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Review

General Aspects and Applications of Juazeiro (*Ziziphus joazeiro* Mart.): Bioactive Compounds, Antioxidant Activity, and Antimicrobial Potential

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Abstract

Ziziphus joazeiro Mart., commonly known as juazeiro, is a tree species native to the Brazilian semi-arid region. It produces yellow drupe fruits with white, mucilaginous pulp known as juá. Various parts of the plant, such as its leaves and stem bark, have been widely used in traditional medicine to treat wounds, ulcers, and dermatitis, as well as to combat fever and bacterial infections. While its fruits are highly recommended for human consumption due to their nutritional composition, they also present significant potential for exploration as a raw material rich in biological properties. This is evidenced by their traditional use in folk medicine and other phytotherapeutic applications, such as the utilization of the trunk bark for oral hygiene and in the production of cosmetics and shampoos, owing to its saponin content, which possesses foaming properties. This review aims to present the relevant literature on *Z. joazeiro* Mart. while highlighting the comparatively limited attention given to the fruit, particularly regarding its bioactive and functional properties associated with the presence of antioxidant compounds.

Keywords: medicinal plants; phytochemicals; bioactive compounds phenolic compounds

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1. Introduction

The juazeiro (*Ziziphus joazeiro* Mart.), a member of the Rhamnaceae family, is an arboreal species endemic to the Caatinga biome, with broad ecological, medicinal, and socioeconomic relevance. Botanically, it is a perennial, thorny tree that can reach up to 15 m in height, characterized by a dense crown and deciduous leaves adapted to withstand the adverse conditions of the semi-arid environment. Its flowers are small, yellowish-green, and arranged in axillary clusters, while its fruits are drupaceous and rounded, with a fleshy mesocarp and a stony endocarp enclosing one or two seeds [1,2]. These morphological traits provide the juazeiro with a strategic role in ensuring resilience within the Caatinga ecosystem while also reinforcing its cultural symbolism in the Brazilian semi-arid region.

Traditionally, different parts of the plant have been employed in popular therapeutic practices, particularly the leaves and bark, due to their well-recognized bactericidal, analgesic, and wound-healing properties. The consolidated use of these plant organs is largely associated with the presence of saponins and other bioactive secondary metabolites. Conversely, the fruits, although less commercially explored, present remarkable functional potential and are reported to be rich in phenolic compounds and vitamin C, elements directly linked to antioxidant activity [3].

Beyond its medicinal importance, the species is widely used as an ornamental plant, a source of energy, and a raw material for the cosmetic and hygiene industries. The fruits, despite being undervalued, play a relevant nutritional and ecological role, serving as food for both humans and animals, particularly during drought periods, and have been associated with antipyretic and antioxidant properties [4].

Despite its broad applicability, the exploitation of juazeiro remains predominantly extractive, a practice that limits both the conservation of the species and the sustainable use of its resources. Scientific knowledge accumulated to date remains insufficient to support technological advances, particularly with regard to the fruit, which remains underexplored in the literature. Most studies focus on the leaves and bark, neglecting the potential of integral utilization of the plant, which reveals significant gaps to be addressed [5].

In this context, the present review aims to bring together general aspects and applications of *Ziziphus joazeiro* Mart., with emphasis on the phytochemical and nutritional composition of its fruits and their functional properties. Particular attention is given to bioactive compounds, antioxidant activity, and the antimicrobial potential of different plant parts, as well as to the methods of obtaining these compounds. This approach establishes an analytical framework that highlights both the potentialities and the current limitations of *Ziziphus joazeiro* research. Notably, there is a need to expand investigations focusing on the fruit, which remains comparatively underexplored in relation to the bark and leaves, while also identifying pathways toward the integral valorization of the species.

The scarcity of publications on *Ziziphus joazeiro* Mart. highlights both the originality and the urgency of more systematic and interdisciplinary studies. Investigations ranging from the assessment of physical characteristics to the development of sustainable extraction methods are fundamental for advancing knowledge and promoting the technological utilization of this species. Furthermore, the incorporation of innovative approaches may broaden its application potential in foods, cosmetics, and herbal medicines, thereby adding value to the biodiversity of the Brazilian semi-arid region and reinforcing the strategic role of juazeiro as a natural resource with multiple uses.

2. Bibliographic Analysis

2.1. Origin and Botanical and Ecological Aspects of the Juazeiro

The juazeiro (*Ziziphus joazeiro* Mart.) belongs to the Rhamnaceae family, with the genus Ziziphus comprising one hundred species distributed worldwide, nine of which are found in Brazil. Of these, five are endemic, including *Z. joazeiro* Mart., a tree native to the Brazilian semi-arid region, typical of the Caatinga biome [6,7].

The Caatinga is an exclusively Brazilian biome that covers 11% of the national territory and can be divided into two groups: the hypoxerophytic and the hyperxerophytic. The first group consists of arboreal vegetation, including the species *Z. joazeiro* Mart. [3]. The juazeiro is one of the tree species that remains evergreen, not losing its foliage completely, and generally renews its leaves in October [8]. This behavior is characteristic of a perennifolious, heliophytic, autotrophic plant, with deep pivoting roots that allow it to access water from the underground [9].

The juazeiro has leathery, coriaceous leaves with a texture similar to leather, which break easily, are glossy and elliptical, and bear small yellow-greenish flowers in clusters with axillary formations, and it has a deep root system [10]. Figure 1 illustrates the tree bearing fruits at an advanced stage of maturity.



Figure 1. Specimen of *Ziziphus joazeiro* Mart. with fruits at mature ripening stage. Source: Author's own.

According to [11], Rhamnaceae species are characterized by their ability to thrive under the adverse climatic conditions of the Caatinga, which experiences hot and dry summers and cold, rainy winters. In its natural habitat, the growth of *Ziziphus joazeiro* is slow, not exceeding 1 m per year in adulthood [1]. It has the ability to withstand long periods of drought. The juazeiro remains evergreen throughout its lifespan, living up to 100 years [11]. It is widely distributed across four distinct mesoregions of the state of Paraíba, located in the Brazilian Northeast: Mata Paraibana, Borborema, Agreste, and Sertão Paraibano. The species *Ziziphus joazeiro* Mart., native to the Brazilian semi-arid region, is widely distributed across the mesoregions, where the climatic conditions and shallow soils typical of the semi-arid environment favor its development. Figure 2 illustrates the location of the state of Paraíba within Brazil and highlights its four mesoregions: Sertão, Borborema, Agreste, and Zona da Mata (Forest Zone of Paraíba).

The geographic distribution of *Ziziphus joazeiro* Mart. in Paraíba state, Brazil, is strongly associated with the predominant edaphoclimatic characteristics of the Sertão and Borborema mesoregions (Figure 2). These regions, characterized by a semiarid climate, low annual precipitation, and high solar radiation, favor the growth of species adapted to water scarcity and high temperatures, such as *Z. joazeiro*. However, factors such as difficulty in seed germination pose a risk to the survival of this species, especially considering the gradual destruction of native vegetation due to the uncontrolled expansion of human activities, although it has high growth potential in different edaphic environments, adapting well to soils of varied textures and chemical compositions [12]. According to [13], it is considered a priority species for the development of research related to its conservation, since its deep roots help to fix the soil and reduce erosion in arid areas, while the fruits serve as food for wild birds and mammals, while the dense canopy offers shelter for different species in addition to providing wood and energy, animal fodder and properties in traditional medicine, thus presenting economic and ecological importance for the Northeast region of Brazil.

