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Cerrado fruits as sources of bioactive extracts: functional food applications and emerging technologies for sustainable extraction

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Cerrado fruits, adapted to dry/rainy seasons and nutrient-poor soils, are rich sources of diverse bioactive phytochemicals, including phenolics, carotenoids, and alkaloids. These fruits, such as buriti, cagaita, pequi, and baru, possess unique phytochemical and nutritional profiles, making them promising functional food ingredients. This review highlights their biochemical composition and associated bioactivities, including antioxidant, anti-inflammatory, and antimicrobial effects. It also addresses advanced extraction techniques like supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and enzyme-assisted extraction (EAE), focusing on their efficiency, selectivity, and environmental impact. Key challenges include incomplete quantification and structural elucidation of phytochemicals, suboptimal solvent–matrix interactions, and insufficient knowledge of bioactive stability during processing and storage. Encapsulation technologies, such as nanoemulsions and biopolymeric carriers, are suggested to improve bioavailability and protect bioactives from degradation. Future research should emphasize metabolomic profiling using advanced chromatographic and spectrometric methods, optimization of extraction parameters according to fruit matrices, and scaling up extraction protocols supported by techno-economic and life-cycle assessments. Collaborations among researchers and local producers are essential for sustainable bioprospecting, enabling the valorization of Cerrado fruits as high-value bioactive ingredients for functional food, nutraceutical and pharmaceutical sectors.

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Sustainability spotlight

This review highlights the potential of native fruits from the Brazilian Cerrado, one of the world's most biodiverse biomes in Brazil, with a focus on pequi, buriti, and cagaita. These fruits are valuable sources of bioactive compounds, offering significant nutritional and health benefits. The true innovation, however, lies in how those compounds are accessed. Emerging green extraction technologies—such as Supercritical Fluid Extraction (SFE) and Ultrasound-Assisted Extraction (UAE)—minimize environmental impact, reduce waste, and preserve the integrity of these valuable natural compounds. Valorizing these native fruits creates powerful new economic opportunities for local and indigenous communities, supporting livelihoods and encouraging the conservation of their natural habitat. The circular bioeconomy concept transforms natural resources and their byproducts into high-value ingredients for the food, cosmetic, and pharmaceutical industries. It is a crucial step toward building resilient local economies while protecting the irreplaceable biodiversity of the Cerrado for future generations.

1. Introduction

Particularly since the COVID-19 pandemic, which sparked a renewed interest in health-conscious eating, the market for functional products has grown dramatically in recent years. The increasing demand from consumers for foods that promote health, and general well-being is the main driver of this growth.[1,2] As a result, there is growing interest in creating novel goods that meet these consumer demands.[3] Functional foods are among those that provide health advantages beyond simple sustenance.

The Agência Nacional de Vigilância Sanitária (ANVISA) defines a functional food or ingredient as one that can provide metabolic, physiological, and/or health benefits without the need for medical supervision, in addition to fulfilling basic nutritional functions.[4] Functional foods are generally defined as those that provide health benefits either by their inherent composition or by the addition of active ingredients, despite the lack of a widely agreed-upon definition.[5,6] These foods fall into three categories: modified foods, like fermented products and orange juice fortified with calcium; conventional foods, like fruits, vegetables, grains, dairy, meat, and fish; and food ingredients, like non-digestible carbohydrates that have prebiotic properties.[6] The goal of ongoing research in this area is to better understand the nature, safety, and health effects of functional foods as well as how they affect consumer behavior.[7]

In this context, native fruits from the Brazilian Cerrado biome emerge as promising sources of bioactive compounds with significant potential for the development of functional foods. Numerous understudied plant species that are abundant in nutrients and bioactives like phenolic compounds, carotenoids, vitamins, and fatty acids can be found in the Cerrado, which is regarded as one of the most biodiverse regions in the

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world. These native fruits, including Cagaita (*Eugenia dysenterica*), Pequi (*Caryocar brasiliense*), Buriti (*Mauritia flexuosa*), and Araticum (*Annona crassiflora*), have been traditionally consumed by local communities and show promising biological activities such as antioxidant, anti-inflammatory, antimicrobial, and hypoglycemic effects.[8–11] Their valuation supports regional economic growth and food security in addition to encouraging the sustainable use of biodiversity.

Cerrado fruits are widely used by small and medium-sized local producers to create homemade products such as jams, preserves, liqueurs, popsicles, and canned goods. Furthermore, these fruits are essential ingredients in local cuisine, featured in traditional dishes like rice with pequi, jatobá pie, and buriti paçoca.[12] However, the value of these fruits extends beyond traditional use. The presence of bioactive compounds, such as polyphenols and carotenoids, has sparked scientific interest.[13] While the pulp and seeds are commonly used in human and animal food, the extraction of these bioactive compounds is particularly valuable for isolating and concentrating them to harness their benefits, such as antioxidant, anti-inflammatory, and antimicrobial properties.[13,14]

Antioxidant activity constitutes an essential defense against oxidative stress,[15] a condition defined by the imbalance between the generation of reactive oxygen species (ROS) and the ability of biological systems to neutralize them.[16] This protection is exerted by bioactive compounds through multiple mechanisms, including their redox potential to stabilize free radicals and the modulation of cellular defenses. The same structural features that confer this antioxidant property, such as the presence of hydroxyl groups in phenolic compounds, are also responsible for their remarkable antimicrobial activity.[17] Phytochemicals like phenolic acids, tannins, and flavonoids demonstrate efficacy against various pathogens, including resistant ones, through a multi-target action. This strategy ranges from the disruption of the cell membrane, caused by the interaction of hydroxyl groups, to the inhibition of vital enzymes and the modulation of bacterial communication systems, such as quorum sensing.[17,18]

Bioactive compounds derived from fruits are known to modulate metabolic pathways and exert protective effects against chronic diseases such as diabetes, cardiovascular disorders, obesity, and certain types of câncer.[19–24] These compounds' positive health effects have prompted their use in nutraceuticals and functional foods. Nevertheless, there are still issues with these compounds' stability, bioaccessibility, and extraction effectiveness, particularly when using traditional extraction techniques.

Emerging technologies like ohmic heating, microwave extraction, supercritical fluid extraction, and ultrasound extraction have been studied as creative ways to enhance the recovery and preservation of bioactive compounds from plant matrices to get around these restrictions.[25–28] Green chemistry and sustainable processing are supported by these methods, which not only boost extraction yields and shorten processing times but also minimize the use of hazardous solvents and maintain the structural integrity of delicate compounds.[29] Thus, using these technologies on Cerrado fruits could improve their industrial viability and functional qualities, enhancing the development of new ingredients and products with added value (bioactive-rich extracts, specialty oils, natural colorants, nutraceuticals, gourmet foods, and cosmetic ingredients).

In this context, lthough native fruits from the Brazilian Cerrado have known nutritional and functional potential, these fruits remain underutilized, mainly due to limitations in traditional extraction methods that affect the stability and yield of sensitive compounds. Thus this review highlight the value of Cerrado fruits and explore sustainable and efficient extraction technologies, such as supercritical fluid, ultrasound-assisted, and enzyme-assisted extraction, that can enhance the recovery and application of their bioactive compounds in functional

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food systems. Finally, it discusses stability challenges and preservation strategies for industrial applications.

