of continuous growth can be observed, driven particularly by the electric mobility and renewable energy generation sectors. This reinforces the need for studies focusing on the efficient use of these materials and the development of technological alternatives.

Figure 3

Demand for rare earth elements in US\$ billions



Source: IBGE, 2025.

The increase in demand reflects the extensive application of rare earth elements in energy-transition technologies, particularly permanent magnet synchronous motors and wind generators. In electrical engineering, this growth is associated with improvements in the electromagnetic performance, power density, and energy efficiency of electrical machines.

The establishment of a national policy for strategic minerals is essential if Brazil is to convert its geological potential into competitiveness within the global value chain. Synergies among mineral reserves, the expansion of renewable energy, and excellence in research enable the development of national technologies. Accordingly, integration among academia, industry, and government is the path toward transforming the country from a mere exporter of raw materials into a technological leader in the sustainable energy transition.

MATERIALS AND METHODS

This study is characterized as qualitative, exploratory research based on a systematic literature review. Data were collected from international scientific databases, including Scopus, ScienceDirect, and IEEE Xplore, considering publications issued between 2018 and 2025.

Technical search terms such as “rare earth elements,” “permanent magnet motors,” and “energy efficiency” were used. The inclusion criteria comprised peer-reviewed studies focusing on electromagnetic performance and energy applications. Duplicate studies, studies outside the scope of the research, and studies lacking technical relevance were excluded.

Data analysis followed a series of structured stages: (i) problem definition, (ii) systematic search, (iii) study selection, (iv) critical analysis, and (v) synthesis of the results.

In addition, mathematical modeling based on the dq reference frame was used to evaluate the electromagnetic behavior of permanent magnet synchronous machines. This approach allows for the analysis of parameters such as torque, magnetic flux, and electrical losses, which are widely used in the Electrical Engineering literature.

The methodological sequence comprises the following stages: problem definition, systematic database searching, application of the study-selection criteria, study screening and selection, critical data analysis, and synthesis and discussion of the results.

RESULTS AND DISCUSSION

IMPACT OF RARE EARTH ELEMENTS ON THE ELECTROMAGNETIC PERFORMANCE OF ELECTRICAL MACHINES

The technical literature and mathematical modeling indicate that rare earth permanent magnets, particularly NdFeB magnets, significantly increase the magnetic flux in the air gap of electrical machines. As shown in Equations (2) and (3), an increase in the equivalent magnetic field raises the flux density and the total flux Φ , as expressed in Equation (3).

$$B_g \approx \mu_0 H_m \quad (2)$$

Where H_m is the equivalent magnetic field produced by the magnet. A greater B_g implies a greater total flux, represented in Equation (3):

$$\Phi = B_g A \quad (3)$$

This effect increases the induced electromotive force in accordance with Equation (4), allowing higher voltage levels without a proportional increase in current, thereby reducing resistive losses and improving energy efficiency. In addition, the high $(BH)_{max}$ values of NdFeB magnets enable the construction of more compact machines with greater electromagnetic performance than those using conventional materials such as ferrites.

$$e = -N \frac{d\Phi}{dt} \quad (4)$$

Table 1 presents a comparison between conventional magnetic materials and rare earth magnets based on typical values widely reported in the technical literature, corroborating the results.

NdFeB magnets exhibit the highest energy product, allowing more intense magnetic fields to be produced in smaller volumes. This result supports the increase in power density and reduction in active mass found in modern electrical machines (Coe, 2010; Callister; Rethwisch, 2016).

INFLUENCE OF RARE EARTH ELEMENTS ON ELECTROMAGNETIC TORQUE AND VECTOR CONTROL

Application of the dq model to permanent magnet synchronous machines shows that, in systems using rare earth metals, the term associated with the permanent magnet flux (λ_f) dominates the electromagnetic torque equation, Equation (1). Consequently:

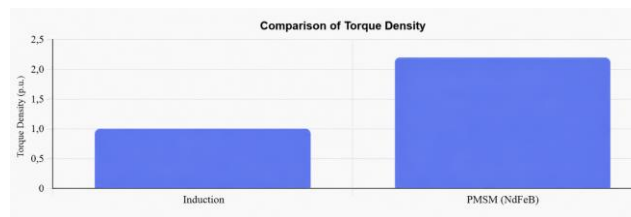
$$T_e \propto \lambda_f i_q \quad (5)$$

For the same torque level, lower i_q currents are required in PMSMs, resulting in greater torque per ampere and reduced copper losses because of the quadratic dependence on current. In addition, strategies such as maximum torque per ampere (MTPA) become more effective in these systems.

In field-oriented control (FOC), the stability of the magnetic flux produced by permanent magnets facilitates decoupling of the d and q axes, providing a better dynamic response and greater control accuracy. Based on dq modeling and comparative studies, Figure 4 presents the normalized torque densities of induction motors and synchronous motors equipped with NdFeB magnets.

Figure 4

Comparison of torque density, normalized values



Source: author, 2026.

PMSMs equipped with rare earth magnets exhibit torque densities up to twice those of induction motors in the same class. This gain results directly from the increase in λ_f , as shown in Equation (1), confirming that torque per ampere is significantly greater. This result explains the widespread adoption of these motors in electric vehicles and modern wind turbines.

REDUCTION OF LOSSES AND OVERALL ENERGY EFFICIENCY

Based on theoretical modeling and data from the literature, it can be observed that reducing the current required to produce torque directly decreases copper losses. According to Equation 6, a 20% reduction in current can result in losses that are more than 35% lower, due to the nonlinear behavior of the I^2 term.

$$\lambda_d = L_d i_d + \lambda_f \quad (6)$$

This effect influences the system's overall efficiency, as expressed in Equation (7):

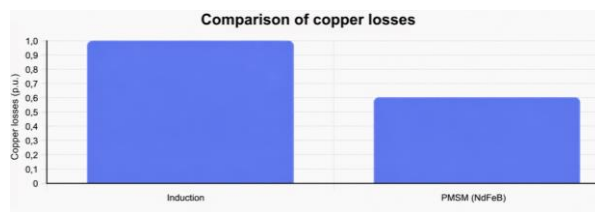
$$\eta = \frac{P_{out}}{P_{in}} \quad (7)$$

Electrical machines equipped with rare earth magnets exhibit less winding heating, a longer electrical-insulation service life, and less need for forced ventilation. These characteristics are relevant to continuous and high-power applications, such as wind power generation and electric traction.

Figure 5 illustrates a comparison of normalized copper losses under rated operating conditions.

Figure 5

Comparison of copper losses, normalized values



Source: author, 2026.

PMSMs equipped with NdFeB magnets exhibit an approximate 40% reduction in copper losses.

The reduction in current made possible by the greater magnetic flux has a direct impact, as demonstrated by the relationship $P_{cu} \propto I^2$.

This result confirms substantial gains in thermal and electrical efficiency.

INCREASED POWER DENSITY AND STRUCTURAL IMPLICATIONS

The application of Equations (7) and (8) demonstrates that machines equipped with NdFeB magnets have greater power density by mass and volume than conventional machines. This makes it possible to reduce the active mass of the rotor and stator while maintaining high power levels and enabling more compact designs.

$$\rho p = \frac{P}{m} \quad (7)$$

- ρp – power density (W/m³)
- P – Power(W)
- m – Mass (Kg)

$$\rho P_v = \frac{P}{V} \quad (8)$$

- ρp_v – volumetric power density (W/m³)
- V – Volume (m³)

However, increased power density intensifies thermal and mechanical challenges, requiring greater heat dissipation, more resistant structural materials, and advanced electrical-insulation techniques.

The gains provided by rare earth elements therefore require an integrated design approach encompassing electromagnetism, mechanics, and thermal engineering.

Table 2 presents a typical comparison of gravimetric and volumetric power densities across different electrical machine technologies.

Table 2
Comparison of power density in electrical machines

Technology	ρ_p (kW/kg)	ρ_{pv} (kW/m ³)
Induction motor	1,5 – 2,5	5.000 – 8.000
PMSM (ferrite)	2,0 – 3,0	7.000 – 10.000
PMSM (NdFeB)	4,0 – 6,0	12.000 – 20.000

Source: author, 2026.

The results show that rare earth magnets can double or triple power density, a critical factor in applications in which weight and volume are subject to severe constraints, as in offshore wind turbines, electric vehicles, and aerospace systems.

TECHNOLOGICAL AND STRATEGIC IMPLICATIONS

The results of the technical review and theoretical analysis confirm that rare earth elements are essential to the energy transition because they enable more efficient wind generators, electric motors that provide greater vehicle range, and more compact electrical power systems. Nevertheless, challenges associated with the concentration of the production chain and environmental impacts reinforce the need for sustainable strategies and industrial diversification.

Table 3 consolidates the principal technical impacts identified through the methodology applied.

Table 3
Summary of the impacts of rare earth elements on electrical machines

Evaluation parameter	Observed impact
Air-gap flux	Significant increase
Torque per ampere	High
Copper losses	Substantial reduction
Overall efficiency	Increase
Power density	Substantial increase
System mass and volume	Reduction
Thermal complexity	Increase, representing a challenge

Source: author, 2026.

At the same time, the results demonstrate that technological advancement is accompanied by new thermal, structural, and geopolitical challenges, reinforcing the need for integrated engineering approaches and industrial policies. It is also evident that the concentration of production in China (USGS, 2023) constitutes a strategic risk because it concentrates essential resources in a single country.

CONCLUSION

The energy transition requires not only the replacement of fossil-fuel energy sources but also improvements in the performance of electromechanical conversion systems. In this context, the study analyzed the contribution of rare earth elements to the efficiency, power density, and reliability of modern electrical machines.

The technical review and modeling of synchronous machines showed that rare earth-based permanent magnets, particularly NdFeB magnets, possess superior magnetic properties, enabling greater air-gap flux, increased electromagnetic torque, and higher power density. Analysis using the dq model also indicated greater torque per ampere and lower electrical currents, thereby reducing copper losses and improving energy efficiency and thermal performance.

Furthermore, rare earth elements enable the construction of more compact and lightweight machines, which are essential in applications such as offshore wind turbines and electric traction systems. However, the use of these materials involves thermal, structural, environmental, and geopolitical challenges related to the concentration of their production.

It is concluded that rare earth elements are fundamental to modern electrical systems and the energy transition because they provide significant gains in performance and efficiency. However, their effective use depends on investments in innovation, industrial policies, and sustainable practices that ensure security of supply and the responsible use of these resources.

