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Functional activities and applications of Pequi Oil: a systematic review and meta-analysis

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Abstract

Pequi oil is a promising raw material known for its high content of unsaturated fatty acids, polyphenols, and carotenoids. This systematic review focuses on its potential and industrial applications. A total of 27 studies were selected, and 14 were meta-analyzed. The results demonstrated the oil's potential in the food industry, where natural antioxidants served as preservatives, stabilizers, and additives, thereby extending the shelf life of products like yogurt and cheese. Additionally, pequi oil has applications in pharmaceuticals, phyto-cosmetics, as well as in nano-emulsions and nanocomposites. The meta-analysis revealed a total effect size of 0.73 with a 95% confidence interval of 0.67–0.79 and a significant *p*-value ($p < .01$). Heterogeneity was observed ($I^2 = 95\%$; $p < .0011$), supporting the practical application of pequi oil in various therapeutic interventions. These include antioxidant, anti-inflammatory, antigenotoxic, and anticarcinogenic effects, as well as potential treatments for diseases related to oxidative stress, glycemic control, anemia, reduction of low-density lipoproteins cholesterol, osteoarthritis symptoms, and dermal wound healing. Pequi oil shows considerable potential for product development across various industrial sectors. However, it is essential to explore alternative methods of its exploitation to expand its practical applications and foster new product development.

Keywords: pequi oil; potential; industrial application; functional property.

Practical Application: Versatility of pequi oil as a natural preservative, therapeutic potential, and nanoencapsulation.

1 INTRODUCTION

Native Brazilian fruits from various biomes, such as the Amazon, Caatinga, Cerrado, Atlantic Forest, and other forest regions, have attracted growing economic interest in several niche markets, both in Brazil and abroad (Lisboa et al., 2020). Among these fruits, pequi (*Caryocar brasiliense* Cambess) has stood out in research due to its high potential for the development of new products, as it is a raw material that can be fully utilized (Carneiro et al., 2023).

The main co-products of pequi are the pulp and the almond. The pulp, which is yellow and has a distinctive taste, is rich in carbohydrates (57.83%), lipids (33.53%), total fiber (5.29%), and protein (3.28%), as well as in carotenoids. The almond contains high levels of lipids (55.76%), predominantly unsaturated (52.63%) and saturated (41.34%) fatty acids, and proteins (29.24%) (Geöcze et al., 2021).

Among the products derived from it, the oil has shown promise, both for its nutritional value and for its functional properties, for being rich in monounsaturated (MUFA), polyunsaturated (PUFA) and saturated (SFA) fatty acids, especially oleic (C18:1; 42.47%), palmitic (C16:0; 39.49%) and linoleic (C18:2; 10.17%) acids, as well as fatty acids such as myristic, palmitoleic, and stearic (Lima et al., 2020; Nascimento-Silva & Naves, 2019). Its antioxidant, anti-inflammatory, antigenotoxic, anticarcinogenic, and analgesic properties (Brito et al., 2022; Coutinho et al., 2020) expand the possibilities for application in areas such as animal science, technology, and nutrition.

Considering the characteristics and benefits of pequi oil, it is essential to deepen scientific knowledge about its new applications and technological prospects. Therefore, this study proposes a systematic review and meta-analysis of the potential of pequi oil, with a view to supporting its commercial exploitation and viability in different industrial sectors. The approach aimed to

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contribute to scientific progress and innovation in the use of native Brazilian resources.

1.1 Relevance of the work

This work is relevant as it highlights the potential of pequi oil in various industrial applications, such as food, cosmetics, and pharmaceutical products. The research demonstrates its antioxidant, anti-inflammatory, and therapeutic properties, which can significantly contribute to the development of new products and treatments. Furthermore, the meta-analysis provides a solid foundation for future research and practical applications of pequi oil in key sectors, promoting innovation and expanding its uses, particularly in the context of seeking natural and sustainable alternatives in the market.