2. The Cerrado and its food biodiversity

One of the biomes with the highest biodiversity in the world is the Brazilian Cerrado, which spans about 204 million hectares.[30] Many endemic species, especially plants that have adapted to survive harsh environmental conditions, can be found in this vast ecosystem, which is dominated by savannas, open woodlands, and grasslands. According to some authors,[31–33] these include high temperatures, protracted droughts, acidic and nutrient-deficient soils, intense UV radiation, microbial attacks, and frequent wildfires. Despite these limitations, the Cerrado is home to a remarkable diversity of species, many of which have distinctive physiological and structural adaptations. The vegetation has also been shaped by periodic fires, which are frequent during the dry season. This has encouraged the evolution of species that can survive in these fire-prone environments.[34–36] Cerrado plants have evolved adaptive mechanisms to counteract oxidative stress in response to these environmental pressures. These mechanisms include the activation of antioxidant enzymes and increased synthesis of phytochemicals, particularly phenolic compounds, which greatly enhance the plants' nutritional and functional value.[33,37]

The socioeconomic significance of these native fruits extends beyond their ecological value. For centuries, indigenous and rural communities have relied on these fruits as both a source of food and a source of income. According to de Lima *et al.*[38] and Gomes *et al.*[39] these fruits are essential to traditional dietary practices and support cultural identity and nutritional diversity. Furthermore, rural populations now have new economic opportunities due to their increasing recognition in international markets as nutraceuticals and functional ingredients.[40] Native fruits can be sold fresh or as ingredients in various products, such as juices, ice creams, sweets, jams, porridges, cakes, and liqueurs.[41] Oils sourced from the pulps, seeds, and kernels of Cerrado fruits—like buriti oil and the oils from pequi, araticum, and baru—have caught the attention of the food and cosmetic industries.[37] In addition, the sustainable cultivation of these native species provides a viable alternative to deforestation and contributes to the long-term preservation of the Cerrado ecosystem.[40] In this context the Law No. 15.089, January 7, 2025, known as "Lei do Pequi", establishes a national policy for the sustainable management, planting, extraction, consumption, commercialization, and processing of pequi and other native fruits and products of the Cerrado biome, aiming to combine environmental preservation with the socioeconomic development of the communities dependent on this ecosystem.[42]

Native fruits of the Brazilian Cerrado, such as pequi and buriti, play a significant role in the region's economy and rural livelihoods. Pequi commercialization alone generates around R$ 3.5 million annually nationwide and over R$ 50 million in northern Minas Gerais,[43] with extractivist families earning approximately R$ 1080 per hectare from pequi oil. Buriti extractivism also offers a valuable income source, allowing some families to earn up to R$ 10 000 per month during the harvest season. These figures highlight the strong potential of Cerrado fruits to support local economies while promoting sustainable land use and biodiversity conservation.[44]

In recent years, there has been an increasing focus on innovative agricultural practices that promote sustainable land management while also improving productivity. Integrating Cerrado fruits into sustainable farming systems can simultaneously conserve biodiversity and stimulate rural economic growth.[45,46] By encouraging the growth of local value chains and improving smallholder farmers' ability to adjust to market swings and unstable finances, policies that promote the value-adding of native species can also be crucial in propelling the socioeconomic transformation of the area.[47]

In this context, Cerrado fruits offer dual potential for both economic development and health improvement. They hold promise for enhancing food security and addressing public health challenges by alleviating chronic diseases such as diabetes, cardiovascular diseases, and obesity. Emerging technologies that optimize extraction and processing can help advance and commercialize these native fruits, which can support biodiversity conservation and environmental sustainability while fostering the creation of novel products and functional ingredients.[48]

3. Cerrado fruits: nutritional characteristics and traditional uses

The Brazilian Cerrado hosts a vast array of native fruits that are gaining increasing attention due to their high nutritional value, diverse phytochemical composition, and cultural relevance. The species that are most frequently used and researched are buriti (*Mauritia flexuosa*), cagaita (*Eugenia dysenterica*), pequi (*Caryocar brasiliense*), and baru nuts (*Dipteryx alata*). Table 1 summarizes their fractions, identified compounds and potential health benefits.

Each of these fruits exhibits a unique nutritional profile. Baru nuts are notably rich in protein, dietary fiber, and unsaturated fatty acids (mainly oleic and linoleic acids), in addition to sugars, bioactive compounds, and essential micronutrients such as zinc, magnesium, and iron.[49–51] These nutritional attributes contribute to their potential in promoting cardiovascular health and providing essential nutrients.

Pequi pulp is particularly high in lipids, especially monounsaturated fatty acids like oleic acid, which constitute a significant portion of its oil content. Additionally, it contains substantial amounts of dietary fiber, carotenoids (such as β-carotene), and essential minerals including zinc, magnesium, and calcium.[52] The fruit also exhibits high levels of phenolic compounds, contributing to its antioxidant properties. These compounds include flavonoids like quercetin and quercetin-3-*O*-arabinoside, as well as acids such as gallic and quinic acid.[53] Furthermore, flour made from the pequi shell has been identified as a valuable source of dietary fiber (47.92 g/100 g) and

Table 1 Bioactive compounds found in some typical Cerrado fruits and their health potential

Fruit	Fraction	Compounds	Potential health benefits	References
Pequi (*Caryocar brasiliense*) 	Pulp	Carotenoids, lipidis, dietary fiber, zinc, magnesium, calcium and polyphenols	Antioxidant, cell protection	64 and 65
	Shell	Dietary fibers (including soluble fibers) and phenolic compounds (gallic acid, ellagic acid and quercetin)	Antioxidant; antitumor (osteosarcoma)	64–66
	Oil	Monounsaturated fatty acids (oleic acid) and saturated fatty acids (palmitic acid)	Anti-inflammatory, cardioprotective, and antigenotoxic; antioxidant hepatic protection	64 and 65
Buriti (*Mauritia flexuosa*) 	Pulp	Monounsaturated fatty acids (oleic acid), saturated fatty acids (palmitic acid), carotenoids and phenolic compounds (phenolic acids and flavonoids)	Protective action to inflammatory and cardiovascular diseases; prevents ocular derangements; can be applied in neurodegenerative, câncer and cardiovascular diseases	67
	Shell flour	Fatty acids (oleic acid and palmitic acid), phenolics, flavonoids, flavonols, condensed tannins	Antioxidant, antimicrobial, anticancer, anti-inflammatory, and hypoglycemic effects	68
	Oil	Monounsaturated fatty acids, carotenoids and tocopherols	Antioxidant, antimicrobial, chemopreventive immunomodulatory and gastroprotective effect,	66
Cagaita (*Eugenia dysentrica*) 	Pulp	Phenolic compounds (phenolic acids, flavonoids, anthocyanins and organic acids)	Reduce inflammation and oxidative stress, prevents the development of obesity and type 2 diabetes	69
	Oil seed	Fatty acids (linoleic acid and oleic acid), tocopherols (α-tocoferol)	Prevents cardiovascular diseases and has protective effect against neurodegenerative diseases	70
	Leafs	Polyphenols (γ-cadinene, β-caryophyllene and δ-cadinene)	Antioxidant properties, reduce inflammation and oxidative stress, supports the anti-inflammation and metabolic disorders;[7] antioxidant and neuroprotective properties	11
Baru nuts (*Dipteryx alata*) 	Oil	Unsaturated fatty acids (oleic acid and linolenic acid)	Prevents metabolic diseases (diabetes and cardiovascular events)	71
	Partially defatted baru flour	Phenolic compounds, flavonoids (catechin and epicatechin), condensed tannins	The consumption of these compounds are associated to antimicrobial, anticancer, anti-inflammatory, and hypoglycemic effects	68 and 72
	Almond flour	Lipids, fibers, minerals (especially calcium)	Protects cardiovascular system, controls body weight gains and blood glucose and triglyceride levels	73

phenolic compounds (14 062.40 mg_{GAE}/100 g), reinforcing its potential as a functional food ingredient.[54] The oil extracted from pequi pulp is traditionally used in cooking, imparting a distinctive flavor to regional dishes. Additionally, pequi has applications in traditional medicine and is utilized in the production of artisanal products.

Cagaita is widely recognized as a natural source of vitamin C and phenolic compounds, such as quercetin, ellagitannins, ellagic acid, and kaempferol, known for their antioxidant and anti-inflammatory effects.[55] These bioactive constituents have been associated with beneficial biological activities, particularly in the prevention of metabolic disorders like obesity and type 2 diabetes.[56] Cagaita fruits are frequently used in local culinary preparations, such as juices, liqueurs, ice creams, and jams. In addition to their culinary applications, local communities have long utilized fruits and leaves in folk medicine to treat conditions such as diabetes, jaundice, and diarrhea.[57]

Buriti pulp is an exceptional source of β-carotene and contains significant amounts of tocopherols and unsaturated fatty acids, especially oleic acid. β-Carotene contributes to its intense orange color and makes it a valuable source of provitamin A.[58,59] Buriti oil, extracted from the pulp, contains high levels of monounsaturated fatty acids (especially oleic acid), tocopherols, and other antioxidants, which support its growing use in the cosmetic and food industries.[60] Traditional uses of buriti include consumption such as fresh fruit, juice, sweets, and fermented beverages, while its oil is also used in the production of artisanal soaps and skincare products. Additionally, buriti plays an important role in local and indigenous diets, not only for its nutritional benefits but also for its cultural significance and seasonal abundance.[61] Its antioxidant profile has attracted scientific interest due to its potential in reducing oxidative stress and inflammatory markers,[9] highlighting buriti's potential as a functional ingredient in nutraceutical formulations.