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BIBLIOMETRIC OVERVIEW OF SCIENTIFIC OUTPUT ON THE USE OF MICROORGANISMS IN THE BIOLOGICAL CONTROL OF AGRICULTURAL PESTS

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Abstract

The intensification of agricultural production and dependence on synthetic pesticides have increased the demand for more sustainable pest management alternatives. In this context, microorganism-based biological control stands out as a promising strategy, particularly through the use of fungi, bacteria, and other agents capable of acting against pests and phytopathogens. This study aimed to analyze the landscape of scientific output on the use of microorganisms in the biological control of agricultural pests through a bibliometric analysis of the Scopus database. The study encompassed publications from 2015 to 2025, considering open-access articles in Portuguese and English in the fields of *Agricultural and Biological Sciences* and Environmental Science, resulting in 1,034 documents for analysis. The most frequently cited articles, temporal evolution of publications, geographical distribution, keywords, leading authors, journals, and scientific collaboration networks were evaluated. The results showed substantial growth in scientific output, from 26 articles in 2015 to 221 in 2025. China and the United States exhibited the highest density of scientific output, while Brazil and Spain stood out as important points of connection. The keywords demonstrated the centrality of *biological control* and *biocontrol*, with particular emphasis on *Beauveria bassiana*, *Metarhizium anisopliae*, and *Bacillus thuringiensis*. The analysis also revealed an interdisciplinary scientific structure that was relatively fragmented in terms of coauthorship. It is concluded that the use of microorganisms in biological control constitutes an expanding scientific field associated with the development of more sustainable agricultural strategies and integrated pest management.

Keywords: Agriculture, Bibliometrics, Microbial agents.

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INTRODUCTION

The intensification of agricultural production has increased the demand for efficient pest management strategies, which have historically been based on the use of chemical pesticides (Ediagbonya et al., 2025). Large-scale global production has increased the use of synthetic pesticides to 3.5 billion kg/year. Although these products play an important role in maintaining productivity, they cause several adverse environmental and health impacts, driving the search for alternative pest control methods (Pretty; Bharucha, 2015).

In this context, biological control using microorganisms has become established as a promising alternative, employing bacteria, fungi, viruses, and other agents capable of reducing agricultural pest populations in a more selective and environmentally compatible manner (Chaudhary et al., 2024; Villavicencio-Vásquez et al., 2025). As Brazil has one of the world's largest agricultural sectors and extensive microbial biodiversity, research on this topic has grown in the country, contributing to advances in integrated pest management and sustainable agriculture (Boaventura; Quintela, 2025).

Despite this progress, few studies have elucidated the evolution of scientific output on the use of microorganisms in the biological control of agricultural pests. Bibliometric analysis can thus provide a broader perspective on productivity and impact within a given research topic by examining citations per year, researcher performance, the use of indicators, and keyword occurrence. It is an important tool for understanding and managing scientific research, providing both quantitative and qualitative information (Hassan; Duarte, 2024).

In view of the foregoing, this study aims to analyze the landscape of scientific output on the use of microorganisms in the biological control of agricultural pests through bibliometric indicators obtained from the Scopus database, thereby contributing to an understanding of the field's evolution and to the identification of future research prospects.

METHODOLOGY

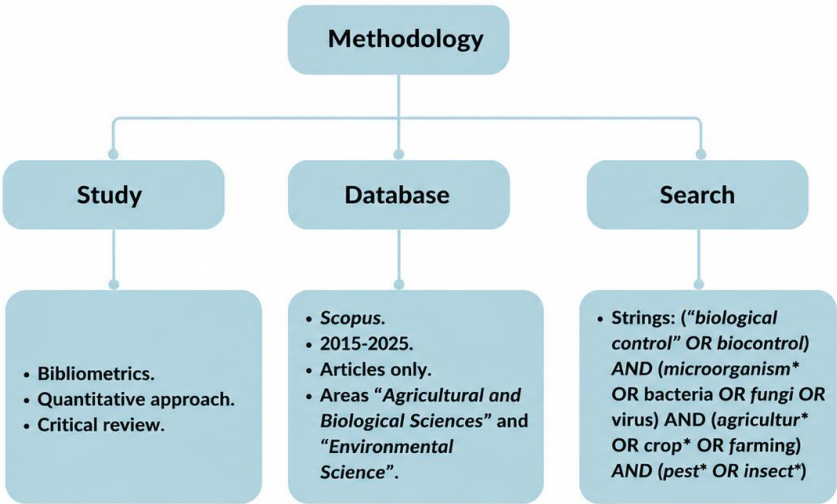
This research is characterized as a bibliometric study employing a qualitative and quantitative approach, with the objective of identifying the predominant characteristics and trends in scientific output on the use of microorganisms in the biological control of agricultural pests. The choice of bibliometric methodology is justified by its ability to quantify and analyze the evolution, distribution, and trends of scientific output in a given field of knowledge, enabling a structured understanding of the development of research on the topic over time (Hassan; Duarte, 2024).

The bibliometric search was conducted in the *Scopus* database using the following search strings, combined with the Boolean operators “OR” and “AND”: ((“*biological control*” OR *biocontrol*) AND (*microorganism** OR *bacteria* OR *fungi* OR *virus*) AND (*agricultur** OR *crop** OR *farming*) AND (*pest** OR *insect**)). At this stage, with no additional filters applied, 6,798 documents were identified.

Following the initial search, filters were applied to restrict the documents retrieved, retaining only those most relevant to this study. Only articles published between 2015 and 2025 were selected so that the time frame would encompass the most recent scientific output on the topic. In addition, the selection was restricted to articles in Portuguese and English, further narrowing the study. By limiting the search to the subject areas of “*Agricultural and Biological Sciences*” and “*Environmental Science*” and selecting only open-access articles, the number of documents was reduced from 6,798 to 1,034. Figure 1 therefore presents a flowchart of the search process.

Figure 1

Flowchart of the methodological process used to search for the topic in the database.



Source: Authors, 2026.

The file corresponding to the search conducted in the *Scopus* database was downloaded in CSV format to enable data processing and the development of the bibliometric analyses presented in Section 3, Results and Discussion. The graphs used to present and discuss the results were produced partly with the VOSviewer bibliometric tool and partly using the Canva platform. All 1,034 documents retrieved by the search were included, as the use of the entire dataset provides greater representativeness and robustness to the bibliometric analyses performed.

Subsequently, a list of the 10 most frequently cited articles among the documents analyzed was compiled. These studies were used as bibliographic references to support the discussion presented in Subsections 3.1 and 3.2. All figures were produced using Canva, an editor for images and other types of designs.

RESULTS AND DISCUSSION

HIGHEST-IMPACT ARTICLES

Based on the bibliometric survey, a list was compiled of the 10 articles with the highest numbers of citations among the documents identified in the *Scopus* database. The purpose of selecting these studies was to highlight the publications with the greatest impact and visibility within the body of research related to the topic under investigation. Bibliographic data such as title, authorship, year of publication, journal, and number of citations were considered for each article, allowing the principal references identified in the survey to be organized and characterized.

The 10 selected articles were used as bibliographic references to underpin and support the discussion presented in this section. Analysis of these studies made it possible to identify different approaches to biological control, including the use of invertebrates and microorganisms, entomopathogenic fungi, bacteria that promote phytopathogen control, microbial metabolites, mycoviruses, and other management strategies. The selected publications therefore helped establish a theoretical foundation for interpreting the results and contextualizing the principal trends identified in the literature analyzed. Table 1 lists the highest-impact studies within the body of literature analyzed, based on the total number of accumulated citations.

Table 1

The 10 most frequently cited articles on the topic in Scopus.

Article Title	Authors	Year	Journal	Citations
Biological control using invertebrates and microorganisms: plenty of new opportunities	van Lenteren J.C.; Bolckmans K.; Köhl J.; Ravensberg W.J.; Urbaneja A.	2018	<i>BioControl</i>	813
MAPK Signaling Pathway Alters Expression of Midgut ALP and ABCC Genes and Causes Resistance to <i>Bacillus thuringiensis</i> Cry1Ac Toxin in Diamondback Moth	Guo Z.; Kang S.; Chen D.; Wu Q.; Wang S.; Xie W.; Zhu X.; Baxter S.W.; Zhou X.; Jurat-Fuentes J.L.; Zhang Y.	2015	<i>PLoS Genetics</i>	236

Characterization and biotoxicity of <i>Hypnea musciformis</i> -synthesized silver nanoparticles as potential eco-friendly control tool against <i>Aedes aegypti</i> and <i>Plutella xylostella</i>	Roni M.; Murugan K.; Panneerselvam C.; Subramaniam J.; Nicoletti M.; Madhiyazhagan P.; Dinesh D.; Suresh U.; Khater H.F.; Wei H.; Canale A.; Alarfaj A.A.; Munusamy M.A.; Higuchi A.; Benelli G.	2015	<i>Ecotoxicology and Environmental Safety</i>	215
A review of the biology and control of whitefly, <i>Bemisia tabaci</i> (Hemiptera: Aleyrodidae), with special reference to biological control using entomopathogenic fungi	Sani I.; Ismail S.I.; Abdullah S.; Jalinas J.; Jamian S.; Saad N.	2020	<i>Insects</i>	191
Bio-organic soil amendment promotes the suppression of <i>Ralstonia solanacearum</i> by inducing changes in the functionality and composition of rhizosphere bacterial communities	Deng X.; Zhang N.; Li Y.; Zhu C.; Qu B.; Liu H.; Li R.; Bai Y.; Shen Q.; Falcao Salles J.	2022	<i>New Phytologist</i>	189
An endophytic <i>Beauveria bassiana</i> strain increases spike production in bread and durum wheat plants and effectively controls cotton leafworm (<i>Spodoptera littoralis</i>) larvae	Sánchez-Rodríguez A.R.; Raya-Díaz S.; Zamarreño Á.M.; García-Mina J.M.; del Campillo M.C.; Quesada Moraga E.	2018	<i>Biological Control</i>	178
Sustainable Crop and Weed Management in the Era of the EU Green Deal: A Survival Guide	Tataridas A.; Kanatas P.; Chatzigeorgiou A.; Zannopoulos S.; Travlos I.	2022	<i>Agronomy</i>	156
Fengycin produced by <i>Bacillus amyloliquefaciens</i> FZB42 inhibits <i>Fusarium graminearum</i> growth and mycotoxins biosynthesis	Hanif A.; Zhang F.; Li P.; Li C.; Xu Y.; Zubair M.; Zhang M.; Jia D.; Zhao X.; Liang J.; Majid T.; Yan J.; Farzand A.; Wu H.; Gu Q.; Gao X.	2019	<i>Toxins</i>	153
Pathogens and Molds Affecting Production and Quality of <i>Cannabis sativa</i> L.	Punja Z.K.; Collyer D.; Scott C.; Lung S.; Holmes J.; Sutton D.	2019	<i>Frontiers in Plant Science</i>	140
Mycoviruses in biological control: From basic research to field implementation	García-Pedrajas M.D.; Cañizares M.C.; Sarmiento Villamil J.L.; Jacquat A.G.; Dambolena J.S.	2019	<i>Phytopathology</i>	130

Source: Authors, 2026.

PEST CONTROL USING BIOLOGICAL AGENTS

The literature on biological control demonstrates the expansion of strategies used to reduce populations of agricultural pests and disease-causing organisms. Van Lenteren et al. (2018) discuss augmentative biological control using invertebrate organisms and microorganisms released in large quantities, highlighting its worldwide application and the commercial availability of more than 440 species of control agents. The authors associate the expansion of this approach with reduced use of synthetic pesticides, lower residue levels, and the possibility of integrating it into different management systems. However, the study by Guo et al. (2015) demonstrates that target organisms can also evolve resistance to biological control agents. In their study of *Plutella xylostella*, the authors found that resistance to the Cry1Ac toxin produced by *Bacillus thuringiensis* was associated with the differential expression of a midgut membrane alkaline phosphatase and genes from the ABCC family. The study also associated the mitogen-activated protein kinase (MAPK) signaling pathway with changes in the expression of these genes and with the resistance phenotype, demonstrating the importance of the molecular mechanisms involved in insect responses to control agents.