2 MATERIALS AND METHODS

The article presents a systematic review and meta-analysis, conducted between June 2022 and March 2023, following the criteria outlined in the Cochrane Handbook for Systematic Reviews. The aim was to explore new industrial applications of pequi oil, considering its bioactive, antioxidant, and antimicrobial properties. The search covered publications between 2017 and 2022, consulting databases such as Scopus, Web of Science, and PubMed. The keywords used were combined using Boolean operators, including terms such as "oil of pequi" AND "Caryocar" AND "potential", "oil of pequi" AND "bioactive compounds", and variations related to functional and antioxidant properties.

The article selection process involved an initial analysis of the title, abstract, and keywords, prioritizing studies that addressed the physical-chemical properties, as well as the composition and potential applications of pequi oil. Full reading was reserved for articles focusing on innovations and new possibilities for industrial use. Publications outside the defined period, reviews, dissertations, book chapters, case reports, response letters, retrospective studies, duplicate articles, or those not indexed in reliable databases were excluded. Only articles in English with a relevant impact factor were included.

The organization of the review followed the Preferred Reporting Items for Systematic reviews and Meta-Analyses (O'Dea et al., 2021) flowchart, which guided the selection of the most relevant articles. To analyze the data, a table was drawn up containing information on authors, title, year of publication, type of study, objectives, and main results. Quantitative studies were analyzed in a meta-analysis using fixed and random effect models to evaluate properties such as chemical composition, antioxidant capacity, and antimicrobial properties. Studies without quantitative data or with insufficient information for statistical analysis were excluded. For example, studies such as "In vitro release and antioxidative potential of pequi oil-based biopolymers" and "Reducing carotenoid loss during storage by co-encapsulation of pequi and buriti oils" were disregarded due to lack of uniform data.

The statistical analysis included an evaluation of proportions and 95% confidence intervals (95%CI) for each study, using the "meta" package of R software version 4.3. Heterogeneity between studies was analyzed quantitatively using the chi-squared test and measured by the I^2 index (values above 50% indicated significant heterogeneity). In addition, a funnel plot was generated to assess possible publication bias.

Alongside the systematic review, a scient-metric analysis was carried out to identify trends and patterns in research on pequi oil. The same databases and keywords were used, with articles selected between 2017 and 2022. Only publications in English, not related to reviews or meta-analyses, were considered. The extracted data was processed using VOSviewer software, allowing relationships between keywords and titles to be visualized.

The results of this systematic review and meta-analysis highlight the potential of pequi oil in industrial applications, its functional properties, and challenges related to the heterogeneity of the methods and data presented in the studies. The scientometric analysis reinforces the growing relevance of pequi oil in areas such as functional foods, polymers, and bioactive compounds, suggesting possibilities for future advances and research.

3 RESULTS

The search in databases for systematic review and meta-analysis yielded in 422 articles, initially pre-selected based on keywords, titles, and abstracts. A total of 132 articles were found in Scopus and 290 articles in Web of Science, and 219 were excluded due to duplications, publications shorter than the time period, language, articles without an impact factor, articles recently published and not indexed, as well as articles shared between the databases. After analyzing titles and abstracts, 152 articles were excluded because they dealt with studies on the pequi tree, fruit, pulp, bark, flour, residues, and extracts, and they did not correlate with the aim of the research, leaving 51 articles for careful analysis and full reading of the text. Of these 51 articles, 24 were excluded because they did not deal with new applications for pequi oil and the production of biodiesel, which was not in line with the research interest. After selection, 27 studies that met the eligibility criteria were included, as shown in the Prisma-based flowchart in Figure 1.

For the meta-analysis, 14 studies were selected once they presented clear outcomes, quantitative data, and sufficient information, allowing an analysis of the information, and 13 articles were excluded because they did not present clear results on some of the properties of pequi oil. For the scientometric analysis, 73 publications were found in the Web of Science database, and excluding duplicates, reviews, and meta-analyses, 23 articles were identified that met the selection criteria.