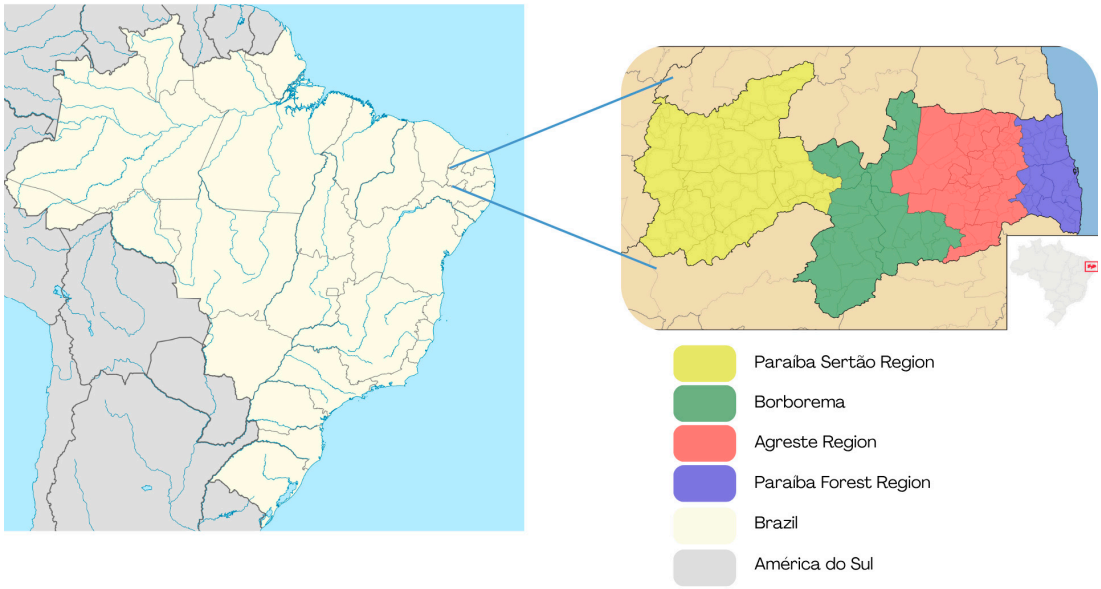


Figure 2. Map of the mesoregions of Paraíba, Brazil (IBGE, 2022). Source: Author's own.

The Sertão mesoregion, represented in yellow in Figure 2, constitutes one of the driest areas of the state, with Caatinga vegetation predominating. In this environment, *Z. joazeiro* occurs naturally and abundantly, playing a key ecological role in maintaining local biodiversity and serving as forage for ruminants during drought periods. Borborema, shown in green, although presenting greater altitudinal variation and slightly higher rainfall indices, still retains typical semi-arid conditions across much of its territory, allowing for the species' presence.

The other mesoregions, such as Agreste (red) and Zona da Mata (blue), exhibit less favorable conditions for the natural occurrence of the species due to higher relative humidity and denser vegetation cover. However, isolated individuals of *Z. joazeiro* can still be found in these areas, particularly in ecological transition zones or as a result of anthropogenic introduction.

Its main characteristic is the ability to thrive under adverse climatic conditions. The species holds socioeconomic importance for the northeastern and semi-arid regions of Brazil, with its parts (stem, bark, leaves, fruit, and roots) being used for food and medicinal purposes, as well as in rural construction and firewood production [3].

The understanding of the origin, botanical aspects, and ecological interactions of *Ziziphus joazeiro* Mart. provides the necessary foundation to explain its broad spectrum of applications. Its morphological and physiological characteristics—such as the ability to withstand the adverse conditions of the semi-arid environment, natural regeneration, and the phytochemical diversity distributed among leaves, bark, fruits, and roots—not only ensure its ecological relevance but also support the various uses already consolidated in traditional medicine and local cultural practices [14]. This set of attributes demonstrates the close relationship between the species' adaptation to the Caatinga environment and its biotechnological potential, justifying the scientific attention directed toward the integral valorization of juazeiro.

The understanding of the origin, morphology, and ecological role of *Ziziphus joazeiro* Mart. provides the foundation for explaining the growing scientific interest in this species. The adaptations that ensure its survival in the semi-arid environment, together with the phytochemical diversity distributed across leaves, bark, and fruits, underscore its relevance as a natural resource with multiple uses. In this context, the trends in scientific publications reflect the pursuit of deeper knowledge about these characteristics and the expansion of their potential applications across different fields of study.

2.2. Scientific Publication Trends on *Ziziphus joazeiro* Mart.

A search was conducted in the Web of Science online database. As illustrated (Figure 3), the number of research articles indexed using the keyword "*Ziziphus joazeiro* Mart." was analyzed.

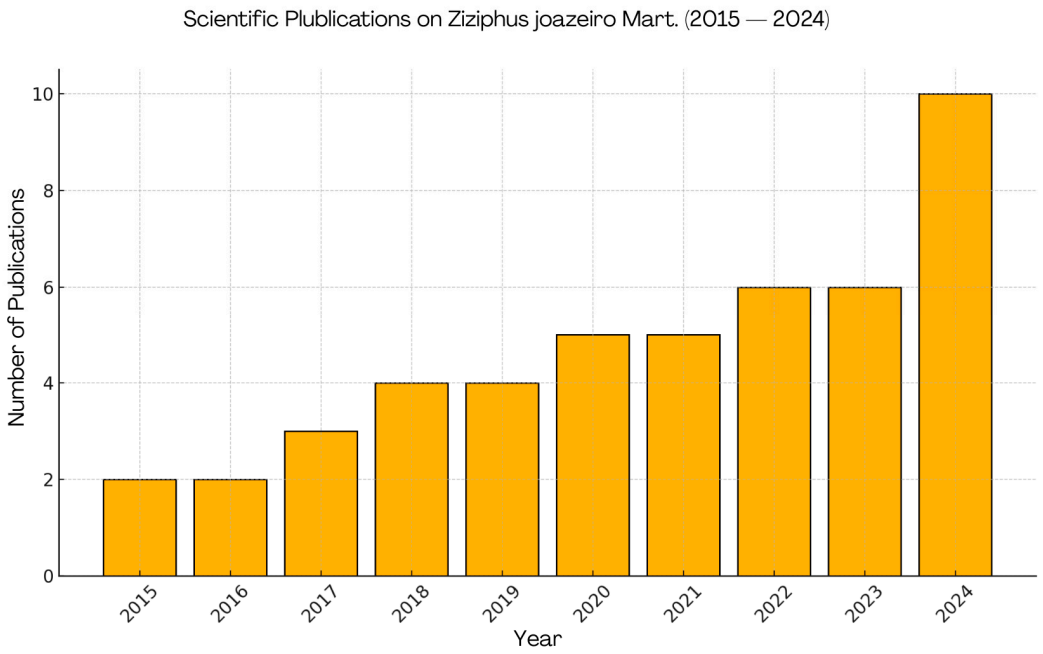


Figure 3. Estimated number of research articles on *Ziziphus joazeiro* Mart. indexed in Web of Science from 2015 to 2024, based on a total of 47 publications. Source: Author's own.

In order to contextualize the originality and relevance of this study, a bibliographic search was conducted using the Web of Science database, covering the period from 2015 to 2024. The results revealed that only 47 scientific articles on *Ziziphus joazeiro* Mart. were published over the past ten years (Figure 3), highlighting the limited scientific exploration of this plant species.

A relatively stable publication trend was observed, with a slight increase from 2018 onward; however, the number of publications remains modest, especially when compared to other tropical species with similar biotechnological potential. Most studies focus on the use of leaves, bark, and roots, primarily for the extraction of bioactive compounds with pharmacological or ethnobotanical purposes. Within this context, the present work emerges as a novel and strategic contribution, by investigating, in an integrated manner, the physicochemical properties, nutritional composition, and bioactive potential of the fruits. This research not only expands the current scientific understanding of *Z. joazeiro* but also opens new perspectives for its technological application in food and functional formulations.

The significant concentration of studies in the field of Biological Sciences suggests that *Ziziphus joazeiro* Mart. has been predominantly investigated from a botanical, pharmacological, or ecological perspective. In contrast, the limited number of publications in Agricultural Sciences, Engineering, and Multidisciplinary fields highlights an opportunity for more integrated approaches focused on technological applications and product development.