Value-added products made from Cerrado native species are being developed and commercialized in line with bioeconomy strategies that support biodiversity conservation, sustainable livelihoods, and the responsible utilization of natural resources.[62] In Brazil, the National Solid Waste Policy (Federal Law No. 12,305/2010) establishes guidelines for the integrated management of solid waste, including agro-industrial waste. This policy encourages the adoption of practices that reduce the amount of waste generated at the source, such as the reuse of materials, process optimization, and shifting to more sustainable consumption habits. Examples include composting, anaerobic digestion for biogas production, reuse in animal feed, and the production of sustainable packaging.[63]

4. Bioactive compounds found in Cerrado fruits

The functional food market has been diversifying, classifying products based on the type of active component, whether added or naturally occurring, such as fibers, flavonoids, vitamins, fatty acids, minerals, and carotenoids. Thus, fruits from the Cerrado have gained prominence as rich natural sources of these components, making them promising raw materials for the development of functional products.

Cerrado fruits have emerged as a valuable source of naturally occurring bioactive compounds, including phenolic acids, flavonoids, tannins, carotenoids, and essential fatty acids. Numerous health-promoting qualities, including cardioprotective, antidiabetic, anti-inflammatory, and antioxidant effects, are linked to these compounds. The presence of secondary metabolites such as anthocyanins, tocopherols, and stilbenes further contributes to their functional potential.[74,75]

Recent studies have demonstrated that certain Cerrado fruits exhibit total phenolic contents exceeding 500 mg_{GAE}/100 g, including mirindiba (*Buchenavia tomentosa*), bacaba (*Oenocarpus distichus*), and puçá-preto (*Mouriri pusa*). For example, puçá-preto showed a total phenolic content of 868 ± 51 mg_{GAE}/100 g, indicating a high antioxidant capacity. According to some reports, Bacaba has a high phenolic content, which adds to its antioxidant qualities.[76,77] These values are same those found in fruits that are well-known for their high phenolic content, such as acerola, camu–camu, raspberries, and blueberries. For comparison, sour cherries have been reported to contain total phenolic content ranging from 78 to 500 mg_{GAE}/100 g.[78]

Moreover, fruits like murici (*Byrsonima crassifolia*) and bacupari (*Garcinia brasiliensis*) that have a moderate phenolic content (100–500 mg_{GAE}/100 g) resemble sour cherries, red plums, guavas, and strawberries. *Garcinia brasiliensis* has shown phenolic content within this range, while murici has been reported to contain approximately 222.2 ± 6.1 mg_{GAE}/100 g.[79,80] Fruits with lower phenolic content (<100 mg_{GAE}/100 g), such as biribá, araçá-boi, and cajuí, have levels like those of apples and pears, which are frequently consumed. Biribá reportedly contains 65.7 mg_{GAE}/100 g, and araçá-boi 184.05 ± 8.25 mg_{GAE}/100 g.[81,82] These comparative values reinforce the positioning of Cerrado fruits among antioxidant-rich superfruits with relevant bioactive properties.[83]

Cerrado fruits also show great promise in the development of functional products. The highlight that buriti (*Mauritia flexuosa*) residue flour is rich in individual phenolics and bioactive compounds, supporting its incorporation into baked goods to enhance nutritional content.[84] Furthermore, flour derived from seriguela peel, pulp, and seeds contains significant dietary fiber, enabling its application across diverse food matrices. These flours also exhibit favorable technological properties, allowing versatile uses depending on the formulation. Furthermore, the presence of ellagitannins and non-extractable phenolics enhances the antioxidant, antimicrobial, and anti-inflammatory potential of Cerrado-derived ingredients.[85]

Fruits are a major source of dietary polyphenols and other bioactive compounds that contribute to their functional and nutraceutical potential, including antioxidant, anti-inflammatory, antimutagenic, and anticancer properties.[86] Fruits' antioxidant content is strongly linked to preventing chronic degenerative diseases like heart disease, type 2 diabetes, and some types of cancer. When consumed adequately, these compounds may reduce the risk of diseases such as atherosclerosis and cancer.[87] Additionally, they have chemopreventive, cardioprotective, and anticancer properties.[88]

Flavonoids, carotenoids, and vitamins are the primary bioactive substances found in fruits. Flavonoids have a variety of biological properties, such as anti-inflammatory, antimicrobial, and antioxidant properties. They are divided into subclasses such as flavonols (*e.g.*, quercetin), flavones (*e.g.*, apigenin), and flavanones (*e.g.*, naringenin), and their distribution in fruit tissues varies. Carotenoids, like lycopene and β-carotene, are precursors of vitamin A and scavenge free radicals to produce antioxidant effects.[89,90] Vitamins C and E help prevent lipid oxidation and support immune function by protecting cells against oxidative stress, a condition linked to obesity.[91,92]

Extracts from a variety of plant sources are frequently used as natural flavorings and/or colorants. They also serve as ingredients in food, medicine, cosmetics, and to produce packaging materials.[93,94] Additionally, plant extracts are used as natural preservatives and ingredients in functional foods, contributing to cleaner label formulations and improved health claims.[95]

To replace artificial additives, the food industry is increasingly using plant-derived extracts in formulations. These extracts not only enhance the nutritional quality of food products but also provide market appeal by highlighting their natural and health-promoting properties.[96] The use of *Citrus unshiu* peel extract in dairy products serves as an example, as it successfully prevented *Listeria monocytogenes* from growing during 21 days of refrigeration at 4 °C.[97]

The utilization of plant extracts offers additional benefits beyond their functional properties, particularly in terms of sustainability, circular economy, and waste reduction. Fruits are primarily consumed fresh or processed into juices, frozen pulps, jams, syrups, and dehydrated forms.[98] However, these processing methods generate significant amounts of waste, which require appropriate disposal and financial investment. Instead of being discarded, these residues can be repurposed as sources of valuable bioactive compounds, contributing to sustainability and economic viability.[99]

5. Conventional methods for the extraction of bioactive compounds

Bioactive compounds are present throughout the fruit, but their concentration varies in each part. Generally, the pulp and the peel tend to have the highest concentration of these compounds.[85] The extraction of bioactive compounds from fruits and other plant materials poses significant challenges due to the natural variability in the composition of raw materials, which may affect the reproducibility and standardization of the final product.[100] Therefore, the selection of an appropriate extraction method must consider factors such as cost, processing time, and equipment availability, while ensuring efficiency, selectivity, and reproducibility.[101]

Among the conventional techniques, maceration, percolation, infusion, decoction, and ethanol reflux extraction are the most employed. Maceration involves grinding the sample to increase the contact surface, mixing it with a solvent, at room temperature for at least three days with occasional agitation. This process softens plant tissues and disrupts cell walls, facilitating the release of phytochemicals. The extract is then separated by pressing or filtration. While maceration is suitable for thermolabile compounds, it is limited by long extraction times and relatively low efficiency.[102]

Percolation improves efficiency by continuously renewing the solvent as it passes through the plant material. The process starts with maceration in a percolator for about two hours, after which the solvent is allowed to drip slowly (*e.g.*, six drops per minute) through the packed plant powder until extraction is complete. The final product is often concentrated by evaporation.[103] This method offers better solvent penetration and mass transfer rates compared to static maceration, enhancing the yield of extracted compounds.

Infusion and decoction are based on the same principle as maceration, utilizing water as the solvent. Infusion typically involves a shorter extraction time and is performed using hot or cold water. Decoction, on the other hand, is more intense, requiring the plant material to be boiled in water for a specific time (*e.g.*, 1 : 4 or 1 : 16 w/v ratio), followed by cooling and filtration.[104] This method is particularly suitable for extracting heat-stable compounds from tough plant parts like roots and barks and often yields more oil-soluble compounds compared to maceration and infusion.[103] These water-based methods are traditionally used in herbal medicine and continue to be applied due to their simplicity and accessibility, especially in small-scale extractions.

Reflux extraction with supercritical fluid or solid–liquid extraction, involves heating the solvent and sample together in a closed system, allowing vapor condensation and continuous contact between solvent and solute. This method improves extraction efficiency and reduces solvent use; however, it is not recommended for heat-sensitive compounds due to the elevated temperatures.[100,105] Its controlled environment enables better reproducibility, making it useful in laboratory-scale applications despite its limitations for certain phytochemicals.