Biologically derived products and formulations based on entomopathogenic fungi also stand out among the alternatives for arthropod control. Roni et al. (2015) evaluated silver nanoparticles synthesized from an aqueous extract of the alga *Hypnea musciformis*. The nanoparticles were predominantly spherical, crystalline in nature, and had an average size of between 40 and 65 nm. They were evaluated under laboratory conditions against the larvae and pupae of *Aedes aegypti* and *Plutella xylostella*. The authors observed larvicidal and pupicidal toxicity, as well as reduced longevity and fecundity among treated adults. Sani et al. (2020), in turn, conducted a review of the biology and control of *Bemisia tabaci*, with an emphasis on entomopathogenic fungi. The study indicates that *B. tabaci* is a major pest of agricultural crops and a vector of plant viruses, while the intensive use of chemical insecticides is associated with problems such as resistance, environmental contamination, and effects on nontarget organisms. The authors highlight entomopathogenic fungi as an alternative within integrated pest

management and report that hyphomycete species are among the most widely used agents, with the second instar of *B. tabaci* identified as the stage most susceptible to infection.

Biological control can also occur through the modification of soil-associated microbial communities and the use of endophytic microorganisms. Deng et al. (2022) investigated the suppression of *Ralstonia solanacearum* through the continuous application of bio-organic fertilizers in a long-term field experiment. The results indicated that disease suppressiveness was primarily associated with changes in the composition of rhizosphere bacterial communities rather than solely with the abundance of the microorganism introduced as a biocontrol agent. Metagenomic analysis also revealed an enrichment of members of the families *Sphingomonadaceae* and *Xanthomonadaceae* capable of producing secondary metabolites, particularly following pathogen invasion. Sánchez-Rodríguez et al. (2018), meanwhile, evaluated the endophytic colonization of wheat plants by a strain of *Beauveria bassiana*. The fungus was able to colonize bread and durum wheat, and inoculation treatments involving seed coating and soil application increased spike production under certain conditions. In addition, *Spodoptera littoralis* larvae fed leaves from colonized plants exhibited mortality rates ranging from 30% to 57%, depending on the inoculation method, whereas larvae fed control leaves exhibited no mortality.

The search for agricultural systems that are less dependent on chemical products is also addressed by Tataridas et al. (2022), who present a comprehensive framework for sustainable crop and weed management in the context of the European Green Deal. The authors discuss the vulnerability of agricultural systems associated with dependence on herbicides and increased weed resistance, proposing the integration of nonchemical alternatives such as crop rotation and diversification, reduced tillage, intercropping, beneficial microorganisms, biological control agents, soil cover, and precision agriculture technologies. Regarding disease control, Hanif et al. (2019) studied fengycin produced by *Bacillus amyloliquefaciens* FZB42 and its activity against *Fusarium graminearum*, a pathogen associated with *Fusarium* head blight in cereal crops. The study investigated the ability of fengycin to inhibit fungal

growth and mycotoxin biosynthesis, thereby placing metabolites produced by bacteria of the genus *Bacillus* among the microbial compounds that may be used to control pathogens. The two studies therefore address distinct but complementary strategies for reducing dependence on chemical inputs, encompassing both agroecosystem management practices and products derived from microorganisms.

Finally, the studies by Punja et al. (2019) and García-Pedrajas et al. (2019) broaden the discussion to encompass disease management and new forms of control involving microorganisms. Punja et al. (2019) characterized pathogens and fungi associated with the production of *Cannabis sativa* under different cultivation systems, identifying, among others, *Fusarium* and *Pythium* species associated with root diseases, powdery mildew on leaves, and inflorescence rots caused by *Penicillium*, *Botrytis*, and *Fusarium*. The study also detected different fungi in cultivation environments and found that biocontrol products containing *Beauveria bassiana* and *Trichoderma* contributed to the presence of these fungi in air samples. García-Pedrajas et al. (2019), in turn, reviewed the potential of mycoviruses as biological control agents against phytopathogenic fungi. The authors emphasize that certain mycoviruses can induce hypovirulence, or reduced virulence, in their fungal hosts, but note that their application depends on their capacity for transmission and spread within natural pathogen populations. Transmission occurs primarily horizontally through hyphal anastomosis and vertically through conidia, while factors related to both the fungal host and the virus influence transmission efficiency.

In conclusion, the references analyzed demonstrate different levels of biological control activity, ranging from organisms and molecules applied directly against pests and pathogens to modifications in microbial communities and virus-fungus interactions.

TEMPORAL EVOLUTION OF SCIENTIFIC OUTPUT

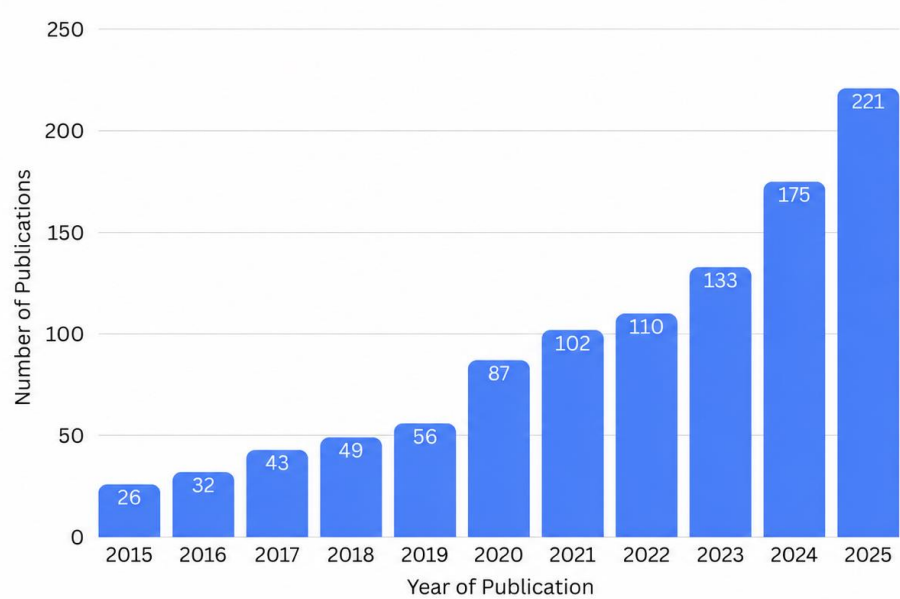
Global analysis of article output

The analysis of scientific output between 2015 and 2025, presented in Figure 2, shows continuous growth in research on the use of microorganisms to control agricultural pests. In 2015, 26 publications

were recorded, whereas this number reached 221 in 2025, demonstrating a substantial expansion of scientific interest in the topic.

During the initial years, growth occurred gradually, rising from 26 publications in 2015 to 56 in 2019. Beginning in 2020, however, a more pronounced acceleration can be observed, with 87 publications, followed by 102 in 2021, 110 in 2022, and 133 in 2023. This increase may be associated with the search for more sustainable alternatives to conventional pesticide use, as well as growing interest in biological control and integrated pest management.

Figure 2
Number of articles published per year from 2015 to 2025.



Source: Authors, 2026.

Growth became even more evident in the final years, with 175 publications in 2024 and 221 in 2025, the highest value in the entire series. This result indicates that the topic remains in expansion and is gaining prominence in agricultural research. Growing concern about the environmental impacts of pesticides, pest resistance, and the need for more sustainable agricultural systems may help explain this scenario.

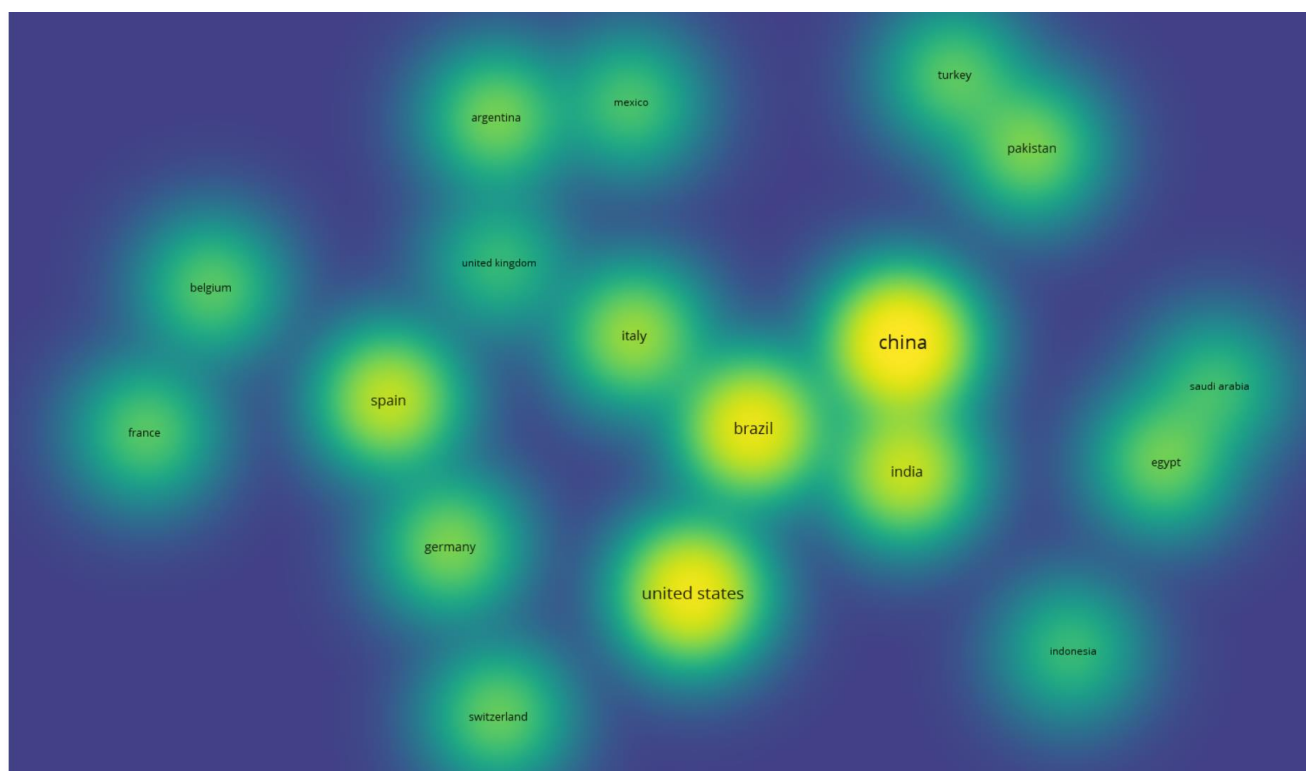
It is important to emphasize that the graph alone does not make it possible to determine which factors were responsible for the increase in publications. Nevertheless, it clearly demonstrates that the use of microorganisms for pest control is an increasingly relevant field of research.