Figure 4 shows the percentage distribution of scientific articles published on *Ziziphus joazeiro* Mart. between 2014 and 2024, by field of knowledge.

The analysis of the scientific output related to *Ziziphus joazeiro* Mart. between 2014 and 2024 revealed a marked predominance of the Biological Sciences, accounting for approximately 83.3% of the articles indexed in the Web of Science database. This result highlights the prevailing interest of the scientific community in the biological aspects of the species, such as its phytochemical characterization, pharmacological properties, antioxidant

and antimicrobial potential, and general biological activities. This concentration may also reflect the longstanding tradition of ethnobotanical and ethnopharmacological studies involving Caatinga plants—a biome in which *Z. joazeiro* is native and widely used by traditional communities.

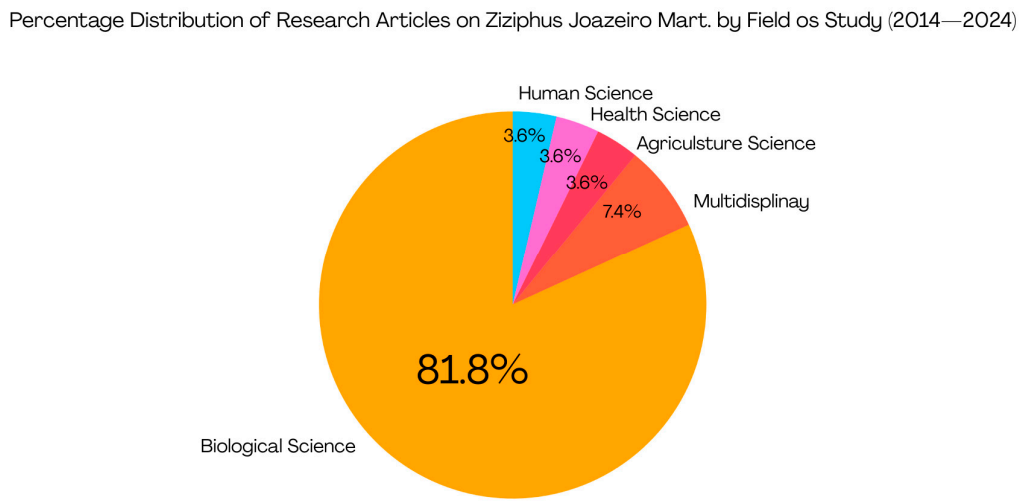


Figure 4. Percentage distribution of research articles on *Ziziphus joazeiro* Mart. by field of study between 2014 and 2024. Source: Author's own.

Other research areas—Multidisciplinary (7.4%), Agricultural Sciences (3.7%), Health Sciences (3.7%), and Human Sciences (3.7%)—appear far less frequently. The presence of articles classified as Multidisciplinary suggests integrative, albeit infrequent, approaches involving social, economic, and ecological dimensions of joazeiro usage. Meanwhile, publications in Agricultural Sciences indicate an emerging field concerning the species' agronomic potential and sustainable management, particularly in relation to cultivation in semiarid regions, soil recovery, and the use of its fruits and leaves as inputs for animal feed or green manure.

The limited number of studies in Health Sciences is particularly noteworthy, as it points to a gap in research aimed at developing herbal medicines or pharmaceutical products derived from plant extracts or isolated active compounds. Despite extensive literature on its traditional medicinal uses, there is little evidence of translating this knowledge into clinical research, technological development, or therapeutic applications.

The inclusion of studies in the Human Sciences, although occasional, may be associated with analyses of cultural practices, traditional knowledge, and historical aspects related to the use of *Ziziphus joazeiro* in semiarid communities. Such perspectives are essential for understanding the sociocultural role of the species and its interface with traditional knowledge systems.

It is also worth highlighting the absence of publications in the field of Engineering, which presents an opportunity for future research focused on technological applications of the species. The exploration of its fibers, extracts, or bioactive compounds in cosmetic formulations, biodegradable packaging, controlled-release systems, or biomaterials could open new research frontiers—particularly aligned with the principles of bioeconomy and sustainability.

The growth of scientific publications on *Ziziphus joazeiro* Mart. reflects the increasing interest in deepening knowledge of its properties and expanding the possibilities for its utilization. This trend directly aligns with the uses already consolidated in traditional medicine and with experimental evidence that highlights potential applications across different sectors. In this way, the scientific literature has contributed to transforming empirical knowledge into technological foundations, paving the way for the development of products derived from the leaves, bark, fruits, and other parts of the juazeiro.

2.3. Uses and Potential Applications of Parts of the Juazeiro

The mature tree has dense foliage and is used for ornamental purposes, as an energy source, in traditional medicine as an expectorant and for the treatment of gastric ulcers, as well as in the production of cosmetics, anti-dandruff shampoos, and toothpaste. Additionally, it holds ecological significance [7,14].

It is commonly maintained in pastures to provide shade for livestock. The tree has the ability to regenerate from the base of the stem after being cut at ground level, making it frequent in areas undergoing natural regeneration [14]. Among its biological activities, antibacterial, antifungal, antiparasitic, antioxidant, and gastroprotective properties stand out [15].

Figure 5 illustrates the functional anatomy of *Ziziphus joazeiro* Mart., highlighting the use of different parts of the plant—flowers, fruits, leaves, bark, and roots—for ecological, nutritional, medicinal, and biotechnological purposes.

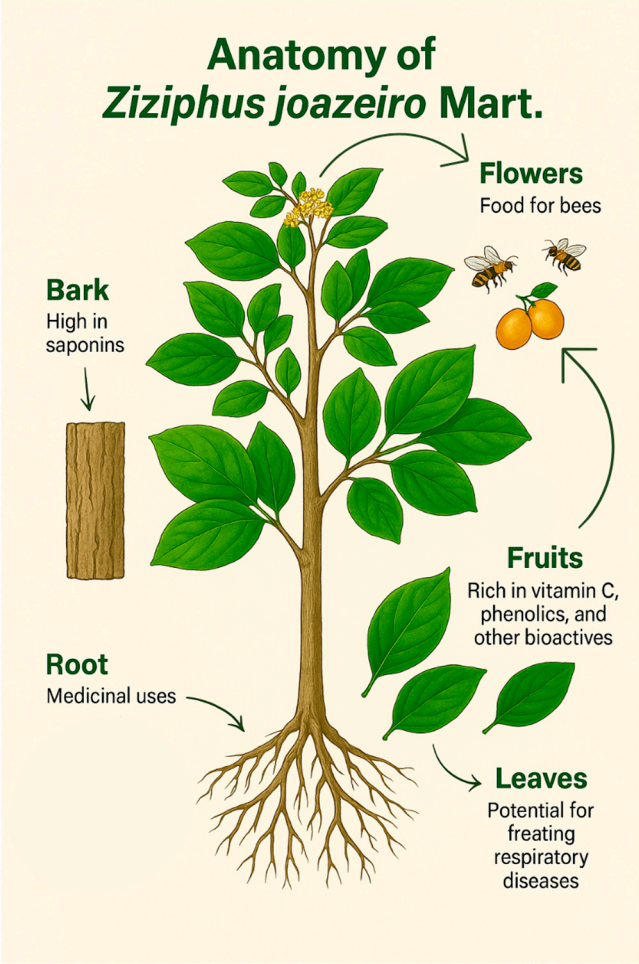


Figure 5. Anatomy of the *Ziziphus joazeiro* Mart. plant by parts and their respective traditional applications. Source: Author's own.