Conventional extraction methods are widely used and have historical significance, but they have drawbacks like lengthy processing times, poor extraction yields, and high solvent consumption that can make them unsuitable for use in industrial or large-scale settings. In addition, some of these techniques' use of organic solvents poses health and environmental risks, which fuels the need for more environmentally friendly technologies. These limitations have fueled the creation and use of new extraction technologies, which seek to address these issues by providing more effective, discerning, and ecologically friendly substitutes. These novel techniques and their benefits for recovering bioactive compounds from plant-based matrices are examined in the following section.[106]

6. Emerging technologies for the extraction of bioactive compounds

Agro-industrial residues such as fruit peels, seeds, and pulp can be revalorized to obtain bioactive compounds. This strategy aligns with the core tenets of the circular economy, which advocate for reduced dependence on raw materials, the reuse of resources, and the extension of product life cycles.[98] By valorizing agricultural residues, industries not only reduce their environmental footprint but also create new economic opportunities from materials once deemed disposable.[107] Although using plant-derived extracts in food systems has many advantages, several technological issues must be resolved to guarantee their stability and efficacy. One of the primary concerns is the chemical instability of polyphenolic compounds, which are highly sensitive to environmental factors such as pH, light, oxygen, and temperature.[108]

Polyphenol stability is particularly influenced by pH. Certain dietary polyphenols – such as caffeic acid, chlorogenic acid, and gallic acid – are prone to degradation under alkaline conditions. These degradation reactions are often irreversible, resulting in a loss of biological activity and potential nutritional value.[109] Consequently, the pH of food matrices must be carefully considered when incorporating such compounds, especially in formulations prone to alkalinity. A critical factor affecting the stability of polyphenols is light exposure. Studies involving grape cane extracts have demonstrated that compounds like *trans*-resveratrol and ε-viniferin undergo significant degradation when exposed to light, particularly at elevated temperatures.[110] Similarly, polyphenols extracted from grape seeds show high sensitivity to oxygen, light, and extreme pH values (both acidic and alkaline), although they exhibit relatively greater thermal stability.[111]

Furthermore, enzymatic oxidation represents an additional degradation pathway for polyphenols in fresh produce. Colorless flavanols such as catechin and epicatechin, commonly found in fruits and vegetables, are rapidly oxidized by polyphenol oxidase (PPO). This enzymatic activity leads to the browning of damaged produce – including apples, pears, and peaches, as well as fruit-derived products like juices, reducing both aesthetic and nutritional quality.[111] The instability of polyphenolic compounds under factors like pH, light, and oxidation highlights the need for emerging extraction technologies.[108] Supercritical fluids, ultrasound, microwaves, pulsed electric fields, and enzymatic methods are examples of innovative techniques that have been successful in improving extraction efficiency while maintaining the biological activity of these compounds.[98]

6.1 Supercritical fluid extraction (SFE)

Using supercritical CO_2 as a solvent, Supercritical Fluid Extraction (SFE) is a promising green technology that enables the effective and selective recovery of bioactive compounds from plant matrices. This approach is notable for its capacity to extract thermolabile and hydrophobic compounds with the least amount of organic solvents, providing a greener substitute for traditional methods. By operating at moderate temperatures and tunable pressures, SFE enables the preservation of compound integrity and customization of extraction conditions for specific targets. SFE offers advantages such as high extraction yields, reduced processing times, and enhanced selectivity, making it highly suitable for food, pharmaceutical, and cosmetic applications.[112,113]

Research has shown that SFE is an efficient method for obtaining valuable compounds from Brazilian Cerrado fruits. As an illustration of the potential of SFE in obtaining compounds with therapeutic applications, Favareto *et al.*[114] reported high yields of biologically active sesquiterpenes from the leaves of *Duguetia furfuracea*. The use of SFE to extract bioactive compounds from the pulp of *Byrsonima crassifolia* (murici) was also investigated by Pires *et al.*[115] High levels of lutein, bioactive triglycerides, and essential fatty acids (oleic, palmitic, and linoleic) were detected in the extracts. Notably, the oil fraction had a cytoprotective effect in HepG2 cell models, while the ethanolic extract demonstrated superior antioxidant activity and neither extract exhibited cytotoxicity. These findings underscore the potential of SFE to produce high-value extracts for use in food and health-related industries, using sustainable and efficient practices.

A similar trend is observed in the supercritical extraction of *Mauritia flexuosa* (buriti) oil, as discussed by Ferreira *et al.*[116] This review emphasizes the potential of SFE as an innovative approach to obtain natural food ingredients from Amazonian biodiversity. High concentrations of carotenoids, tocopherols, and unsaturated fatty acids are retained in buriti oil extracted u with aupwsing SFE. SFE provides better compound stability and purity than traditional solvent extraction, guaranteeing less degradation and solvent contamination. In addition to preserving sensitive bioactive compounds, the technique aligns with sustainability goals by reducing solvent residues and enabling the development of clean-label products. The authors highlight that SFE-extracted buriti oil can serve as a natural colorant and antioxidant for food formulations, reinforcing the economic and ecological benefits of integrating SFE into ingredient production chains.

Additionally, the combination of SFE with Pressurized Liquid Extraction (PLE) has shown great promise. A variety of bioactives, such as carotenoids, tocols, ellagic acid, and antioxidants with potent radical-scavenging activity, were recovered in a study utilizing *Caryocar brasiliense* (pequi) almonds using SFE and PLE.[117] By using clean solvents and valuing agricultural by-products, this methodical approach not only optimized the recovery of bioactive compounds but also adhered to green chemistry principles. The collaboration between SFE and PLE shows how technology integration can improve the sustainability and extraction efficiency of native fruit value-adding. Overall, these studies reinforce the role of SFE as a key technology for sustainable extraction of bioactive compounds from Cerrado biodiversity.

6.2 Ultrasound-assisted extraction (UAE)

Ultrasound-Assisted Extraction (UAE) has emerged as an efficient and sustainable technique for extracting bioactive compounds from fruit matrices. The process utilizes high-frequency ultrasonic waves (typically 20–100 kHz) to induce acoustic cavitation, which involves the formation and subsequent collapse of microbubbles in a liquid medium.[118] This phenomenon generates localized high pressure and temperature, resulting in mechanical shear forces that disrupt the cell walls of plant tissues, thereby enhancing solvent penetration and facilitating the rapid release of intracellular compounds.[119] UAE non-thermal properties aid in the preservation of thermolabile substances, which makes it especially appropriate for sensitive bioactives like vitamins and polyphenols.

Several studies have shown how successful the UAE is at valuing Brazilian Cerrado fruits. For example, extracts with strong antioxidant potential, especially in scavenging peroxyl and hydroxyl radicals, were produced by optimizing UAE for the extraction of phenolic compounds from *Annona crassiflora* (araticum) peel. The technique demonstrated capacity to recover compounds with notable bioactivity and was quick, easy, and sustainable.[120] These results highlight the method's benefit of improving bioactive compound extraction while reducing environmental impact.

Similarly, Silva *et al.*[121] optimized carotenoid extraction from *Mauritia flexuosa* (buriti) pulp using UAE combined with experimental design strategies. The study identified optimal ultrasound parameters that significantly increased carotenoid yield, offering a greener and more time-efficient alternative to traditional extraction techniques. The optimized UAE method was further applied to a variety of other matrices – such as tomato, guava, carrot, mango, acerola, papaya, and pumpkin – achieving up to a 5.5-fold higher yield compared to previously reported methods. These results demonstrate its robustness and broad applicability, making UAE a highly efficient tool for recovering valuable bioactives from native Brazilian fruits. This method shows strong potential for applications in the food and nutraceutical industries, contributing to the sustainable recovery of bioactive compounds.

To create bioinputs with biological functionality, UAE was optimized to recover phenolic compounds from *Eugenia dysenterica* (cagaita), which include seeds and peels. Both liquid and lyophilized extracts were produced because of the identification of two ideal extraction conditions. According to Barbosa *et al.*,[122] extracts produced under ideal conditions demonstrated strong antimicrobial and antibiofilm properties as well as a high antioxidant capacity. These extracts were effective against pathogens like *Pseudomonas aeruginosa*, *Escherichia coli*, *Streptococcus* species, and *Staphylococcus* coagulase. These results underscore UAE's potential as a sustainable tool for transforming agroindustrial residues into functional ingredients, supporting applications in food preservation and natural therapeutics.