The results therefore reveal a consistent upward trend in scientific output, reinforcing the potential of microorganisms as tools for developing more sustainable pest control strategies. This progress also highlights the importance of continuing to invest in research that evaluates their efficacy, environmental safety, and practical application in agriculture.

Figure 3 presents a geographical density visualization of scientific output, generated through country mapping. The bright yellow regions identify the principal areas of concentration and relevance in the field under study.

Figure 3

Geographical density visualization map of scientific output on the topic.



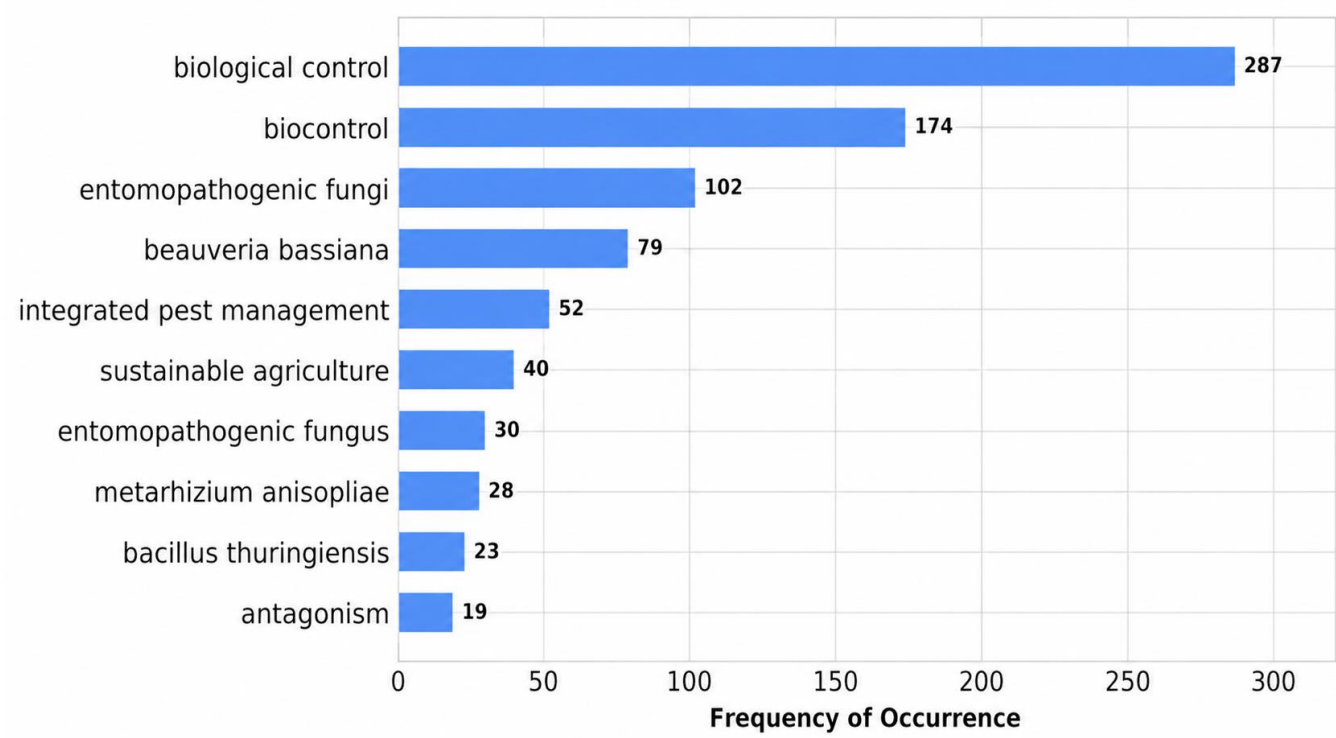
Source: Authors, 2026.

China and the United States predominate as the world’s leading centers of academic output density. Countries such as Brazil and Spain also play a central role as important bridges connecting different collaboration networks. While continental Europe forms a cohesive and well-distributed cluster, including Spain, Italy, Germany, and the United Kingdom, emerging and Middle Eastern countries such as Türkiye, Pakistan, and Egypt exhibit peripheral consolidation, indicating areas of recent expansion within the research field.

Prominent keywords

The general terms *biological control* (287) and *biocontrol* (174) exhibit clear predominance, confirming the centrality of the topic. Figure 4 illustrates the frequency of occurrence of the principal keywords identified in the literature analyzed.

Figure 4
Frequency of occurrence of the principal keywords.



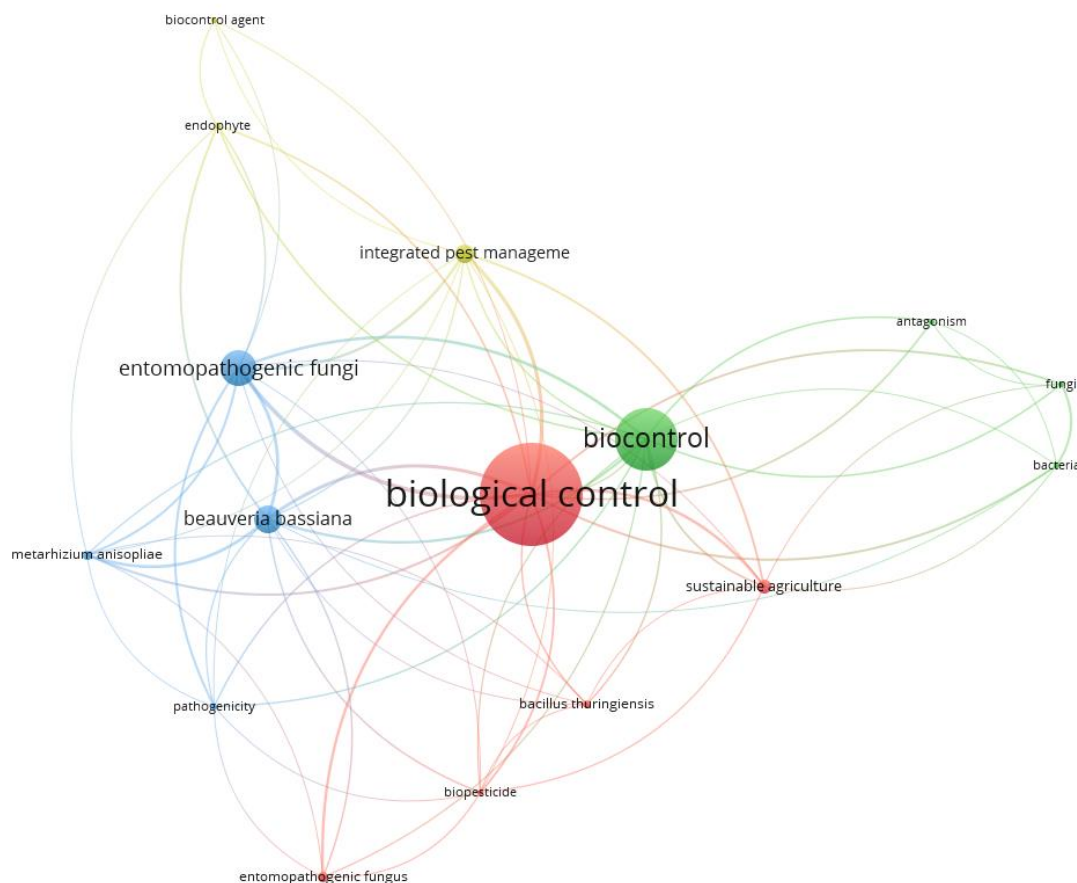
Source: Authors, 2026.

Among biological agents, entomopathogenic fungi play a particularly prominent role, standing out in both general terminology and taxonomic specification. *Beauveria bassiana* stands out as the most frequently investigated organism (79), surpassing other important control agents such as *Metarhizium anisopliae* (28) and *Bacillus thuringiensis* (23). In addition, the data reveal a strong association between the topic and applied, sustainable approaches to production, as demonstrated by the recurring concepts of *integrated pest management* (52) and *sustainable agriculture* (40), as well as mechanistic aspects such as *antagonism* (19).

VOSviewer can be used to generate a visualization of the connections among the most frequently used keywords. Figure 5 therefore shows the formation of three clusters and the relationships among them.

Figure 5

Network map of connections among the prominent keywords.



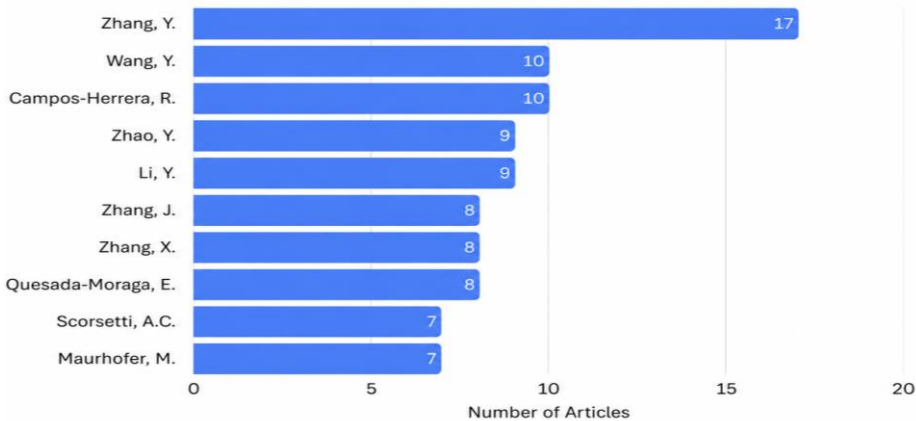
Source: Authors, 2026.

Node size reflects term frequency, while the edges indicate the strength of co-occurrence among the terms. *Biological control* and *biocontrol* act as the network’s central hubs, linking the other subfields. The mapping enabled the identification of distinct thematic clusters. The entomopathogenicity cluster, shown in blue, highlights the relevance of fungi in biocontrol, with strong links between the general term *entomopathogenic fungi* and key species such as *Beauveria bassiana* and *Metarhizium anisopliae*, which are associated with the attribute of *pathogenicity*. The inputs and sustainability cluster, shown in red, connects the practice of biological control with the development of new inputs, including *biopesticide* and *Bacillus thuringiensis*, and their role in *sustainable agriculture*. The integrated management cluster, shown in yellow, links system-level concepts such as *integrated pest management* to ecological aspects of plant-microorganism interactions, including *endophyte* and *biocontrol agent*.

Leading authors and journals

Academic leadership in the field is represented by researchers with substantial productivity and citation counts. The most productive author in the dataset is Zhang Y., with 17 publications and 446 citations, followed by Wang Y. and Campos-Herrera R., with 10 articles each, as shown in Figure 6.

Figure 6
Ranking of the 10 most productive authors.



Source: Authors, 2026.