The leaves are used in traditional medicine to treat respiratory diseases such as asthma, pneumonia, and bronchitis, as well as other ailments [11]. They can also be used as an alternative feed resource for goats and sheep during the dry season [8] and in the production of anti-dandruff shampoo and hair tonic, as well as for washing utensils, cotton fabrics, and glass objects [16,17]. The juazeiro (*Ziziphus joazeiro* Mart.), showing simple, leathery and glossy leaves, together with axillary inflorescences formed by small greenish flowers, is illustrated in Figure 6.



Figure 6. Leaves and flowers of *Ziziphus joazeiro* Mart., highlighting the broad, glossy leaves and the small yellowish-green axillary flowers characteristic of the species.

The flowers are discoid, greenish in color, and produce a small amount of nectar, though with a high sugar concentration, which may be explained by the type of pollinator. These flowers serve as an important food source for stingless bees, which are used in meliponiculture as an alternative source of income for producers in certain areas of the Caatinga [18].

Juá, as the fruit of *Ziziphus joazeiro* mart. is known, is small and round, yellow in color and has a sweet flavor. Although it is commonly used by the local population, scientific data on its chemical composition remain scarce. However, evidence suggests that the fruit is rich in bioactive compounds, including vitamin C and phenolic compounds [11]. In this context, the presence of phenolics and vitamin C in the fruit indicates a dual role: in addition to providing protection against oxidative reactions that compromise the quality of food products, these compounds can also add nutritional and functional value to formulations. The integral utilization of the fruit—abundant, accessible, and still underexplored—may help reduce the pressure on the bark, historically used on a larger scale, thus reconciling species conservation with sustainable exploitation. Therefore, the available data suggest that juazeiro should not be regarded solely as an ethnobotanical resource of cultural value, but also as a native matrix with high potential to generate innovative and sustainable solutions in food systems.

The study in [19] found that the fruit is rich in dietary fiber and phenolic compounds with high antioxidant activity. Some of these compounds can be identified in Figure 7. It highlights the effect of edible coatings based on juá pulp mucilage on the physicochemical, bioactive, and antioxidant quality of foods, aiming at food preservation. In a study by [20], the determination of the thermodynamic properties of *Ziziphus joazeiro* Mart. seed flour provided information about the seed kernel present in the fruit, reporting the flour's hygroscopic parameters and facilitating possible applications of this product to ensure proper storage.

Due to its natural abundance and ease of harvesting, *Ziziphus joazeiro* Mart. can be considered a promising natural product with biotechnological applications, particularly as an alternative source of hydrocolloids for the development of edible coatings [21]. The fact that different parts of the plant exhibit specific functions—from the medicinal use of the leaves and bark to the technological potential of the fruits—suggests that the species encompasses a diverse phytochemical profile, capable of supporting multiple application pathways. This diversity broadens the perspectives for utilization, particularly in food systems, where bioactive compounds with antioxidant and antimicrobial properties can act simultaneously in food preservation and in providing functional benefits to consumers.

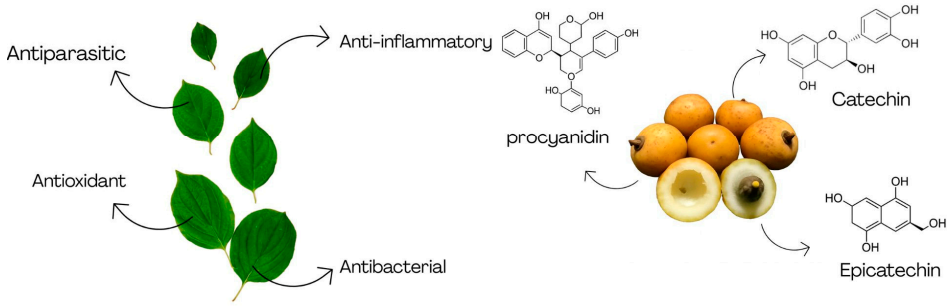


Figure 7. Main bioactive compounds identified in the leaves and fruits of *Ziziphus joazeiro* Mart. and their associated biological activities.

Table 1 presents several studies that have used *Ziziphus joazeiro* Mart. as the material of analysis, evaluating its potential from different perspectives. Most of the cited studies explore the antioxidant and antimicrobial potential of *Ziziphus joazeiro*, with a greater focus on the extraction and characterization of these compounds. These studies primarily target the stem bark and leaves of the plant, comparing their results to hypothesize which may be more promising for potential applications in future research.

Table 1. Studies conducted on different parts of the *Ziziphus joazeiro* plant.

Plant Part	Study	Potential Applications	Reference
Fruit	Effect of an edible coating with juá mucilage, incorporated with juá phenolic extract and juá mucilage with gum arabic, on the physicochemical quality, bioactive compounds, and antioxidant activity of freshly cut pineapple	Food coating	[20]
Leaf and bark	Chemical composition of the aqueous extracts from the leaves and stem bark of *Ziziphus joazeiro*, as well as the antibacterial action of the extracts alone and in combination with conventional antibiotics to assess their potential as antibiotic-modifying agents	Antibiotic-modifying agents	[4]
Leaf	Chemical profile of the hydroalcoholic extract from *Ziziphus joazeiro* Mart. leaves and its antioxidant, antiparasitic (*Trypanosoma cruzi* and Leishmania), and antibiotic (bacteria and fungi) activity, either alone or in combination with currently used conventional antibiotics	Hydroalcoholic extract	[22]
Bark and leaf	Antioxidant and antimicrobial activity of ethanolic extracts from *Ziziphus joazeiro* Mart., through a comparative investigation between bark and leaves	Antioxidant and antimicrobial ethanolic extracts	[23]
Stem bar	Description of the corrosion-inhibiting properties of the aqueous extract from the stem bark of *Ziziphus joazeiro*	Corrosion-inhibiting	[7]
Flowers	Analysis of the reproductive phenology, floral biology, and pollination system of *Ziziphus joazeiro*	Nectar with high sugar concentration	[18]
Leaf	The synthesis and optimization of silver nanoparticle preparation through the reduction of silver nitrate by the action of the aqueous extract of *Ziziphus joazeiro*, demonstrating effective antimicrobial activity against Staphylococcus aureus and *Escherichia coli*	Efficacy against Gram-positive and Gram-negative bacteria	[24]

Table 1. *Cont.*

Plant Part	Study	Potential Applications	Reference
Bark and leaf	Evaluation of the action of the aqueous extract from the bark and leaves of *Ziziphus joazeiro* in the eradication of bacterial and fungal biofilms, comparing these effects with those of the stem bark extract as well as standard conventional drugs	Bacterial and fungal biofilms	[25]
Leaf and bark	Allelopathic potential of leaf, bark, and root extracts of *Ziziphus joazeiro* on the germination and development of the weed species Calotropis procera and Cyperus echinatus	Control of the weed *C. echinatus* and possibly other monocotyledonous species	[21]
Seed	To evaluate the allelopathic activity of seed extract from *Ziziphus joazeiro* Mart. on the germination of lettuce (*Lactuca sativa* L.) seeds	Allelopathic potential of seeds from *Ziziphus joazeiro* Mart	[25]
Bark	Study of a natural alternative from *Ziziphus joazeiro* bark for the adsorption of indigo blue textile dye	Treatment of textile effluents containing indigo blue dye	[26]
Stem bark	Antimicrobial and antifungal activity of crude stem extract from juá for traditional use in combating mycoses	Combating myco	[27]

The diversity of extraction methodologies employed—including techniques such as maceration, ultrasound, and the use of solvents with varying polarities—contributes to a deeper understanding of the phytochemical composition of the species.

The main compounds identified, such as saponins, flavonoids, and tannins, have demonstrated not only significant biological activity but also stability and applicability in cosmetic, pharmaceutical, and food formulations. Similarly, the antimicrobial action of tannins and saponins can be explored as a natural alternative to the use of synthetic preservatives, contributing to the extension of shelf life without compromising food safety. The emulsifying and foaming properties of saponins also deserve emphasis, as they reveal technological functions that go beyond their biological effects and allow the incorporation of these compounds into industrialized products such as beverages, desserts, sauces, and other formulations.