Compared to conventional extraction methods, UAE offers numerous advantages, such as reduced solvent consumption, shorter extraction times, increased yields, and improved preservation of thermolabile phytochemicals like flavonoids, anthocyanins, and polyphenols.[123] Furthermore, UAE is considered an environmentally friendly approach due to its energy efficiency and the potential use of green solvents like water or ethanol. This makes it an attractive alternative for industries aiming to reduce their ecological impact while maintaining high-quality bioactive products.[124]

6.3 Microwave-assisted extraction (MAE)

Microwave-assisted extraction (MAE) stands out as a highly efficient method for recovering bioactive compounds from fruit residues, although it may pose risks related to oxidation. This method uses microwave energy to create heat, which either directly or indirectly interacts with the sample.[113] Microwaves belong to the electromagnetic spectrum, comprising electric and magnetic fields, with frequencies typically between 300 MHz and 300 GHz and wavelengths ranging from 1 cm to 1 m. In MAE processes, however, the operational frequencies are most commonly between 915 MHz and 2450 MHz, with corresponding wavelengths from 12 to 20 cm.[125,126]

The microwave energy induces heating within the sample through molecular mechanisms such as dipole rotation and ionic conduction, which leads to internal heating that propagates outward.[127–129] These processes facilitate mass and heat transfer across the cellular matrix. As water inside the cells evaporates due to the heating effect, the pressure causes cellular disruption, enabling the release of both volatile and non-volatile bioactive compounds. The rupture of cell walls under microwave exposure enhances the release of these compounds into the surrounding medium.[129,130] The inherent moisture in the biomass, combined with microwave energy, accelerates both the heating process and the efficiency of compound extraction.[128]

Despite MAE's well-established benefits, research on its use for the extraction of bioactive compounds from Cerrado fruits is evidently lacking. Given the rich phytochemical profile of these native species, this knowledge gap offers a chance for additional research.

In a study by Vila Verde *et al.*,[131] variables like time, moisture, and microwave power were evaluated while the volatile oil from *Pterodon emarginatus* fruits was extracted using MAE and compared to conventional extraction. In addition to requiring fewer reagents, MAE dramatically decreased extraction time (by 14 times), energy consumption (by 6 times), and waste generation. Gas Chromatography-Mass Spectrometry (GC-MS) analysis revealed that the extraction method influenced the chemical composition of oils. Interestingly, the predominant compounds in MAE samples were caryophyllene (25.65%) and *trans*-α-bisabolol (6.24%), whereas in conventionally extracted samples, the predominant compounds were caryophyllene (6.75%) and γ-elemene (7.02%). These findings highlight the advantages of MAE in enhancing the yield of economically relevant bioactive compounds from plant matrices. Such results highlight MAE's potential as a more effective substitute for conventional techniques in the recovery of bioactive compounds from understudied Cerrado plant species.

6.4 Pulsed electric fields (PEF)

Pulsed Electric Fields (PEF) is a non-thermal technology that enhances the extraction of bioactive compounds from plant materials through electroporation, which increases cell membrane permeability and facilitates the release of intracellular compounds. It is particularly beneficial for preserving heat-sensitive compounds like phenolics, carotenoids, and vitamins, as it operates at low temperatures, maintaining their nutritional and functional properties.[132] Higher extraction efficiency, less processing time and energy consumption, and compatibility with environmentally friendly practices are just a few benefits of PEF. High equipment costs, the requirement for meticulous process optimization, and decreased efficacy in solid or heterogeneous matrices are some of its drawbacks.[133–135]

As of currently, no published research has directly used PEF technology to extract bioactive compounds from Brazilian Cerrado fruits. Nonetheless, some studies show how this technology can be used to maximize the recovery of antioxidants, carotenoids, and phenolic compounds in tropical and underutilized fruits, indicating that Cerrado fruits may be a good fit for it. Barba *et al.*[133] demonstrated that PEF treatment greatly enhanced the extraction of antioxidants and phenolic compounds from exotic fruit residues, including papaya and mango peels. Since these fruits and those of the Cerrado, like pequi (*Caryocar brasiliense*) and cagaita (*Eugenia dysenterica*), have similar bioactive compositions, it is probable that using PEF to extract bioactive compounds from these native species could have comparable advantages.

Research on the use of PEF on fruits such as blackcurrants and blueberries has also revealed improvements in antioxidant activity and anthocyanin extraction, suggesting that this technology has potential for fruits high in phenolic compounds.[136,137] Therefore, although specific studies on Cerrado fruits are still needed, existing evidence suggests that PEF is a promising technology for the extraction of bioactive compounds from these fruits.

6.5 Enzyme-assisted extraction (EAE)

Using enzymes to break down plant cell walls, enzyme-assisted extraction (EAE) is a new and sustainable method that increases the release of bioactive substances like carotenoids, flavonoids, and phenolics. This approach is notable for its low reliance on organic solvents, high selectivity, and gentle operating conditions. Additionally, EAE promotes biodegradation, reduces environmental impact, and helps to reduce energy and time consumption. Its specificity for molecular linkages enables a more efficient and targeted extraction process.[138,139]

A native fruit known for its antioxidant properties, *Anacardium othonianum* (Cerrado cashew apple), has shown improved phenolic compound extraction *via* enzymatic hydrolysis.[140] The study compared pomaces from yellow, orange, and red cashew apples, revealing notable differences in their mineral (particularly potassium and iron), monosaccharide (mainly glucose and uronic acid), and polyphenolic profiles. Significant amounts of key phenolics – myricetin (up to 44.26 mg kg^{-1}), vanillic acid (up to 32.32 mg kg^{-1}), and gallic acid (up to 29.25 mg kg^{-1}) – were recovered when the cashew apple pomace was subjected to enzyme-assisted treatment using a cellulolytic enzymatic complex. This complex contained a broad spectrum of carbohydrate-hydrolyzing enzymes, including arabinase, cellulase, β-glucanase, hemicellulase, and xylanase.[140] These results highlight how effectively EAE works to increase the release of bioactive compounds from Cerrado fruit residues, highlighting its potential for creating useful and sustainable ingredients from underutilized native biodiversity.

Despite the evident potential, more direct investigations applying EAE to Cerrado fruits are needed. Toward fully utilizing the bioactive potential of each fruit matrix, future research should concentrate on optimizing the enzymatic conditions (such as enzyme type and concentration, temperature, pH, and time). In addition to supporting regional development and the development of novel functional ingredients, the application of EAE offers a promising path toward improving the sustainable use of underutilized fruits from the Cerrado.

6.6 Green solventes

The pursuit of safer and more efficient industrial processes has prioritized the adoption of greener technologies, driven by environmental regulations and a growing awareness of sustainability.[141] In this context, green solvents have emerged as promising alternatives, with the literature exploring several categories: ionic liquids, deep eutectic solvents, supercritical fluids, gas-expanded liquids, and bio-based and supramolecular solvents Ionic liquids (ILs) and deep eutectic solvents (DESs) are widely recognized for their effectiveness in extracting bioactive compounds.[142–145] Both are considered "designer solvents" because their properties can be tailored for specific applications.[146] DESs, in particular, are mixtures of naturally occurring compounds with a low melting point.[146] They share many characteristics with ILs, such as low vapor pressure, high thermal stability, and easy recyclability.[143] Their composition—which includes choline chloride, glycerol, and amino acids—ensures high biodegradability, low toxicity, low cost, and ease of preparation, making them ideal for various processes.[143] DESs have shown promise in extracting phytoconstituents from medicinal plants, such as phenolic acids and flavonoids, with notable results in antioxidant, antibacterial, and anti-inflammatory activities.[147]

Another important category is supercritical fluids, especially supercritical CO_2, which is widely used for extracting bioactive compounds due to its unique properties, which lie between those of a gas and a liquid.[145,148] Its ability to penetrate the sample matrix and dissolve the desired compounds makes it one of the most popular green solvents.[148]

Techniques like gas-expanded liquid extraction, which uses CO_2–ethanol–water mixtures, are also green approaches for obtaining bioactive compounds, even if they require larger solvent volumes and longer extraction timess.[149] The combination of supercritical CO_2 with other green solvents has been described as a "smart extraction chain," which increases yield and allows for the sequential extraction of different classes of compounds.[150]