However, this configuration changes when the authors are ranked by number of citations. Analysis of the most frequently cited authors reveals the presence of researchers with different levels of contribution and impact in the field of microorganism use for the control of agricultural pests. The 10 authors presented accounted for 93 documents and 2,341 citations, corresponding to an overall average of approximately 25.2 citations per document, as shown in Table 2.

Table 2

Ranking of the most frequently cited authors.

Author	Number of Articles	Citations	Average Citations
Zhang, Y.	17	446	26,24
Li, Y.	9	363	40,33
Quesada-Moraga, E.	8	343	42,88
Maurhofer, M.	7	285	40,71
Scorsetti, A.C.	7	222	31,71
Campos-Herrera, R.	10	170	17,00
Zhao, Y.	9	143	15,89
Zhang, X.	8	141	17,62
Zhang, J.	8	120	15,00
Wang, Y.	10	108	10,80

Source: Authors, 2026.

The data show substantial participation by a group of researchers in scientific output on the use of microorganisms to control agricultural pests. Among the authors analyzed, Zhang Y. exhibits the highest productivity, with 17 documents and 446 citations, standing out in terms of the number of studies published.

When the average impact of the publications is considered, the highest values belong to Quesada-Moraga E. (42.88 citations/document), Maurhofer M. (40.71), and Li Y. (40.33). Although these authors have fewer documents than Zhang Y., their studies have had a greater impact on the scientific literature.

Overall, the results demonstrate that productivity and scientific impact are not necessarily proportional. While some researchers stand out for the volume of their publications, others exert greater influence per published study.

Coauthorship relationships also form part of bibliometric analyses. The network visualization generated in VOSviewer presents the coauthorship network of the authors identified in the set of documents analyzed. The visualization shows the formation of two principal clusters, indicating different centers of scientific collaboration among the researchers, as presented in Figure 7.

Figure 7

Coauthorship network visualization map.



Source: Authors, 2026.

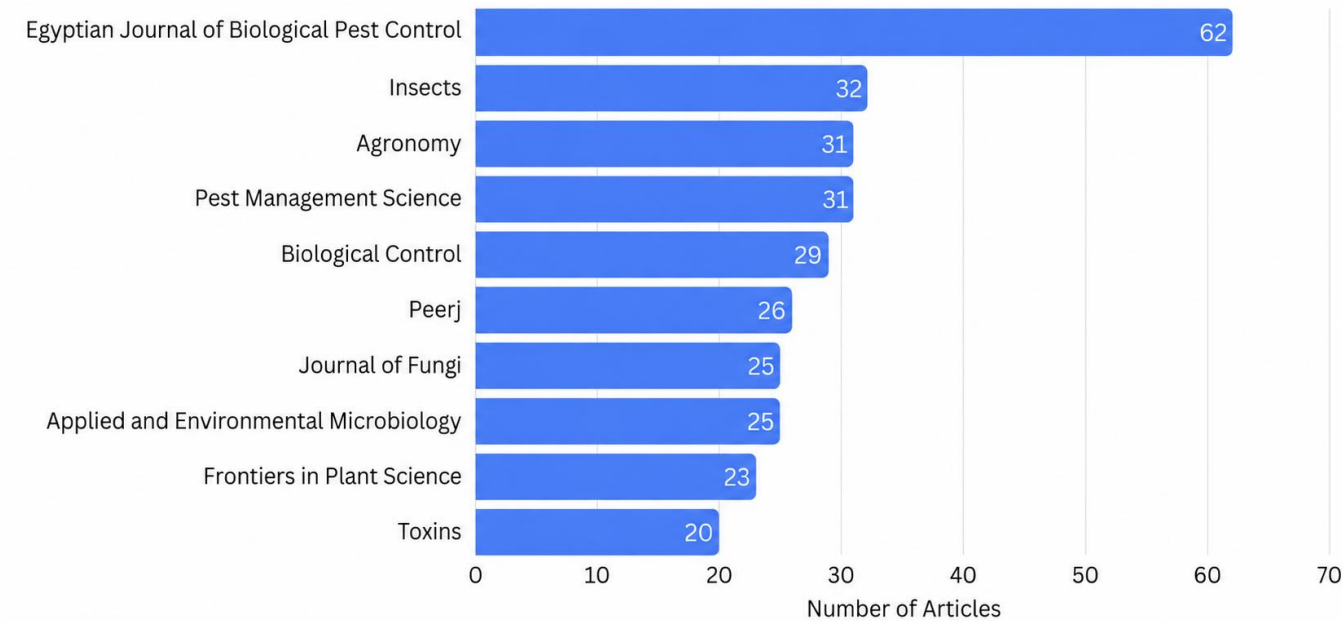
The absence of connections between the two clusters and the formation of a larger number of these networks demonstrate that no coauthorship relationships were identified between researchers belonging to different clusters within the set of documents analyzed. The network therefore reveals a relatively fragmented scientific collaboration structure, comprising groups of researchers whose work is concentrated within their own collaboration centers.

Figure 8 presents the 10 journals with the highest publication volumes on the topic investigated. The *Egyptian Journal of Biological Pest Control* clearly predominates, accounting for 62 articles and

standing out considerably from the other journals. It is followed by *Insects*, with 32 articles, and *Agronomy* and *Pest Management Science*, each with 31 published articles.

Figure 8

Ranking of the 10 journals with the most publications on the topic.



Source: Authors, 2026.

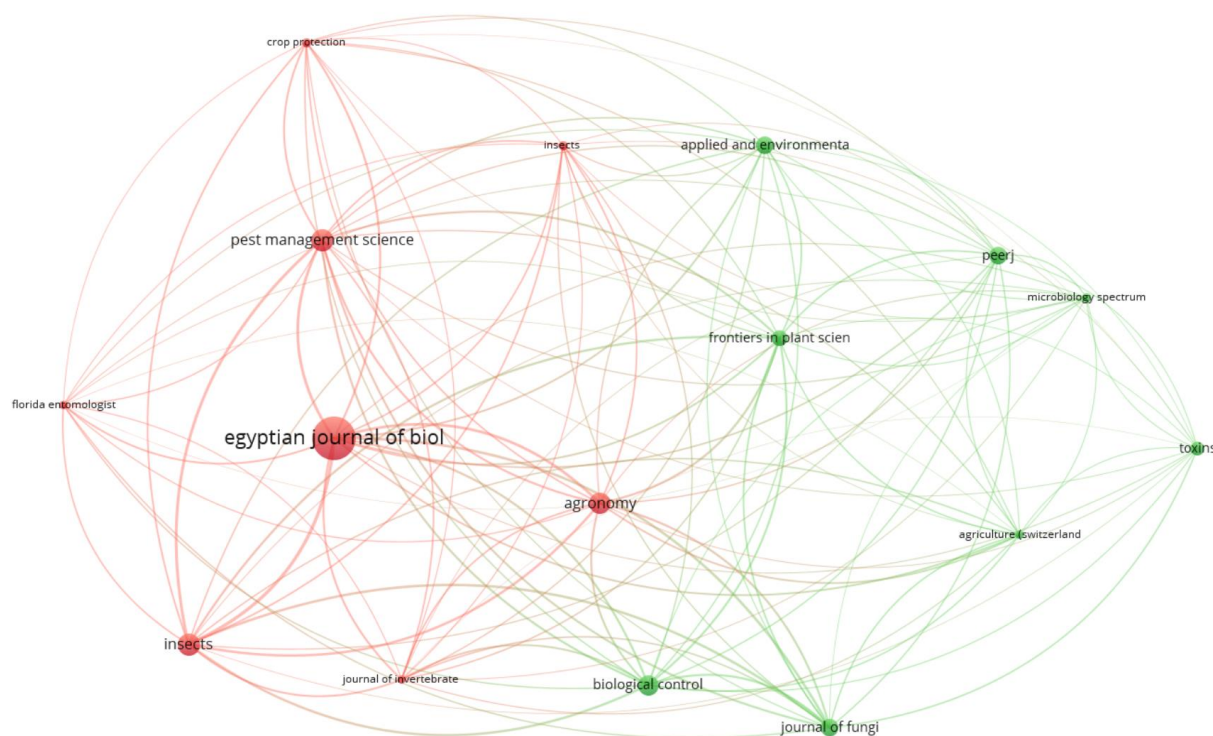
The observed distribution demonstrates that scientific output on the topic is concentrated primarily in journals directly related to biological control, entomology, pest management, agronomy, and microbiology. The prominence of the *Egyptian Journal of Biological Pest Control*, which accounted for 62 publications, demonstrates the importance of this journal as one of the primary outlets for disseminating the studies analyzed. Conversely, the presence of journals from different fields, such as *Journal of Fungi*, *Applied and Environmental Microbiology*, and *Toxins*, demonstrates the interdisciplinary nature of the topic, encompassing aspects related to microbiology, fungi, biological agents, and the production of metabolites or toxins with potential applications in the control of agricultural pests.

Figure 9 presents the relationship network among the journals that stood out in the scientific output analyzed, which was also produced using VOSviewer. Two principal clusters, identified by the

colors red and green, can be observed, demonstrating different centers of relationships among the journals.

Figure 9

Network map of relationships among the journals.



Source: Authors, 2026.

The red cluster primarily comprises journals related to the management and control of agricultural pests, with the *Egyptian Journal of Biological Pest Control* standing out as one of the network's central nodes because of its larger size and the number of connections established. *Pest Management Science*, *Insects*, *Agronomy*, *Crop Protection*, and *Florida Entomologist* also occupy prominent positions within this cluster. The proximity and number of links among these journals indicate a strong thematic association with studies focusing on pest control, crop protection, and agricultural entomology. The green cluster, in turn, is more strongly associated with biological control, microbiology, and plant sciences, comprising journals such as *Applied and Environmental Microbiology*, *Frontiers in Plant Science*, *PeerJ*,

Biological Control, *Journal of Fungi*, *Toxins*, and *Microbiology Spectrum*. The presence of these journals highlights the role of microbiological and biotechnological approaches in research on the biological control of pests.

CONCLUSION

The bibliometric analysis provided a comprehensive overview of the conceptual, intellectual, and dissemination structure of research on biological control. The results reveal that the field is organized around the sustainable pest management paradigm, fundamentally based on the use of entomopathogenic microorganisms.

From a conceptual perspective, the general terms *biological control* and *biocontrol* constitute the principal organizing axes of scientific output. Analysis of the keyword networks demonstrated that the literature is structured into three integrated domains: entomopathogenicity, with *Beauveria bassiana* playing a particularly prominent role compared with the other agents; the development of biotechnological inputs, including *biopesticides* and *Bacillus thuringiensis*, for sustainable agriculture; and integrated pest management, which connects systemic ecological approaches with plant-microorganism interactions.

Regarding the authorship structure, the data demonstrated that publication volume and scientific impact follow distinct dynamics. Although researchers such as Zhang Y. lead in terms of publication volume, authors such as Quesada-Moraga E., Maurhofer M., and Li Y. stand out for having the highest citation rates per document, indicating the substantial impact of their publications. In addition, analysis of the coauthorship network revealed a relatively fragmented scientific community characterized by isolated centers of collaboration, with no direct interconnections between the principal clusters.