In this context, *Ziziphus joazeiro* emerges as a native species of high biotechnological value, whose sustainable exploitation may contribute to the development of functional products and add value to Brazilian biodiversity. The bark extracts of *Ziziphus joazeiro* Mart. are the most studied, being rich in saponins and phenolic compounds with well-documented antimicrobial activity and traditional use in oral hygiene. The leaves also contain bioactive compounds with antioxidant and antimicrobial properties, though to a lesser extent. The fruits, however, remain underexplored but show potential as a source of nutrients and bioactives for functional food applications, requiring further in vivo and clinical studies.

The broad spectrum of applications attributed to *Ziziphus joazeiro* Mart. is intrinsically linked to its phytochemical composition. The various uses reported for its leaves, bark, and fruits—ranging from traditional medicine to formulations with potential technological and industrial relevance—are supported by the presence of secondary metabolites with well-documented biological activity. Among these, phenolics, flavonoids, tannins, and saponins are particularly noteworthy, with their antioxidant properties representing one of the primary mechanisms underlying both the therapeutic effects described and the technological applications in foods and functional products.

2.4. Bioactive Compounds and Antioxidant Activity

Bioactive compounds have functional properties and can provide health benefits, exerting various biological actions such as antioxidant activity, modulation of detoxifying enzymes, stimulation of the immune system, reduction of platelet aggregation, as well as antibacterial and antiviral activities. These compounds are found in many plant species and can be extracted from pulps, seeds, peels, and leaves [28].

Phenolic compounds, or polyphenols, are secondary metabolites that exist in two forms: soluble and insoluble. Soluble phenolics are often located in plant vacuoles, whereas insoluble bound phenolics are embedded in the cell wall matrix [29]. Polyphenols share a common chemical structure derived from benzene, linked to a hydrophilic group [30].

When evaluating the hydroalcoholic extract of *Ziziphus joazeiro* Mart. leaves to determine its chemical profile, as well as its antioxidant, antimicrobial, and antiparasitic activities [22], the results revealed the presence of flavonoids, tannins, and phenolic acids. According to the authors, these compound groups can be found in different parts of the plant, including the bark, leaves, fruits, and seeds. The diversity of bioactive compounds reported in different parts of *Ziziphus joazeiro* Mart. reinforces the wide spectrum of biological activities attributed to the species. The presence of flavonoids, tannins, phenols, and alkaloids, already identified in leaves, bark, and fruits, is directly associated with the described antioxidant, antimicrobial, and anti-inflammatory properties. These findings suggest that the phytochemical variability of the plant contributes significantly to its therapeutic potential and to its possible applications across different sectors, ranging from traditional medicine to functional foods and cosmetics.

Studies on the pharmacological properties of tannins suggest significant antibacterial activity, in addition to anti-inflammatory, antiparasitic, and gastroprotective effects. Tannins and flavonoids may benefit human health by exerting various biological effects, including free radical scavenging, metal chelation, and modulation of enzymatic activity [31].

The diversity of functional groups in flavonoids grants them various functions, contributing to their anti-inflammatory, antiviral, and anticancer properties. They can also be used as natural pigments, among other pharmaceutical and medicinal applications [32].

In a study conducted by [33] aimed at evaluating the in vitro antimicrobial activity of different extracts of *Ziziphus joazeiro* Mart. against microorganisms, the presence of alkaloids in ripe fruits was observed, along with the presence of flavonoids.

Regarding antioxidant activity, the results indicated that the leaves exhibited superior activity compared to the bark, highlighting that replacing the traditional medicinal use of bark with leaves could be an important measure for species conservation. Despite the significant antioxidant activity observed, particularly in the leaves compared to the bark, there are still gaps in understanding the specific contribution of each class of compounds to the overall biological performance. In this regard, the findings highlight the need to deepen knowledge on the distribution of bioactives across the different plant organs, as well as to explore utilization strategies that prioritize species conservation, replacing bark use with other parts that are equally rich in phenolic compounds.

In China, the fruit is primarily used in medicine for the treatment of cardiovascular diseases and tumors, as well as being consumed in both fresh and dried forms [34]. The high antioxidant activity of extracts from different parts of the fruit (bark, pulp, and seeds) has also been highlighted and attributed to the elevated levels of phenolic compounds [35]. According to [36], the presence of bioactive compounds may explain the anti-inflammatory, antioxidant, and anti-obesity activities, among other benefits, although a more systematic study of antioxidant compounds is still necessary.

It is possible to observe the application of distinct identification methodologies, ranging from classical colorimetric assays and spectrophotometry to advanced techniques such

as HPLC, UHPLC, NMR, and mass spectrometry, reflecting both the diversity of analytical approaches and the evolution of methods over time. These studies highlight not only the phytochemical richness of the species but also its pharmacological and technological potential, reinforcing the importance of *Z. joazeiro* as a source of compounds of interest for the food, pharmaceutical, and cosmetic sectors. Table 2 presents the main bioactive compounds identified in different parts of *Ziziphus joazeiro* Mart., with emphasis on triterpenoid saponins and triterpenoids, which are widely distributed in the bark, leaves, and fruits of the species.

Table 2. Bioactive compounds identified in *Ziziphus joazeiro* Mart.

Compounds	Plant Part	Identification Method	Reference
Saponins	Bark	In vitro anthelmintic activity	[37]
Saponins	Bark	Spectrophotometry	[26]
Betulinic acid	Bark	Micro ondas	[38]
Betulinic acid, ursólico e alfitólico, ácido 7 beta-(4-hidroxibenzoiloxi)-betulínico, ácido 7 beta-(4-hidroxi-3′-metoxibenzoiloxi)-betulínico e ácido 27-(4-hidroxi-3′-metoxibenzoiloxi)-betulínico	Bark	NMR spectroscopy and Mass spectrometry	[39]
Caffeic acid p-Coumaric acid Ferulic acid Cinnamic acid Naringenin Pinocembrin Apigenin	Leaves and bark	HPLC/DAD	[40]
Saponins	Bark	Vanillin–sulfuric acid	[41]
Guanidinosuccinic acid Aconitic acid Malic acid Citric acid Isospinosin Spinosin Ziziphursolic acid Protocatechuic acid Chalconaringenin-di-C-hexoside Betulonic acid + OH Jujuboside B Jujubasaponin III Ziziphin Ziziphus saponin I	Stem bark	UPLC-QTOF-MS/MS	[42]
Mauritine-L Sanjoinine-F Sativanine-C Sanjoinine-A Numularine-B, O, and Xylopyrine B Paliurine-D and C Jubanine-A and B	Stem bark	UHPLC-ESI-Orbitrap-HR-MS	[43]

Table 2. *Cont.*

Compounds	Plant Part	Identification Method	Reference
Jujuboside B Medicoside C 3-O-[β-d-Glucopiranosil (1→2)α-l-arabinopiranosil]-20-O-α-l-ramnopiranosil-jujubogenina	Stem bark	Dionex UHPLC liquid chromatography	[10]
Saponin None C-flavone glycosides Myricetin-0-glucoside Rutin Quercetin-0-hexoside Quercetin-robnoside Ramnazin-3-0-rutinoside Ramnazin-hexoside Dihydroxybenzoic acid pentoside None	Leaves and stem bark	UPLC-MS-ESI-QTOF	[44]
Ellagic acid	Fruits	HPLC	[11]

The bioactive compounds identified in different parts of *Ziziphus joazeiro* Mart., particularly triterpenoid saponins, which are widely detected in the bark and leaves, have been characterized using various analytical approaches. The identification methods employed range from spectrophotometric analyses and colorimetric reactions (vanillin–sulfuric acid) to high-precision instrumental techniques such as HPLC, UHPLC, NMR, and mass spectrometry, reflecting methodological advances and greater accuracy in phytochemical characterization.