Bio-based and supramolecular solvents also contribute to sustainable processes, being explored for the valorization of agri-food waste.[157,167] The extraction of bioactive compounds from microalgae, for instance, benefits from using compressed fluids, which are more efficient for this purpose.[169] Additionally, the combination of emerging technologies, such as ultrasound, with green solvents has proven effective in extracting bioactive compounds from agro-industrial byproducts, such as orange peel, resulting in extracts with high antioxidant capacity.[151]

6.7 Studies on emerging technology-assisted extraction of bioactive compounds from Cerrado fruits

Emerging extraction technologies offer significant advantages in the recovery of bioactive compounds. To illustrate the impact

Table 2 Emerging technology assisted extraction of bioactive compounds from fruits found on Cerrado during the last decade

Fruit	Technology	Highlights	References
Passion fruit peel (*Passiflora edulis* Sims f. *flavicarpa* Degener)	Moderated electric field (60 Hz, 0–240 V)	The moderate electric field showed a lower yield than the conventional extraction. Despite this, it presented similar values in the galacturonic acid content and the degree of esterification	166
Passion fruit dried peel (*Passiflora edulis* Sims f. *flavicarpa* Degener)	Probe ultrasound (probe 1.2 cm, power intensity 664 W cm^{-2}, frequency 20 kHz, time 3–20 min)	The highest pectin extraction occurred with ultrasound-assisted extraction (85 °C, 664 W cm^{-2}, pH 2.0 and 10 min), highlighting that the extraction associated with ultrasound showed an increase of 1.6-fold compared to the conventional under the same conditions	170
Juice of araticum (*Annona crassiflora*)	Probe ultrasound (probe 1.3 cm, power intensity 20–100%, frequency 20 kHz, time 2–10 min)	The study found that the application of ultrasound significantly influenced the content of bioactive compounds, color and rheology of araticum juice. Low power conditions for short or long duration were the ones that presented the best results	156
Dried peel of ciriguela (*Spondia purpurea* L.)	Probe ultrasound (probe 25.4 mm, power intensity 20/60/100%, frequency 20 kHz, time 5/10/15 min) Microwave (power intensity 800 W, temp. 120 °C, time 15 min)	The best recovery of bioactive compounds was using 100% power for 15 minutes, by ultrasound	158
Jua pulp (*Ziziphus joazeiro* M.)	Ultrasound (frequency 37 kHz, temp. 25 °C, time 60 min)	The aqueous extracts extracted by associated ultrasound showed a better recovery of soluble phenolics from jua	159
Cereja do Mato peel (*Eugenia involucrata*)	Probe ultrasound (titanium probe, power intensity 5–500 W, frequency 20 kHz, time 2–45 min)	Ultrasound-assisted extraction showed a higher extract yield, while heat-assisted extraction showed extracts with a higher anthocyanin content in a shorter processing time, demonstrating that heat-assisted extraction can be more efficient in recovering extracts with higher anthocyanin concentrations	163
Buriti pulp (*Mauritia flexuosa*)	Probe ultrasound (probe 25 mm, energetic density 0/0.9/1.8/2.7/6 kJ cm^{-3}, frequency 20 kHz, time 10 min)	Ultrasound applied as pretreatment can improve the bioaccessibility and concentration of bioactive compounds in buriti	183
Cagaite oil seed (*Eugenia dysenterica* DC)	Bath ultrasound (frequency 42 kHz, temp. 25/70 °C, time 3/6/9 hours)	Soxhlet extraction showed higher yield. Regarding oxidative stability, samples extracted by ultrasound with heating showed longer induction periods, demonstrating a correlation with antioxidant activity and phenolic content	162
Yellow shell of passion fruit (*Passiflora edulis* sp.)	Bath ultrasound (fixed power intensity, time 15/38/60 min) Microwave (power intensity 800 W, pressure 30 bar, temp. 60/90/120 °C, time 5/15/25 min)	Conventional heating extraction presented the best yields and lowest energy consumption, with the optimal extraction parameters being 70% ethanol for a period of 2 minutes	169
Passion fruit seed oil (*Passiflora edulis* sp.)	Bath ultrasound (power intensity 165 W, frequency 25 kHz, temp. 60 °C, time 20 min)	The ultrasound-associated method extracted higher concentrations of the analyzed phytosterols, being 3.3 times faster than the saponification method	168
Cereja-do-cerrado mix – peel and pulp – (*Eugenia calycina*)	Bath ultrasound (power intensity 132 W, frequency 40 kHz, temp. 30 °C, time 30 min)	Among the ultrasound extracts of the two fruits analyzed, *E. calcynina* presented a higher concentration of anthocyanins, also showing a high antioxidant capacity	164
Murici pulp (*Byrsonima crassifolia*)	Bath ultrasound (power density 0.04 W cm^{-3}, frequency 40 kHz, temp. 30 °C, time 105 min)	In ultrasound-assisted extraction, the best yield for the extraction of phenolic compounds from the fruit was by the freeze-drying method with the experimental parameters of 80 °C temperature, 25 mg mL^{-1} solid–liquid ratio, 60% ethanol	184

Table 2 (*Contd.*)

Fruit	Technology	Highlights	References
Jatobá leaves, bark, fruits, and seeds (*Hymenaea martina* Hayne)	Ultrasound (temp. 25 °C, time 30 min)	The best method for extracting phenolic compounds was maceration, for the peels. While for the total flavonoid content by ultrasound it was the highest in the peels	167
Uvaia (*Eugenia pyriformis* Cambess)	Bath ultrasound (power intensity 70 W L^{-1}, frequency 25 kHz, temp. 40 °C, time 60 min) Enzymatic treatment (0.1% v/v of pectinase from *A. aculeatus*, temp. 40 °C, time 60 min, enzyme inativation at 97 °C for 30 s)	Enzymatic pre-treatment associated with ultrasound showed greater results for malic acid, higher phenolic values and antioxidant activity	116
Macauba pulp (*Acrocomia aculeata*)	Bath ultrasound (frequency 25/45 kHz, temp. 25–60 °C, time 5–30 min)	The optimal extraction conditions for macauba pulp were ultrasound at 60 °C, frequency 45 kHz for 30 minutes, indicating that higher temperatures favored the extraction process while ultrasound proved efficient even in milder conditions	165
Peel and seeds from Cagaite (*Eugenia dysenterica* DC)	Bath ultrasound (frequency 40 kHz, temp. 59 °C)	The extracts obtained by ultrasound under optimized conditions were promising for phenolic composition, antioxidant, antimicrobial and antibiofilm activity	122
Mixture of fruit pulp, seeds and leaves Cereja-do-cerrado (*Eugenia calycina* Cambess)	Probe ultrasound (probe 13 mm, power intensity 100/475 W, frequency 19 kHz)	High power short time ultrasound treatment increased the recovery of phenolic compounds and antioxidant activity *Eugenia calycina* Cambess	157
Babaçu mesocarp (*Attalea speciosa*)	Probe ultrasound (power intensity 40%, frequency 20 kHz, temp. 20 °C, time 20 min)	The extraction associated with ultrasound generated a greater recovery of bioactive compounds from the babassu mesocarp	161
Baru almond (*D. alata* Vogel)	Supercritical fluid extraction CO_2, flow rate 1.91×10^{-4} kg s^{-1}, temp. 40/50/60 °C, pressure 15/25/35 MPa, time 2 hours Probe ultrasound coupled SFE (flow rate 1.91×10^{-4} kg s^{-1}, pressure 20 MPa, pulse intensity 360 W, frequency 20 kHz, temp. 45 °C, time 6 hours)	The best conditions for baru oil recovery were 40 and 50 °C at 5 MPa by SFE. A higher initial rate of fatty acids was achieved using ultrasound and ultrasound did not modify the fatty acid composition	171
Buriti pulp (*Mauritia flexuosa*)	Bath ultrasound (power intensity 80 W, frequency 40 kHz, time 15 min)	The extraction method using bath ultrasound showed a yield twice as high as previously known methods for the extraction of carotenoids from buriti	177
Pequi almond (*Caryocar brasiliense* Camb.)	Bath ultrasound coupled enzymatic hydrolysis (power intensity 38 W L^{-1}, frequency 25 kHz, temp. reaction 60 °C, time 60 min, 0.1% v/v of alcalase with activity 2.4 U g^{-1} from *B. licheniformis*, pH 7,5)	The use of ultrasound associated with enzymatic hydrolysis of pequi almond protein showed promising results for the multifunctional properties of the hydrolysates. Ultrasound increased the hydrolysis rate, the degree of hydrolysis and the concentration of low molecular weight hydrolysates	177
Araticum peel (*Annona crassiflora* Mart.)	Probe ultrasound (probe 13 mm, power intensity 160–640 W, frequency 19 kHz, time 0.5–5.0 min)	The use of ultrasound increased the recovery of phenolic antioxidants. The study demonstrated a high yield of phenolics and antioxidant activity values in short extraction times at high powers	185
Baru seeds (*Dipteryx alata* Vogel)	Supercritical fluid exctration CO_2, flow rate 2.0 mL min^{-1}, temp. 40–80 °C, pressure 15/20/25 MPa, time 10/30/60 min	The study found that unconventional extractions with compressed propane and CO_2+Ethanol can be used to obtain oil from baru seeds with high nutritional potential	174
Baru nut (*Dipteryx alata* Vog.)	Bath ultrasound (power intensity 50 W, frequency 40 kHz, temp. 25 °C, time 120 min)	The results identified the main phenolics present in roasted baru nuts, and the extracts demonstrated potential in inhibiting colorectal cancer cells	173
Epicarp and external mesocarp pequi (*Caryocar brasiliense*)	Microwave (power intensity 670 W, time 110 s)	The pequi peel extract was effective in the stabilization of the lipid and protein oxidative degradation from broiler meat	152