Finally, the dissemination of scientific knowledge on the topic is both highly concentrated and interdisciplinary. The *Egyptian Journal of Biological Pest Control* stands out as the principal outlet in terms of published article volume and as a central node in the citation and academic relationship network.

The coexistence of two large clusters of journals, one focused on entomology and applied plant protection and the other on microbiology, biotechnology, and plant sciences, reaffirms the field's transdisciplinary character, as it continuously moves from biotechnological and microbiological laboratory research to direct field application.

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NATIONAL PRELIMINARY OVERVIEW OF THE EFFLUENT GENERATED IN MILK PRODUCTION

 <https://doi.org/10.63330/aurumpub.059-009>

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Abstract

The dairy production chain plays an important economic and social role in Brazil. However, the intensification of this activity is also associated with increased waste and effluent generation, making the development of environmental management strategies essential. In this context, the present study aimed to analyze the state of Brazilian milk production and determine how the issue of effluents is addressed in the sector's principal information sources. This descriptive and exploratory study adopted a qualitative and quantitative approach based on a literature review, document analysis, and the analysis of secondary data from the Municipal Livestock Survey (Pesquisa da Pecuária Municipal, PPM/IBGE), accessed through the IBGE Automatic Data Retrieval System (Sistema IBGE de Recuperação Automática, SIDRA), and the Milk Yearbooks published by Embrapa Dairy Cattle, covering the period from 2018 to 2023. The results revealed changes in the dynamics of the dairy chain, including growth in the cattle herd and production value, a reduction in the number of cows milked, and stable milk production, indicating gains in production efficiency. The findings also showed that, although the Milk Yearbooks expanded their discussion of sustainability over the period analyzed, official indicators related to effluent generation, treatment, and disposal remain scarce. It is concluded that incorporating this information into official statistical databases could contribute to the environmental planning of the activity and to the development of public policies and more sustainable management strategies.

Keywords: Dairy chain, Effluents, Sustainability.

INTRODUCTION

The dairy production chain is one of Brazil's principal agricultural activities and plays a fundamental role in generating employment and income and ensuring food security. Brazil is the world's

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fourth-largest milk producer, producing 35.1 billion liters per year according to Embrapa's 2018 Milk Yearbook. Production is distributed throughout all regions of the country and accounts for a substantial share of the national agricultural economy (Bacchi et al., 2022). However, the expansion of the activity and the intensification of production systems have also heightened the challenges associated with water consumption, waste generation, and effluent production, making it essential to develop environmental management strategies that reconcile productivity with sustainability.

The efficient and economically viable disposal of effluents generated by different production sectors is one of the principal environmental challenges facing livestock farming. Among the most widely used alternatives is pretreatment followed by controlled land application, a practice that promotes the degradation of organic matter and, when properly implemented, can help improve the soil's physical, chemical, and biological properties (Neto, 2014).

Milk production requires substantial water consumption throughout every stage of the production process, including providing drinking water for animals and cleaning facilities, milking equipment, storage tanks, and processing areas. According to Udaypal et al. (2025), the dairy industry accounts for approximately 34% of the water used by the food sector worldwide, with between 1 and 10 liters of water required to process each liter of milk. As a result of this high water consumption, large volumes of effluent are generated daily, making their management a fundamental aspect of the activity's sustainability.

Effluents from the dairy chain vary considerably in composition and may contain manure, feed residues, pasture residues, detergents, sanitizers, oils, fats, suspended solids, and high concentrations of organic matter (Neto, 2014). In the dairy industry, their generation is directly associated with the cleaning of tanks, pipes, pumps, processing equipment, floors, and storage areas, as well as with raw-material losses during processing. Because of these characteristics, between 1 and 10 liters of effluent may be

generated for every liter of milk processed, depending on the technological level and characteristics of the industrial facility (Saraiva et al., 2009; Udaypal et al., 2025).

When improperly discharged, these effluents can cause various environmental impacts, including increased biochemical oxygen demand (BOD), reduced dissolved oxygen in water bodies, eutrophication, contamination of soil and surface and groundwater, and greenhouse gas emissions (Udaypal et al., 2025). Proper effluent treatment is therefore essential not only for complying with current environmental legislation, represented primarily by the National Water Resources Policy and National Environmental Council (Conselho Nacional do Meio Ambiente, CONAMA) Resolutions No. 357/2005 and No. 430/2011, given that no regulations specifically govern effluents from milk production, but also for reducing the impacts associated with the activity and promoting more efficient use of natural resources (Brazil, 1997; CONAMA, 2005; CONAMA, 2011).

In recent years, effluents from the dairy chain have come to be viewed as resource streams rich in carbon, nitrogen, and phosphorus. These nutrients can be harnessed to produce biogas, bioenergy, and biofertilizers through processes such as anaerobic digestion (Kunz et al., 2020; Silva et al., 2022). In this context, the use of these effluents as feedstock for anaerobic digestion has attracted interest because it simultaneously enables the removal of the effluent's organic load and the generation of bioenergy coupled with biofertilizer production, thereby contributing to waste valorization and the adoption of circular-economy strategies (Ashekuzzaman et al., 2021; Milanez et al., 2018). These alternatives make it possible to reduce environmental impacts while adding value to the waste generated by the activity.

Despite advances in research on the treatment and reuse of effluents from milk production, consolidated information on the generation, treatment, and disposal of these wastes remains limited in official Brazilian databases. The lack of environmental indicators hinders the preparation of regional- and national-scale assessments, limits public-policy planning, and reduces the availability of information that could support environmental management strategies for the dairy production chain.

Given this scenario, this study aimed to analyze the development of the dairy production chain in Brazil based on official data from the Brazilian Institute of Geography and Statistics (Instituto Brasileiro de Geografia e Estatística, IBGE) and the Milk Yearbooks published by Embrapa Dairy Cattle, discussing the implications of these indicators for effluent generation and management in dairy farming and identifying gaps in the sector's main information sources.

METHODOLOGY

This descriptive and exploratory study adopted a qualitative and quantitative approach and was based on a literature review, document analysis, and the analysis of secondary data from official statistical databases and technical and scientific publications concerning the dairy production chain in Brazil.

To characterize the production and economic landscape of Brazilian dairy farming, data from the Municipal Livestock Survey (Pesquisa da Pecuária Municipal, PPM), made available by the Brazilian Institute of Geography and Statistics (IBGE) through the IBGE Automatic Data Retrieval System (SIDRA), were used alongside the Milk Yearbooks published by Embrapa Dairy Cattle. The period analyzed extended from 2018 to 2023, as it represents a recent time series containing consolidated information that is comparable across the sources consulted, thus allowing an assessment of the development of the dairy chain's principal indicators and of discussions related to sustainability.

Initially, a literature search was conducted in scientific articles, specialized publications, technical reports, and institutional documents concerning the dairy production chain, with an emphasis on its production, economic, and environmental aspects. Statistical data on the cattle herd, number of cows milked, annual volume of milk produced, and value of milk production were then collected, as these indicators can characterize the development of the activity in the country.

The data obtained were organized into tables and graphical representations, allowing the temporal development of the indicators to be analyzed and trends related to production and the economic

importance of the dairy chain to be identified. In addition, a document analysis of Embrapa's Milk Yearbooks was conducted to determine how issues related to sustainability and effluent management were addressed throughout the study period. For this stage, sections concerning environmental management, water use, waste management, anaerobic digesters, biofertilizers, and other practices aimed at the sustainability of milk production were examined.

Finally, information from the statistical databases and document analysis was integrated, making it possible to develop an overview of the Brazilian dairy chain and identify gaps in the availability of information on the generation, treatment, and disposal of effluents from the activity.

RESULTS AND DISCUSSION

The analysis of data from the IBGE Automatic Data Retrieval System (SIDRA) and Embrapa's Milk Yearbooks made it possible to characterize changes in Brazil's cattle herd, milk production, number of cows milked, and gross production value between 2018 and 2023. A joint assessment of these indicators enables an understanding of the transformations that occurred in the dairy production chain during this period and supports a discussion of their implications for effluent generation and management. In addition, the use of this system enables the retrieval of official data on Brazilian agricultural production, allowing time series to be analyzed and production indicators to be compared over time.

Table 1 presents the changes in the main indicators of the Brazilian dairy chain between 2018 and 2023. Overall, the cattle herd and gross production value increased, whereas the number of cows milked decreased over the period analyzed. In contrast, national milk production remained relatively stable, indicating changes in the activity's production dynamics. These results suggest a process of production intensification characterized by productivity gains and greater efficiency in dairy systems.

Table 1

Main data on the milk-producing industry in Brazil.

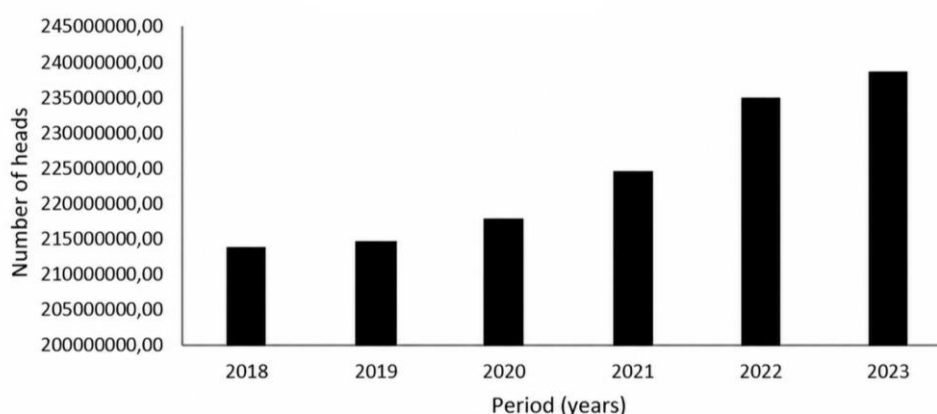
YEAR	HERD (Head)	PRODUCT (liters)		PRODUCT VALUE (R\$)	HERD
	CATTLE (IBGE)	IBGE	EMBRAPA	MILK (IBGE)	COWS MILKED (IBGE)
2018	213809445,00	33.907.899.000,00	24.460.000.000,00	39.344.516.000,00	16.353.091,00
2019	214689984,00	34.871.669.000,00	25.010.000.000,00	43.141.581.000,00	16.291.727,00
2020	217836282,00	35.316.667.000,00	25.060.000.000,00	56.348.186.000,00	15.953.935,00
2021	224601992,00	35.183.066.000,00	25.000.000.000,00	67.987.725.000,00	15.892.943,00
2022	234851536,00	34.554.161.000,00	35.305.000.000,00	79.919.856.000,00	15.675.519,00
2023	238626442,00	35.375.235.000,00	35.375.236.000,00	80.265.338.000,00	15.659.302,00

Source: IBGE Automatic Data Retrieval System (SIDRA) and Embrapa Dairy Cattle Milk Yearbooks.

The analysis of the national cattle herd shows an upward trend over the study period (Figure 1). However, this indicator should be interpreted cautiously when used in studies of the dairy chain because it includes animals raised for both beef and milk production. Its principal contribution is therefore to contextualize the development of Brazilian livestock farming, whereas specific indicators such as the number of cows milked and milk production more accurately characterize the dynamics of dairy farming.