In addition to saponins, the presence of triterpenoids such as betulinic acid and ursolic and aliphatic acids indicates relevant pharmacological potential, including anti-inflammatory and anticancer properties previously reported for these metabolites in other plant species.

It is important to highlight not only the phytochemical diversity of the species but also the methodological breadth employed in its characterization. A predominance of triterpenes, such as betulinic, ursolic, and alphitolic acids, has been reported, mainly isolated from the bark through techniques such as NMR spectroscopy and mass spectrometry, evidencing the pharmacological potential associated with these substances. In addition to triterpenes, simple phenolics and flavonoids (including caffeic acid, ferulic acid, naringenin, and apigenin) have been detected in leaves and bark by HPLC/DAD, indicating a relevant antioxidant profile. Saponins, compounds characteristic of the genus Ziziphus, were confirmed through classical methods, such as the vanillin–sulfuric acid reagent, reinforcing their importance as chemical markers of the species.

Finally, advanced analyses such as UPLC-QTOF-MS/MS enabled the identification of organic acids, phenolic derivatives, and triterpenoid glycosides in the stem bark, expanding the understanding of the plant's metabolic complexity. Thus, the integration of different analytical approaches has provided a robust and multifaceted characterization, reinforcing the biotechnological value of *Z. joazeiro* as a source of bioactive molecules of pharmaceutical, cosmetic, and food interest.

The predominance of studies focused on the bark and fruit reveals a gap in the investigation of other plant parts, suggesting that future explorations could expand the understanding of the chemical profile and the potential technological applications of *Z. joazeiro*. Notably, the chemical and biological properties of these compounds largely depend on the extraction techniques employed.

The recognition of the biological relevance of the compounds in *Ziziphus joazeiro* Mart. highlights the need for appropriate methods for their recovery. The antioxidant activity

associated with these metabolites depends not only on their presence but also on the efficiency of extraction, since yield, selectivity, and stability may vary according to the technique employed. Therefore, understanding advances in extraction technologies is essential to enhance the utilization of these bioactives, enabling their application in foods, cosmetics, and pharmaceuticals in a safer and more sustainable manner.

Extraction Technologies for Bioactives

The integration of advanced extraction technologies into research on *Ziziphus joazeiro* Mart. may represent a decisive step toward consolidating its pharmacological and biotechnological applications. In addition to improving yield and selectivity, these methods enable greater reproducibility and standardization of extracts, thereby strengthening the comparability of results across different studies. Such approaches are particularly relevant for plant organs that remain underexplored, such as fruits and seeds, whose bioactive profiles are less documented compared to bark and leaves.

The use of different parts of *Ziziphus joazeiro* Mart., such as bark, leaves, fruits, and roots, has been investigated with the aim of isolating bioactive compounds of pharmacological, cosmetic, and biotechnological interest. The efficacy of these compounds is closely linked to the extraction method employed, since different techniques and solvents can directly influence the yield, selectivity, and stability of the constituents obtained. According to [44], in the recovery of secondary metabolites from an extract, both the extraction method and the plant part used—such as leaves, bark, flowers, stems, roots, or pulp—must be considered, as the phytochemical composition may vary depending on the plant organ selected.

The choice of technique depends not only on the plant material but also on the intended application of the extract. Extracts obtained through milder methods are often preferable. The principles of green chemistry can be achieved through a variety of techniques applied to assist the extraction of secondary metabolites [44]. The extraction method directly influences the chemical profile of the extract and may favor the selective recovery of specific metabolite classes, which is crucial for pharmacological, cosmetic, and food-related applications. Therefore, the development of efficient extraction protocols is essential to maximize the functional potential of this native species. The principles of green chemistry can be applied through several assisted extraction approaches, including microwave-assisted extraction, ultrasound-assisted extraction, enzyme-assisted extraction, voltage-assisted extractions, and, more recently, shockwave-assisted extraction [45].

Despite the efficiency of both conventional and modern extraction techniques, the use of organic solvents—methanol, ethanol, and acetone, often mixed with water—remains essential for the effective extraction of polyphenols [45]. Various extraction methods, employing different solvents, have been reported in the literature to establish the bioactive profile of plant species, revealing a wide range of extractable and applicable compounds. However, these solvents pose major safety concerns, particularly in food, cosmetic, and pharmaceutical applications. Most solvents are classified as toxic or environmentally hazardous, and their residues may persist in the final extract. If not adequately removed, these residues may present health risks. Thus, the complete or near-complete removal of residual solvents is critical to ensure product safety and consumer confidence.

Natural deep eutectic solvents (NADES) are gaining attention due to their ease of synthesis and high affinity for specific compounds. They are composed of natural molecules (sugars, amino acids, vitamins, or carboxylic acids), homogenized in defined proportions to create a new liquid solvent, offering advantages such as remaining liquid over a wide temperature range, being non-volatile, and exhibiting good thermal stability [46].

The development of pressurized extraction technologies represents a fundamental advancement in obtaining components from natural matrices. Methods such as pressurized

liquid extraction, supercritical fluid extraction, gas-expanded liquid extraction, and subcritical water extraction provide significant advantages in terms of efficiency, sustainability, and the ability to selectively isolate bioactive compounds with high therapeutic potential [46].

According to [47], to overcome challenges associated with the large demand for solvents, degradation of compounds under high temperatures, and prolonged processing times, technologies such as ultrasound-assisted extraction, microwave-assisted extraction, enzyme-assisted extraction, and their combinations offer significant advantages over conventional extraction methods, while being aligned with the principles of green chemistry.

The alignment of these technologies with the principles of green chemistry contributes not only to the production of safer extracts but also to the sustainable utilization of biodiversity. In this regard, the development of optimized and environmentally friendly extraction protocols for *Z. joazeiro* may accelerate the transition from ethnopharmacological knowledge to large-scale industrial applications in the food, cosmetic, and pharmaceutical sectors. Thus, modern extraction strategies represent not only methodological alternatives but also essential tools for expanding the scientific and technological frontier of this native species.

2.5. Antimicrobial Activity

In recent years, the presence of antimicrobial properties has been reported in various extracts from natural products, suggesting their potential use in the formulation of new drugs, possibly reducing undesirable side effects compared to conventional medications. The use of plant extracts with medicinal properties represents a concrete alternative for the treatment of various pathological conditions [48].

When determining the antimicrobial activity of hydroethanolic extracts from the fruit, leaves, and stem bark of *Zizyphus joazeiro* Mart., [33] found that all parts of the plant exhibited inhibitory activity against the tested strains, with the stem bark demonstrating the highest antimicrobial activity against Bacillus subtilis, Candida albicans, and Pseudomonas aeruginosa. The leaf extract showed positive results only against Bacillus subtilis, whereas the extract from the unripe fruit was effective only against Staphylococcus aureus, whereas the ripe fruit exhibited inhibitory activity against Bacillus subtilis.

In a comparative evaluation of the antimicrobial activity of juá bark and leaves, Ref. [23] concluded that the extract with the most significant activity was that of the bark, which inhibited 66.66% of the tested microorganisms. The higher activity observed for stem bark extracts suggests a concentrated presence of compounds with strong antimicrobial action in this tissue, which is consistent with its traditional use in oral hygiene. However, the positive results obtained from leaves and fruits, although more selective, indicate that these organs should not be overlooked as complementary sources of bioactive metabolites. This finding is particularly relevant in view of the need to adopt strategies that reduce the intensive use of bark and contribute to the conservation of the species.

According to [48], the aqueous extract from the inner bark of juá demonstrated activity against oral microbiota bacteria associated with periodontal diseases, such as Prevotella intermedia, Porphyromonas gingivalis, Fusobacterium nucleatum, Streptococcus mutans, and Lactobacillus casei, all of which are cariogenic bacteria. Thus, it can be concluded that saponins, in particular, not only contribute to the antimicrobial effects but also explain the traditional application of *Z. joazeiro* in hygiene products, given their foaming properties. This dual functionality reinforces the versatility of the species, positioning it as a candidate for both pharmaceutical and cosmetic formulations.