Table 2 (*Contd.*)

Fruit	Technology	Highlights	References
Pequi peel (*Caryocar brasiliense* Camb.)	Microwave (power intensity 400/600/800 W, temp. 60/80/100 °C, time 3/6/9 min)	The microwave-assisted extraction of pectin was efficient in a short time (3 min). Temperature was the main factor for increasing pectin yield, the best results being obtained with 108 °C and a power of 600 W	154
Pequi almond (*Caryocar brasiliense Camb.*)	Supercritical fluid exctration CO_2, flow rate 2/3/5 g min^{-1}, temp. 30/45/60 °C, pressure 15/20/25 MPa, time 110 min	The best pequi almond oil extraction conditions were 25 MPa of pressure, 40 °C of temperature, and flow rate of 5 g min^{-1}, to obtain 27.6 wt% of oil. Oleic acid (>50 wt%) and palmitic acid (>35 wt%) were the most abundant fatty acids in the pequi almond oil	155
Buritirana (*Mauritiella armata Mart.*)	Supercritical fluid exctration CO_2, flow rate 5 g min^{-1}, temp. 40/60 °C, pressure 30 MPa, time 210 min	The maximum point of the extraction was reached after 61 minutes at 40 °C, obtained the oil (41.57%) and carotenoids (8.34 mg g^{-1})	175
Coquinho-azedo pulp (*Butia capitata*)	Supercritical fluid exctration CO_2, flow rate 1.66 g L^{-1}, temp. 50 °C, pressure 350 bar, time 5 hours	The combination of pressurized fluids with supercritical fluid extraction showed a better extraction performance, the sequential extraction was effective for extracting higher levels of bioactive compounds compared to conventional methods	176
Pequi almond (*Caryocar brasiliense Camb.*)	Supercritical fluid extraction CO_2, flow rate 1.80×10^{-4} kg s^{-1}, temp. 40/50/60 °C, pressure 15/25/35 MPa, time 120 min	The SFE, followed by pressurized liquid extraction can be used as green strategies intensified by their integration. The SFE in lower temperature and higher pressures resulted in great extraction yields and recovery of target compounds, such as carotenoids. And PLE recovery better compounds with reducing and antioxidante capacity	117
Pequi dried pulp (*Caryocar brasiliense Camb.*)	Supercritical fluid exctration CO_2, flow rate 2.93×10^{-4} kg s^{-1}, temp. 40/60 °C, pressure 20/25/30/35/40 MPa, time 200 min	The optimal parameters for SFE were a temperature of 60 °C and a pressure of 40 MPa. Comparing with the SFE assisted by pressing at the same parameters, an 8-fold higher recovery is revealed in the first minute of extraction, showing that the application of cold pressing before SFE can improve extraction	153

and effectiveness of these approaches in the specific context of Cerrado fruits, a targeted literature review was conducted to evaluate the application of the aforementioned extraction methods and their impacts in published open access research articles (excluding review articles) in the last ten years (2015–2025). The review was performed across three databases (SCOPUS, Web of Science e ScienceDirect) using search terms related to emerging extraction technologies (pulsed electric field, supercritical fluid, ultrasound, microwave, enzyme-assisted and emergent green solvent), combined with the terms "extraction", "fruit", and either "Brazilian", "Cerrado", or "Brazilian Cerrado".

Table 2 summarizes a selection of studies (in the last ten years) that applied emerging technology-assisted extraction of bioactive compounds from Cerrado fruits, consolidating information on the methodologies and the results obtained.

Over the laste decade, 31 studies have been identified that report emerging technology-assisted extraction of bioactive compounds from Cerrado Fruits. The focus on Cerrado fruits revealed that the most frequently studied fruits were pequi (*Caryocar brasiliense* Camb.), with six studies[51,116,117,122,152–165] and passion fruit (*Passiflora edulis* sp.), with four studies.[166–169]

The most widely applied technology was ultrasound-assisted extraction, employed in 22 studies.[167–173] However, analysis of these studies revealed no consensus on optimal parameters (higher intensity with shorter times *vs.* lower intensity with longer times) for maximizing bioactive compound extraction. This variability may stem from the inherent complexity of food matrices, necessitating factorial studies to optimize extraction parameters (solvent type, processing conditions) and energy consumption to conclusively determine method efficiency. To compare with the conventional methods extraction.

The second most utilized technology was supercritical fluid extraction (SFE), applied in seven studies.[117,153,155,161,174–176] All were published within the last seven years, indicating that SFE applications for fruits found in Cerrado relatively recent. Most studies focused on parameter optimization, primarily temperature and pressure. This emerging technology has demonstrated improved recovery yields while preserving bioactive compound integrity, enhancing potential future applications.

In contrast, fewer studies employed enzyme-assisted extraction[116,177] or pulsed electric field (PEF).[166] The limited adoption of enzymatic methods may be attributed to the high cost of purified enzymes, restricting their use in large-scale optimization studies. Similarly, PEF systems require significant capital investment and meticulous process optimization to maximize efficiency.[132]

6.8 Comparing to conventional methods

Several studies explored combined technologies, such as enzyme-ultrasound[116,177] and SFE-ultrasound or pressurized liquid extraction.[117,153,171,176] These results suggest that integrating emerging technologies can enhance extraction yields, optimize bioactive compound recovery, and minimize degradation while maintaining stability.

None study was identified using green solvents to recover bioactive compounds for fruits typically found in Cerrado, even though, one study from 2013 focus on extraction of saponins from juá (*Ziziphus joazeiro*) using (DESs)[178] showed that was possible to increase the extraction efficiency and selectivity of saponins from juá. Also, a second study consisted in application of subcritical water and pressurized natural deep eutectic solvents to obtain pectin from passion fruit rinds (*Passiflora edulis* sp.)[179] showed the higher yields of pectin were reached using pressurized natural DESs at 120 °C.

A third study[180] was conducted to elaborate lipid nanostructures (NLCs) containing natural deep eutectic solvents (NaDESs) as a way to improve the carry bioactive compounds from taperabá peel (*Spondias mombin*), a Cerrado byproduct, enhance the stability and bioavailability of these antioxidant compounds as encapsulated particles. The results showed that the integration of NLCs with NaDESs improved the physicochemical properties of the nanoparticles and at the same time enhanced the retention and stability of the encapsulated bioactive compounds. Therefore, green solvents can be considered an alternative capable of improving the extraction of bioactive compounds while maintaining their stability.

This highlights the lack of studies on the application of emerging green solvents for the extraction of bioactive compounds from fruits found in the Brazilian Cerrado. Although some studies have employed non-toxic organic solvents, such as ethanol, isopropanol or their mix with water and other solvents, these commonly used solvents are not the focus of this research topic, as they are not considered emergent green solvents as aforementioned.