Figure 1

Number of head of cattle in Brazil.



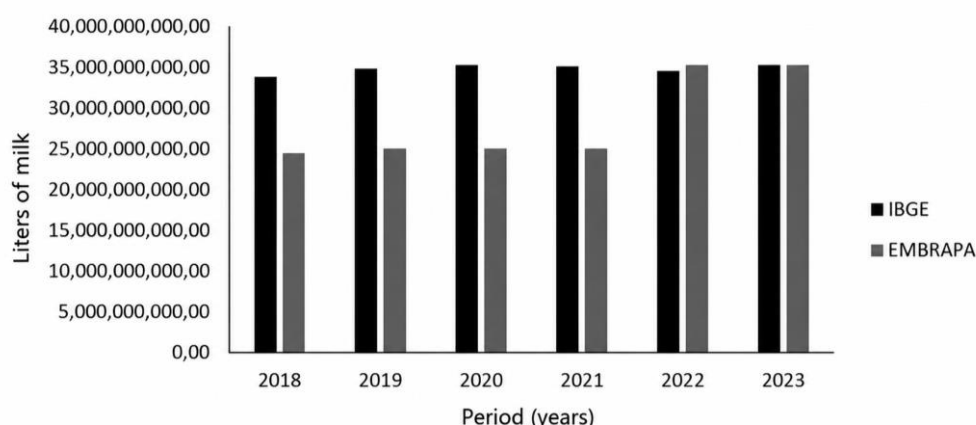
Source: IBGE Automatic Data Retrieval System (SIDRA) and Embrapa Dairy Cattle Milk Yearbooks.

Unlike the pattern observed for the cattle herd, national milk production remained relatively stable throughout the period analyzed, exhibiting only minor annual fluctuations (Figure 2). This pattern

suggests that Brazilian dairy farming is undergoing a process of production reorganization in which substantial increases in output depend less on expanding the number of animals and more on productivity gains achieved through genetic improvement, nutrition, management, and the technological advancement of farms.

Figure 2

Volume of milk produced according to data collected by IBGE and EMBRAPA.

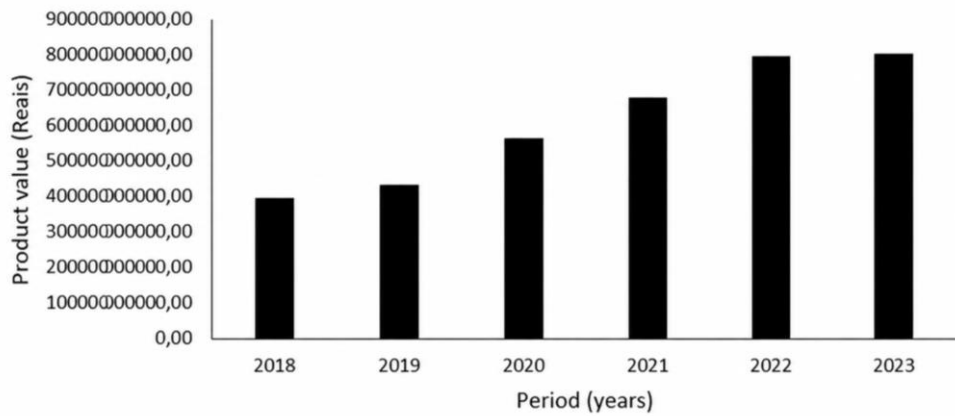


Source: IBGE Automatic Data Retrieval System (SIDRA) and Embrapa Dairy Cattle Milk Yearbooks.

Gross production value increased substantially over the study period (Figure 3), exceeding the change observed in the physical volume of milk produced. This pattern may be associated with increases in the price paid to producers, fluctuations in the national dairy market, production costs, and the inflationary effects recorded during the period, indicating that economic factors significantly influenced the activity's profitability.

Figure 3

Product value in Brazil.

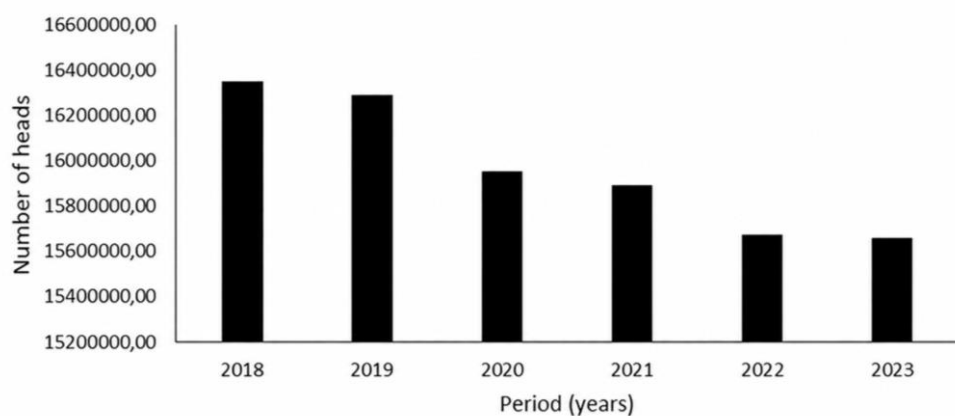


Source: IBGE Automatic Data Retrieval System (SIDRA) and Embrapa Dairy Cattle Milk Yearbooks.

One of the most significant findings of this study was the gradual reduction in the number of cows milked despite stable national milk production (Figure 4). A joint analysis of these indicators demonstrates an increase in average productivity per animal, a result consistent with the growing adoption of management technologies, genetic improvement, and precision feeding in Brazilian dairy farming.

Figure 4

Number of cows milked in Brazil.



Source: IBGE Automatic Data Retrieval System (SIDRA) and Embrapa Dairy Cattle Milk Yearbooks.

The integrated analysis of the indicators reveals changes in the dynamics of the Brazilian dairy chain between 2018 and 2023. Although the national cattle herd increased (Figure 1), the number of cows milked declined (Figure 4), while milk production remained relatively stable (Figure 2) and gross production value increased significantly (Figure 3). Taken together, these results suggest gains in production efficiency, indicating that production was maintained with fewer animals being milked, possibly because of the adoption of genetic, nutritional, and technological improvements in production systems.

From an environmental perspective, the intensification of dairy farming also creates challenges concerning the management of waste and effluents generated on farms. Although the data analyzed do not allow the volume of effluent produced to be quantified directly, Costa et al. (2021) state that between 0.2 and 10 L of effluent are generated per liter of milk processed and must be treated before disposal. This demonstrates that dairy systems consume substantial volumes of water and generate considerable quantities of effluent from cleaning facilities, washing equipment, and managing animal manure (Ruiz-González et al., 2024). As production becomes more intensive, planning strategies for the collection, treatment, reuse, and proper disposal of these effluents become equally important.

In this context, a significant gap is evident in the information made available by official agencies. Records in the IBGE Automatic Data Retrieval System (SIDRA) focus on production indicators such as herd size, number of cows milked, production, and production value, thereby enabling the development of the Brazilian dairy chain to be characterized consistently. However, no information is provided on the generation, treatment, reuse, or disposal of effluents produced on dairy farms. Incorporating these indicators into census surveys could contribute to the development of more accurate environmental assessments and support public policies aimed at the rational use of water, waste management, and the promotion of more sustainable practices throughout the production chain.

Ruiz-González et al. (2024) evaluated the effect of providing exercise areas for dairy cows on effluent properties and emissions of NH₃, carbon dioxide (CO₂), and greenhouse gases (GHGs) during

winter and summer. The authors observed that the characteristics of the effluent varied over the evaluation period and found that some parameters, such as biochemical oxygen demand (BOD) and suspended solids (SS), exceeded the limits established by environmental standards, particularly during winter. In addition to representing an environmental liability when improperly managed, effluents from dairy farming can also constitute a value-added resource. Following appropriate treatment, these wastes can be used to fertigate pastures and agricultural crops, produce biofertilizers, or generate biogas through anaerobic digestion, thereby contributing to the circular economy and reducing the environmental impacts of the activity.

Publications prepared by Embrapa Dairy Cattle, particularly the Milk Yearbooks, use data made available by IBGE through SIDRA as their statistical basis. Accordingly, the milk-production figures presented in these documents essentially correspond to the same data found in official databases. The principal distinction between the two sources lies in how this information is handled. Whereas SIDRA presents raw data organized in statistical tables, Embrapa's yearbooks incorporate interpretive analyses, technical discussions, and reflections on trends in the dairy production chain.

However, an analysis of the variables available in the system shows that there are no specific records concerning effluent generation from dairy farming, nor any data that would allow the volume of liquid waste produced, treated, or discharged into water bodies and soil throughout the production process to be quantified. Thus, although the system provides a detailed overview of the production dimension of dairy farming in the country, it does not include environmental indicators that would allow the impacts associated with the management of waste and effluents generated on rural farms or during the initial stages of the dairy production chain to be assessed directly.

A similar situation can be observed in publications prepared by Embrapa Dairy Cattle, particularly the Milk Yearbooks, which use data from IBGE's own system as their statistical basis. In these publications, quantitative data on milk production remain essentially the same because Embrapa relies on

official statistics to present sector indicators. The principal difference lies in how this information is interpreted and presented, as the yearbooks incorporate technical analyses, discussions of production trends, and reflections on the challenges facing Brazil's dairy chain.

Regarding effluents generated by milk production specifically, this information does not appear systematically in the yearbooks in the form of statistical indicators. Instead, the subject is addressed predominantly through research reports, case studies, and technical articles discussing environmental management practices, waste-treatment technologies, and initiatives aimed at making the activity more sustainable. Consequently, this study brought together and analyzed these different contributions appearing in the yearbooks to understand how the issue of effluents has been addressed over the years in the context of Brazilian milk production.

A chronological analysis of Embrapa's Milk Yearbooks reveals a gradual development in how environmental issues related to the dairy chain were addressed between 2018 and 2023. In the first years analyzed, the publications focused predominantly on production, economic, and technological indicators, whereas environmental aspects were addressed more sporadically. Beginning in 2020, discussions of sustainability expanded, with greater emphasis on topics such as the rational use of water, waste management, anaerobic digesters, biofertilizers, the circular economy, and mitigation of greenhouse gas emissions. This development demonstrates that sustainability has assumed an increasingly prominent place in discussions on the development of the Brazilian dairy chain.

Despite this progress, no quantitative indicators related to the generation, treatment, or disposal of effluents from milk production were identified in Embrapa's Milk Yearbooks. This finding reinforces the gap also observed in IBGE databases, which provide detailed information on livestock, production, and economic indicators but do not include environmental data capable of quantifying effluent generation on farms. The absence of this information limits the preparation of regional- and national-scale environmental assessments, as well as the planning of strategies aimed at efficient water use, effluent

treatment, and the use of these wastes in practices such as fertigation, biofertilizer production, and biogas generation.