In [48], when evaluating the extraction performance of saponins from the bark of *Z. joazeiro* and sisal, it was reported that saponins are present at levels ranging from 2–10% by weight in the bark of *Z. joazeiro*, exhibiting both dentifrice and phytotherapeutic functions. Despite their bitter taste, one of their characteristics is a low abrasive power.

They also present high antimicrobial activity, acting mainly against Streptococcus mutans, the bacterium responsible for dental caries, and also against Staphylococcus epidermidis and Staphylococcus aureus [26].

The crude extract of *Ziziphus joazeiro* presented by [27] exhibited significant antifungal activity and properties for the treatment of mycoses, reinforcing the importance of ethnopharmacological surveys and the selection of plants for bioactivity screening. The ability of *Ziziphus joazeiro* extracts to reduce dental plaque formation and act against species such as Streptococcus mutans, Prevotella intermedia, and Porphyromonas gingivalis supports the ethnopharmacological knowledge already consolidated in the semi-arid region and opens opportunities for the development of natural products aimed at oral care. Such applications gain even greater relevance in light of the evidence of antifungal activity, which broadens the therapeutic scope of the species to conditions such as mycoses. Although in vitro findings highlight the antimicrobial potential of *Ziziphus joazeiro* Mart., further in vivo and clinical studies are essential to validate its efficacy and safety in real oral health conditions.

Regarding its chemical properties, in addition to tannins, polyphenols, and flavonoids, saponins were also identified. Several studies on plants of the same species report the formation of persistent foams, which justifies their use in hygiene products. This is due to their detergent properties, which promote foam formation in aqueous or powdered formulations, acting on oral cavity bacteria, including cariogenic species such as Streptococcus mutans [4,43].

Formulations containing *Ziziphus joazeiro* Mart. contribute to the reduction of dental plaque and exhibit antimicrobial activity against Streptococcus mutans, a cariogenic bacterium of the oral microbiota, as well as periodontal disease-associated bacteria such as Prevotella intermedia and Porphyromonas gingivalis [48] (Figure 8).

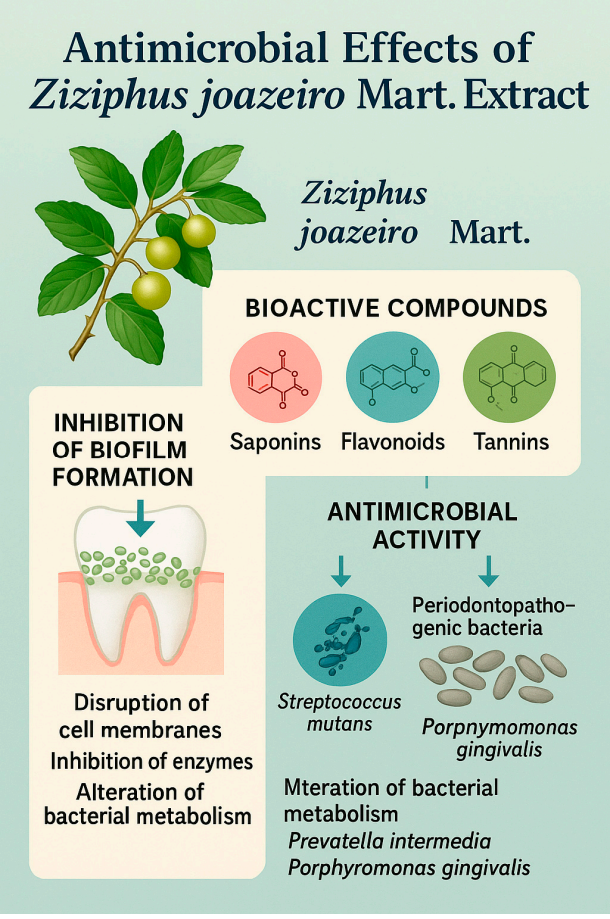


Figure 8. Schematic representation of the antimicrobial effects of *Ziziphus joazeiro* Mart. extract on oral pathogens.

Despite the promising results, the variability in antimicrobial activity among different extracts suggests the need for more in-depth investigations into the influence of extraction methods, phytochemical standardization, and the possible synergism among compound classes. Systematic studies addressing these aspects may guide the rational development of standardized formulations, enhancing both efficacy and safety. Thus, the antimicrobial potential of *Z. joazeiro* represents not only a confirmation of its traditional use but also a promising frontier for innovation in the pharmaceutical, nutraceutical, and hygiene sectors.

2.6. Fruit of Juazeiro

Considering the wide availability of juazeiro fruit in the Caatinga ecosystems and the fact that it is edible, its exploitation represents a strategic opportunity for the integral utilization of the species. This approach not only enables the diversification of biotechnological applications but also contributes to the valorization of local biodiversity and to reducing dependence on the intensive use of bark. Therefore, it is important to understand the physical, physicochemical, and nutritional characteristics of the fruit.

The fruit of juazeiro, known as juá, illustrated in Figure 9, is edible and has the shape of a globose drupe, is yellowish in color, and measures between 1 and 2 cm in length. It has a white, fleshy, and sweet pulp, covered by a thin skin that encases a farinaceous pulp where the seeds are embedded in a transparent mucilage [49].

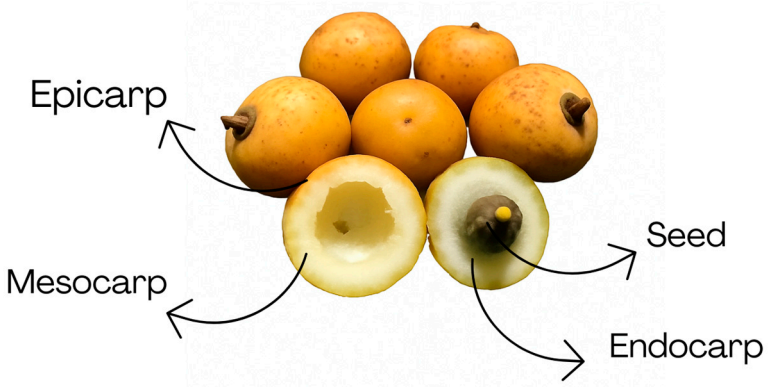


Figure 9. Fruits of juazeiro (*Ziziphus joazeiro* Mart.), showing the yellow epicarp, whitish mesocarp, and the stony endocarp enclosing the seed.

These fruits possess nutritional properties and can be used for human consumption, with potential applications in the food industry for the production of pulps, juices, sweets, jams, ice creams, and beverages. Given its biological properties, it is a highly recommended fruit for consumption [50,51].

The fruits are classified as climacteric and are composed of a high water content, carbohydrates, and vitamin C. They are also a source of dietary fiber, phenolic compounds, and flavonoids such as catechin, epicatechin, and procyanidin, which contribute to their antioxidant capacity [20].

Its physicochemical and nutritional characteristics have been highlighted when assessing its gastronomic potential [20], given that fruits typical of the Caatinga are largely unknown or even scientifically unexplored and are rarely consumed either in their natural form or as ingredients in food products.

According to [5], juá contains a significant amount of vitamin C, carbohydrates, and minerals (K, Ca, and Mg), describing it as an edible fruit with a yellowish-brown color and a sweet appearance. On the other hand, research by [11] states that the amount of ascorbic acid (vitamin C) in the juazeiro fruit is higher than in fruits with similar characteristics that

are more commonly consumed, such as apples, grapes, strawberries, lemons, and peaches, reaching 87.28 mg/100 g of pulp.

Considering the dimensions and weight, Ref. [52] observed that the fruits have a relatively fleshy epicarp and mesocarp, which can be confirmed by comparing the values of fruits with and without these structures. Furthermore, studies have demonstrated a significant composition of various phenolic compounds [36].