The extraction Technologies – Supercritical Fluid Extraction (SFE), Ultrasound-Assisted Extraction (UAE), Microwave-Assisted Extraction (MAE), Pulsed Electric Fields (PEF), and Enzyme-Assisted Extraction (EAE) and Green solvents – all offer distinct advantages in terms of yield, selectivity, and sustainability. The efficacy of extraction varies depending on the target compounds and matrix. As shown in studies on *Byrsonima crassifolia*[115] and *Mauritia flexuosa*,[181] where optimal pressure and temperature conditions led to efficient recovery of lutein and unsaturated fats, SFE stands out for its high yield in extracting hydrophobic and thermolabile compounds, such as carotenoids and essential fatty acids. UAE is a leader in the quick and high-yield extraction of carotenoids and phenolic compounds; studies on *Mauritia flexuosa*[160] and *Annona crassiflora*[120] have shown yields up to 5.5 times higher than those of traditional techniques.

The extraction of oils from *Pterodon emarginatus*[131] demonstrated that MAE offers high efficiency, especially for volatile compounds, as it significantly decreased extraction time and energy consumption. However, some sensitive compounds may be compromised by the oxidation risk associated with MAE.[125,126] According to research on tropical fruits like papaya and mango, PEF has the potential to improve the extraction of heat-sensitive phenolics and antioxidants, even though it is still understudied for Cerrado fruits.[133] Finally, EAE provides a highly selective and sustainable approach, particularly for breaking down complex cell wall structures, as seen in the enzymatic recovery of phenolics from *Anacardium othonianum* pomace.[140] While SFE and UAE currently have the most robust applications for Cerrado fruits, PEF and EAE represent emerging opportunities for optimizing yield and selectivity with minimal environmental impact. SFE and UAE are more sustainable because they use less solvent and are more energy efficient,[123,182] while MAE and PEF need to be further optimized to balance efficiency with possible risks of thermal or oxidative degradation.[133,135]

The choice of extraction technique for fruits should consider the particular bioactive compounds that are being target as well as the distinctive qualities of local fruits like pequi, buriti, and cagaita. Even though SFE and UAE currently show the best results for these species, especially for carotenoids, phenolic compounds, and essential oils. New technologies like PEF and EAE offer promising chances to fully realize the potential of underutilized fruits found in Cerrado biome. Future studies should concentrate on refining these environmentally friendly extraction techniques for regional species, especially tackling issues like the required scalable, economical processing and the thermolability of these fruit compounds. Developing customized extraction protocols that preserve the distinct phytochemical profiles while supporting the sustainable use of this biodiversity can significantly enhance their commercial potential, also considering energy consumption and costs in order to conclusively compare and validate emerging methods against conventional ones.

7. Stability challenges and preservation strategies for industrial applications

The stability of bioactive compounds is susceptible to various factors processing conditions, and storage.[186] The degradation of these substances can be caused by variables like pH, temperature, light exposure, oxygen, and enzymatic activity. The composition of the food matrix and the structural characteristics of the compounds also play a significant role, as some, like proanthocyanins, are more stable during storage than anthocyanins.[187] Environmental factors during storage, such as humidity, light, and oxygen, are critical points for the quality of fruit-based products, contributing to the degradation of compounds.[188] For example, phenolic acids (such as caffeic, chlorogenic, and gallic acids) break down irreversibly in alkaline environments,[109] and substances such as *trans*-resveratrol break down more quickly in light and heat.[111] Browning and antioxidant loss in juices and pulps are also caused by enzymatic oxidation, which is mediated by polyphenol oxidase.[111] The industrial utilization of bioactive compounds from Cerrado fruits faces significant challenges due to their susceptibility to degradation during processing and storage. The stability of polyphenols, anthocyanins, and other bioactive molecules can be compromised by factors such as pH, temperature, light, oxygen, and enzymatic activity, ultimately diminishing their functional properties.

The combination of emerging extraction technologies with encapsulation techniques has emerged as a promising preservation strategy. Extraction methods such as ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), and supercritical fluid extraction (SFE) offer advantages like improved recovery, reduced thermal degradation, and minimized oxidation. When combined with encapsulation techniques, such as protein- or polysaccharide-based carriers for microencapsulation and nano-encapsulation, these technologies allow sensitive bioactive compounds to be stabilized by shielding them from processing-related and environmental stresses.[189,190]

Although the literature on the integration of these two Technologies – particularly focused on bioactives from Cerrado fruits – remains limited, recent studies have started to shed light on their synergistic potential. In a notable example[158] employed ultrasound-assisted extraction followed by spray drying to microencapsulate extracts from ciriguela (*Spondias purpurea*) peel. This combination resulted in superior encapsulation efficiency (98.83%) and high total phenolic content (476.82 $mg_{GAE}\ g^{-1}$), particularly in the spray-dried samples, which exhibited spherical morphology and a rich profile of bioactives such as rutin, epicatechin gallate, and quercetin. Simulated gastrointestinal digestion confirmed the protective effects of encapsulation, with rutin emerging as the dominant compound post-digestion. After 90 days of storage at 7 °C, the microcapsules also retained increased phenolic stability, using the efficacy of this combined approach in creating stable, bioactive-rich powders appropriate for use in food, medicine, and cosmetics.

Similarly, Rezende *et al.*[191] demonstrated the efficiency of ultrasound-assisted extraction combined with spray and freeze drying in the valorization of acerola (*Malpighia emarginata* DC) pulp and residue. The study reported favorable physicochemical properties, such as low hygroscopicity and high solubility, especially in spray-dried powders that retained higher levels of phenolic compounds, flavonoids, and antioxidant activity, using gum arabic and maltodextrin as encapsulating agents. Because spray drying better retains bioactives and antioxidant potential, it proved more effective overall, even though freeze-dried samples had slightly higher microencapsulation efficiency for some compounds.

These studies collectively highlight the untapped but exciting possibilities of combining emerging technologies with encapsulation techniques to stabilize and deliver bioactive compounds from Cerrado fruits. This approach enhances compound stability throughout the entire production chain, from extraction to final use, thereby promoting the development of sustainable and functional food products and increasing the economic and technological value of indigenous Brazilian biodiversity.

8. Conclusion

Cerrado fruits such as buriti, cagaita, pequi, and baru are rich in bioactive compounds and possess significant potential for functional food and nutraceutical applications. However, their valorization is limited by gaps in phytochemical characterization, optimization of sustainable extraction methodologies, and understanding of bioactive stability during processing and storage. Research on the comparative performance of emerging extraction technologies, such as supercritical fluid extraction (SFE), ultrasound-assisted extraction (UAE), and enzyme-assisted extraction (EAE), for Cerrado matrices remains scarce, as does the exploration of underutilized methods like pulsed electric fields (PEF) and microwave-assisted extraction (MAE). These gaps hinder the development of scalable, environmentally friendly processes that preserve thermolabile compounds and maximize yields. Unlocking this potential will require not only technological innovation but also a deeper integration of Cerrado biodiversity into national and international research agendas.

Future efforts should focus on mapping the chemical diversity of priority Cerrado species, tailoring extraction parameters to specific matrices, and integrating advanced stabilization strategies such as encapsulation to enhance bioavailability and functionality. Scaling up these processes, supported by techno-economic and environmental assessments, will be critical to bridging laboratory findings with industrial application. Strategic collaborations among researchers, industry stakeholders, and local communities will ensure equitable benefit-sharing and promote biodiversity conservation, enabling Cerrado fruits to become high-value, sustainably sourced ingredients that contribute to both regional development and global innovation in food and health products. By aligning these initiatives with sustainable development goals, the field can foster resilient value chains that benefit both ecosystems and society.

Author contributions

All authors contributed to the study conception and design. Blenda de Souza Costa: writing-original draft, visualization, writing-review & editing. Philippe Defaveri Bieler: writing-original draft, writing-review & editing. Sepehrdad Dehghani: writing-original draft. Daiana Wischral: writing-original draft, writing-review & editing. Ramila Cristiane Rodrigues: writing-original draft, writing-review & editing. Evandro Martins: writing-review & editing, conceptualization, supervision. Sueli Rodrigues: conceptualization, writing-review & editing supervision. Paulo Cesar Stringheta: writing-review & editing supervision, funding acquisition. Pedro Henrique Campelo: writing-review & editing, conceptualization, supervision, visualization.

Conflicts of interest

The authors declare no potential conflict of interest.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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