In the Anuário Leite 2018 [2018 Milk Yearbook] (EMBRAPA, 2018), for example, no direct references were identified concerning the treatment or use of effluents generated by dairy farming. The publication focuses primarily on presenting production data, market trends, and structural aspects of the dairy chain without examining the environmental management of waste from the activity in greater depth.

A similar situation can be observed in the Anuário do Leite 2019 [2019 Milk Yearbook] (EMBRAPA, 2019). Although this edition contains an article on sustainable products, it does not specifically address the treatment or use of manure and effluents from milk production. This suggests that, at the time, discussion of sustainability in the sector was still at an early stage and was conducted in broader terms, with less focus on environmental issues directly related to the production process.

Beginning in 2020, however, a gradual change in how the topic was addressed can be observed. The Anuário Leite 2020 [2020 Milk Yearbook] (EMBRAPA, 2020) presents two significant topics related to sustainability in milk production. The first concerns the rational use of water and effluent management, emphasizing the importance of adopting technologies that increase production efficiency while reducing the waste of water resources. This discussion is particularly relevant because milk production requires significant volumes of water for activities such as cleaning equipment and facilities and managing animals.

The second topic addressed in this edition concerns the use of anaerobic digestion as an alternative for utilizing the organic waste generated by dairy farming. Anaerobic digestion transforms organic waste into biogas and biofertilizers, simultaneously promoting renewable energy generation and reducing environmental impacts. The material resulting from this process contains significant concentrations of nutrients such as nitrogen, phosphorus, and potassium and can be used as an agricultural fertilizer. Studies cited in this edition indicate that this type of material can partially replace inorganic fertilizers, reducing

the need for mineral fertilization by as much as 22% in crops such as corn, depending on management conditions.

In the Anuário Leite 2021 [2021 Milk Yearbook] (EMBRAPA, 2021), the sustainability debate takes on a broader dimension and begins to encompass strategies related to the environmental management of companies in the sector. In this context, initiatives by different organizations seeking to incorporate sustainable practices into their operations are presented. These initiatives include the incorporation of costs associated with carbon emissions into companies' financial statements, a practice that demonstrates growing concern with internalizing environmental impacts into the economic management of the activity.

In addition, some companies have begun adopting circular-economy principles by promoting the recycling of packaging materials such as plastics and paper and seeking to reduce waste generation throughout the production chain. These initiatives indicate that the sector is gradually moving toward more sustainable production models in which environmental management is regarded as an integral component of competitiveness and market-positioning strategies.

This trend becomes even more apparent in the Anuário Leite 2022 [2022 Milk Yearbook] (EMBRAPA, 2022), which more directly addresses the relationship between milk production and climate change. This edition focuses on strategies for reducing or neutralizing carbon emissions associated with the activity. The practices suggested include improvements in the management of production systems, the adoption of low-impact technologies, and the development of products aligned with emission-reduction targets.

The Anuário Leite 2023 [2023 Milk Yearbook] (EMBRAPA, 2023), in turn, highlights the role of sustainable dairy farms and emphasizes the importance of properly managing production systems to mitigate greenhouse gas emissions. According to the discussions presented, approximately 5% of global greenhouse gas emissions are associated with milk production. In this context, practices such as proper

pasture management, improvements in animal feed efficiency, and appropriate waste management are identified as important strategies for reducing the emission intensity associated with the activity.

The Anuário Leite 2024 [2024 Milk Yearbook] (EMBRAPA, 2024) introduces a discussion of environmental labeling and the carbon footprint of milk. Environmental labeling is presented as an instrument capable of informing consumers about the environmental impacts associated with the production of specific products throughout their life cycles. In the case of milk, the carbon footprint corresponds to the quantity of greenhouse gases emitted during the production process, expressed in kilograms of carbon dioxide equivalent (CO₂eq) per unit of product. This indicator considers different emission sources, including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), which are converted into equivalent CO₂ values for comparison purposes.

Reducing the carbon footprint of milk involves a series of stages ranging from selecting calculation tools to continuously monitoring emissions and implementing mitigation strategies. These stages include collecting data on the production system, identifying the principal emission sources, critically analyzing the results obtained, and planning measures to reduce emissions throughout the production chain.

Finally, the Anuário Leite 2025 [2025 Milk Yearbook] (EMBRAPA, 2025) presents a more comprehensive approach to the relationship between milk production and environmental sustainability, including more direct discussions of effluent treatment. This edition mentions several technological alternatives for properly managing waste generated by the activity, such as anaerobic digesters and composting systems. These technologies reduce the release of gases such as methane and nitrous oxide while allowing the waste to be used to produce biogas and organic fertilizers.

The yearbook also highlights the potential use of agricultural, livestock, and industrial biological inputs as tools for the sustainable management of waste generated by milk production. Although these initiatives are still presented in general terms and without an in-depth account of their implementation

nationwide, they indicate a growing movement within the sector toward adopting more sustainable practices aligned with contemporary demands for environmentally responsible agricultural production.

The analysis conducted throughout this study made it possible to understand how the issue of effluents generated by milk production has been addressed in Brazil, both statistically and in the technical discussions contained in specialized publications. By evaluating the information available in the official databases of the Brazilian Institute of Geography and Statistics (IBGE), particularly through the IBGE Automatic Data Retrieval System, and analyzing the technical publications prepared by Embrapa Dairy Cattle, significant gaps were identified in the consolidation of information concerning the generation, treatment, and disposal of effluents from dairy farming.

One of the main points revealed by this study concerns the absence of specific regulations governing the treatment and management of effluents generated in the milk production process. Although various environmental laws address effluent discharges and the protection of water resources in general, including the National Water Resources Policy (Law No. 9,433/1997) and CONAMA Resolutions No. 357/2005 and No. 430/2011, the analysis did not identify a national regulatory framework specifically addressing the characteristics of effluents generated by milk production. This absence of more specific regulation may hinder the implementation of standardized environmental management practices on rural farms because producers frequently need to interpret broader rules and adapt them to the realities of their production systems.

Another relevant aspect identified concerns how the issue of effluents has been addressed in technical and scientific circles. The analysis of the publications consulted indicates that research and initiatives concerning waste management and effluent use in milk production do exist. However, these studies are relatively scattered and are often associated with specific projects or isolated experiences developed by research institutions. This characteristic prevents the knowledge generated in this field from becoming fully integrated, potentially hindering access to and application of this information by rural producers and other stakeholders in the production chain.

In this context, there is still no clear framework that brings together and systematizes the various existing proposals for managing effluents from milk production. Although technical studies and institutional reports discuss a range of environmental management technologies and practices, such as anaerobic digesters, composting systems, and nutrient-reuse strategies, these solutions are not always organized systematically in guidance documents that can serve as a direct reference for producers.

This gap becomes particularly significant when the scale of Brazil's dairy production chain is considered. The yearbooks analyzed show that milk production involves many rural properties distributed throughout different regions of the country, with production systems that vary considerably in scale, technological level, and investment capacity. In this context, the absence of clearer guidelines may create difficulties in adopting appropriate effluent-management practices, particularly on smaller farms or those with less access to specialized technical assistance.

Another point that warrants attention concerns the responsibility assigned to rural producers for managing the effluents generated by the activity. The analysis shows that a substantial share of the decisions concerning the selection of treatment systems, waste-reduction strategies, and forms of effluent reuse ultimately rests directly with producers themselves. In practice, this means that producers must often seek information, evaluate the technological alternatives available, and decide which measures can be implemented on their farms. Although this autonomy may promote the adoption of solutions tailored to the specific characteristics of each production system, it can also pose a challenge, particularly when accessible information or adequate technical guidance is lacking. In this regard, the absence of clearer guidelines and support instruments may lead to the adoption of inefficient practices or even the continuation of management systems that do not fully meet environmental requirements.

Furthermore, the availability of data on effluent generation and disposal remains limited. As observed in the analysis of IBGE's statistical databases, the available information focuses primarily on the production and economic indicators of dairy farming and does not include specific variables concerning

its environmental dimensions. The absence of consolidated data makes it difficult to prepare more accurate assessments of the volume of effluents generated by the sector and the practices effectively adopted for their treatment and disposal.

It is therefore clearly necessary to expand the mechanisms used to monitor and record information concerning the environmental management of milk production. Incorporating indicators of effluent generation and management into official statistical databases could contribute significantly to the development of more targeted public policies, while also providing support for future research and the formulation of more efficient environmental management strategies.

Another aspect emerging from the study's results concerns the potential integration of production practices and environmental sustainability strategies throughout the dairy chain. Technologies such as anaerobic digesters, nutrient-reuse systems, and proper manure management have the potential not only to reduce environmental impacts but also to generate additional economic benefits for producers, including biogas production and the use of biofertilizers on their own farms. However, for these alternatives to become more widespread, stronger coordination among research institutions, rural extension agencies, and public policies directed toward the sector is essential.

In this regard, initiatives aimed at disseminating knowledge, training producers, and developing incentive programs for the adoption of sustainable technologies could play an important role in promoting more appropriate management practices. Developing technical instruments that bring together and systematize the different solutions available may also help make the decision-making process more accessible to producers.

Finally, the results obtained in this study indicate that, although progress has been made in discussions of sustainability within the dairy production chain, significant gaps remain in the management of effluents generated by the production process. The absence of specific regulations, the fragmented nature of existing research, and the limited availability of consolidated data constitute challenges that must be addressed if the sector is to move toward more sustainable production models.

The importance of expanding the debate on the environmental management of milk production in Brazil is therefore reaffirmed, with a view to promoting greater integration among research, public policy, and production practices. Strengthening this coordination could contribute to the development of more effective effluent-management strategies, thereby supporting both the environmental sustainability of the activity and the continuity and competitiveness of milk production in the country.

Finally, the quantitative data obtained from the statistical databases were analyzed in conjunction with the qualitative information from the literature review. This integrated analysis made it possible to establish relationships between changes in milk production in Brazil and the environmental challenges associated with the activity, particularly regarding the generation and management of effluents in the production process. The methodological approach adopted thus enabled a more comprehensive understanding of the production, economic, and environmental aspects characterizing the country's dairy chain.

The absence of specific indicators in official statistical databases limits the ability to quantitatively assess these environmental impacts, reinforcing the need to expand systems for monitoring and producing information concerning the environmental management of dairy farming in Brazil.

CONCLUSION

This study made it possible to analyze the recent development of the Brazilian dairy chain and identify how the issue of effluents has been addressed in the sector's principal information sources and technical publications. IBGE data revealed changes in production dynamics between 2018 and 2023, characterized by an increase in the cattle herd, a reduction in the number of cows milked, stable milk production, and growth in gross production value. At the same time, the analysis of Embrapa's Milk Yearbooks revealed the increasing incorporation of sustainability-related topics over the years, although

quantitative indicators concerning the generation, treatment, and disposal of effluents from dairy farming remain unavailable.

The results demonstrate the need for greater integration between production and environmental information in the dairy chain by incorporating indicators related to effluent management into official statistical databases and strengthening technical instruments that support producers and public administrators. Consolidating this information could contribute to the environmental planning of the activity, support the formulation of public policies, and encourage the adoption of technologies for treating and reusing effluents, thereby promoting the development of more efficient and sustainable production systems.

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