2.6.1. Physical Characteristics

The physical dimensions of the fruit, such as longitudinal and transverse diameter or length, are relevant for products intended for consumption. However, from an industrial perspective, an important quality parameter is pulp yield, as fruits with higher pulp yield consequently result in greater efficiency in the processing of final products [53].

The physical characteristics of the juazeiro fruit may vary depending on the harvesting area, influenced by factors such as climate, soil conditions, and rainfall index, and it constitutes a valuable food resource for animals during periods of drought [54]. On the other hand, its yield makes juá a viable option for agro-industrial applications, both for pulp production and for the development of derived products. Reference [55] observed in their study that pulp yield increased with fruit maturation, reaching a maximum value of 82.66%, highlighting the potential of juazeiro fruits for use in industrialized products such as pulp, sweets, jams, and other derivatives.

Fruit firmness is considered a highly important physical attribute, as it is related to the solubilization of pectic substances, which, when present in large quantities, confer a soft texture to the fruit and thereby influence consumer acceptance [53].

A greater pulp thickness is desirable, as it increases both the weight and the edible portion of the fruit, making it an important quality attribute [56]. Pulp thickness is a crucial characteristic, particularly in terms of transportation and commercialization. Variations in pulp thickness are associated with changes in fruit weight during storage, resulting from substrate consumption and transpiration [57].

In a study evaluating the physical attributes of juá during storage at room temperature, it was concluded that at more advanced ripening stages, the fruit exhibits higher quality, making it more attractive for consumption and processing [5]. However, during storage, this ripening process leads to substrate consumption, resulting in a reduction of physical attributes. With respect to fruit firmness, it decreases significantly as ripening progresses, while weight, length, and diameter show a slight reduction.

As fruits reach physiological maturity and enter the senescence phase, they soften due to pectin degradation and modifications in the bonds between the polymers that make up the cell walls, leading to cell separation and a loss of wall rigidity. Consequently, fruit firmness decreases throughout the process. This occurs because changes in the composition of the fruit's cell wall cause the pectin content to increase with ripening, with more than 75% of the soluble pectins composed of galacturonic acid and rhamnose [58].

2.6.2. Physicochemical Characteristics and Nutritional Profile

Studies have shown that fruits from species of the *Ziziphus genus* cultivated in European and Asian countries exhibit a significant nutritional composition, including various types of flavonols, procyanidins, and phenolic acids. These fruits are highly recommended for consumption due to their biological properties [3].

The juá fruits exhibited pulp with a high water content, as indicated in Table 3, with values consistently above 69%. Ref. [50] states that the water content in fruits is likely associated with hydric and climatic conditions in the regions where the plant grows, directly influencing the intrinsic water content of the fruit.

Table 3. Proximate and Physicochemical composition of juá pulp.

Parameters	Quantity (%)	References
Water content	79.01	[5]
Protein	2.13	[59]
Lipids	1.15	[59]
Carbohydrates	17.59	[5]
Ashes	0.93	[60]
Total soluble solids (°Brix)	18.98	[5]
Acidity titratable (%citric acid)	0.23	[61]
pH	5.3	[5]
Water activity (Aw)	0.98	[61]
Reducing sugars (% in glucose)	12.12	[60]

The ash content reported by [61] was 0.73%, which is very similar to the 0.76% determined by [5]. On the other hand, refs. [59,60] reported higher ash content values, a fact that may be attributed to the mineral composition of the soil in the respective regions [53]. The importance of determining ash content lies in expressing the mineral substance levels present in the sample. However, there are no established regulatory parameters for the ash content of juá [62].

The protein content reported by the authors (Table 3) was higher than that determined in the study conducted in [63], which evaluated protein levels during the fruit's ripening stages, concluding with a protein percentage of less than 0.5%. The authors state that protein levels during ripening are affected by the increased synthesis of enzymes.

Regarding lipid content, the results presented in Table 2 indicate that the fruit contains a low amount of these compounds. However, Ref. [64] asserts that juá fruits are rich in lipids, particularly linoleic acid (omega-6). Lipids are highly energetic molecules that, however, are generally found in small amounts in fruits and vegetables [65].

The carbohydrate content in juá pulp was found to be significant, according to [60], reaching 24.12%. This value is higher than that reported by the same author in the determination of carbohydrate content in different fruit pulps, such as açaí pulp, with 2.35%, and grumixama (*Eugenia brasiliensis*, Lam), with 4.20% carbohydrates.

The juá fruit, as shown in Table 3, presents a highly promising soluble solid content, indicating the potential for pulp utilization in industrial processes and confirming the presence of sugars in the fruit, as inferred from its sweet taste. Since °Brix values vary according to the fruit's ripening stage, this may explain the total soluble solid content reported in Table 3, based on studies conducted. Acidity is an important parameter for monitoring the preservation state of fruits. The juá pulp exhibited a satisfactory acidity level, as indicated in Table 3, remaining below 0.4%. This value classifies it as a low-acidity fruit, which positively influences palatability, as fruits with a high degree of sweetness and low acidity tend to be more acceptable to consumers. Reference [50] states that juá fruits are characterized as non-acidic, resembling the values described for fruits of the same genus, *Ziziphus jujuba*, in this regard, emphasizing the sweetness/acidity ratio and their good palatability.

Regarding pH, values above 4.5 indicate that the pulp is more susceptible to microbiological deterioration, as reported by [5]. Combined with the water activity value of 0.98 determined by [50], this highlights the need for thermal treatments to ensure the microbiological safety of the fruit. Water activity is one of the factors associated with microbial growth and hydrolytic reactions; however, fruit pulps tend to exhibit water activity levels above 0.98 [66].

The reducing sugars determined by [60] (Table 3) were found to be 12.12%. These sugars play a crucial role in assessing fruit quality for industrial processing in various

applications, such as sweets, preserves, and jams, as higher sugar content generally leads to greater consumer acceptance. The sugar content may vary depending on the fruit's ripening stage and is directly related to the total soluble solid content [61].

Climatic conditions, such as sunlight and rainfall, favor fruit ripening and consequently increase glucose and fructose levels [50]. Fructose has a relatively higher sweetness than glucose, and the perceived sweetness of juá is likely due to the predominance of fructose, which increases as sucrose degrades during the ripening phase [64,65].

3. Conclusions

Various parts of the species *Ziziphus joazeiro* Mart. have been traditionally used in folk medicine as an expectorant, for oral hygiene, and in the treatment of ulcers due to the presence of various phytochemicals. Studies highlight the importance of this species for obtaining extracts with antioxidant, anti-inflammatory, and antimicrobial properties, making it suitable for treating diseases and serving as a raw material for the production of shampoos and other hair care products, as well as general hygiene applications, owing to the presence of saponins in the stem bark.

However, the literature does not report antimicrobial, anti-inflammatory, or antioxidant activity for extracts from the fruit and seeds, only for the stem bark and leaves of the species. Thus, further research is needed to identify bioactive fractions and assess the antimicrobial activity of *Ziziphus joazeiro* Mart. fruit, aiming for qualitative and quantitative determinations of its phenolic composition and other bioactive compounds, including its free radical scavenging capacity.

In conclusion, the species *Ziziphus joazeiro* Mart. represents a valuable medicinal, functional, and technological resource, requiring further studies to determine its bioactive and antioxidant potential and to support its application in products with functional properties. Moreover, expanding investigations to underexplored parts such as fruits and seeds could contribute to the discovery of novel compounds with pharmacological and nutraceutical relevance. Such findings may also promote the sustainable use of this native species, encouraging the development of bioproducts for the food, cosmetic, and pharmaceutical industries. Additionally, future studies addressing extraction optimization, bioaccessibility, and in vivo efficacy will be essential to validate its therapeutic potential and translate its traditional use into scientifically grounded applications.

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