The co-occurrence analysis of keywords showed a high frequency and correlation between them, as well as a high frequency in the field of research in the period from 2018 to 2022, revealing current trends (Figure 2). According to the circles indicating great importance and influence of the nodes in the study, the words found included antioxidants, pequi oil, pequi pulp, bioactive compounds, oxidative stress, phenolic compounds, chemical composition, and antioxidant activity.

The largest circle is the word antioxidants, indicating that it is the most important and influential keyword in the research.

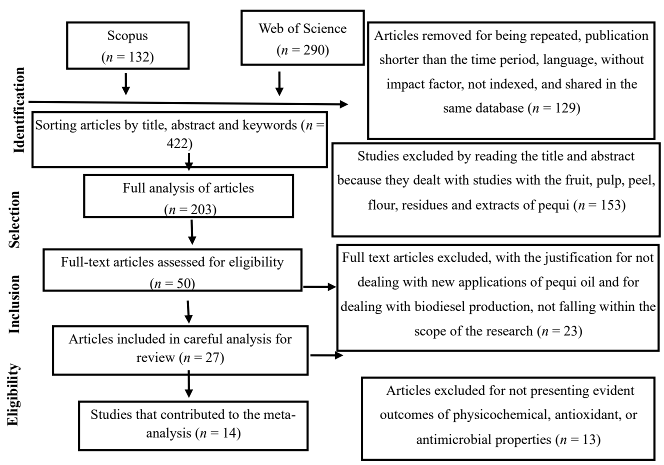
3.1 Characterization of the studies

The characteristics of the 27 studies included in the systematic review and meta-analysis are shown in Table 1, which includes data such as author, year of publication, title, type of study, objectives, and outcomes found. Most articles (92%) were published in international journals, reflecting the growing global interest and the efforts of Brazilian researchers to disseminate their findings.

Of the 27 articles selected, 10 dealt with the applications of pequi oil in technology and the food industry, highlighting its physicochemical properties, such as carotenoids, phenolic compounds, and unsaturated fatty acids. Another 9 articles focused on therapeutic properties, including antioxidant, anti-inflammatory and immunomodulatory action, control of glycemia and cholesterol, and effects on healing. In addition, 3 studies discussed the development of polymeric films, and 1 article covered the manufacture of antimicrobial pharmaceutical products and phyto-cosmetics with antioxidant and photoprotective properties.

The temporal analysis of publications, shown in Figure 3, revealed that the years 2020 and 2022 had the highest percentages of publications (25%), followed by 2018 with 18%. This increase in publications in recent years reflects growing interest in the topic.

In addition, 25% of the studies (7 articles) published between 2020 and 2022 addressed new applications and extraction techniques for pequi oil, focusing on improving its physicochemical properties and use for wound healing, as well as nanoencapsulation techniques and nano-emulsions to preserve



Source: Flowchart based on the Preferred Reporting Items for Systematic reviews and Meta-Analyses (Prisma, 2020).

Figure 1. Flowchart of the selection of articles for the systematic review on the applicability of pequi oil, 2020.

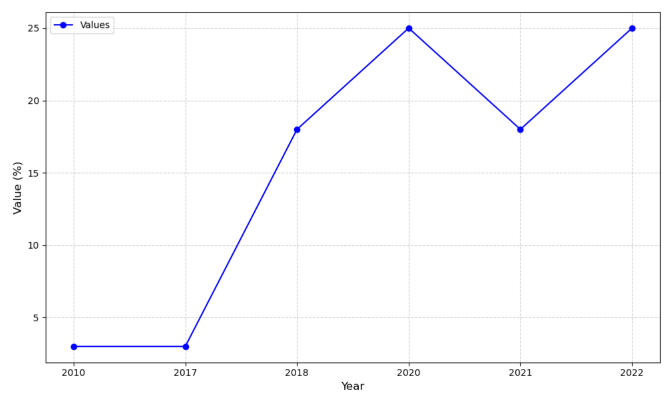


Figure 3. Percentage of papers published per year (*n* = 25) according to the systematic review, 2022.

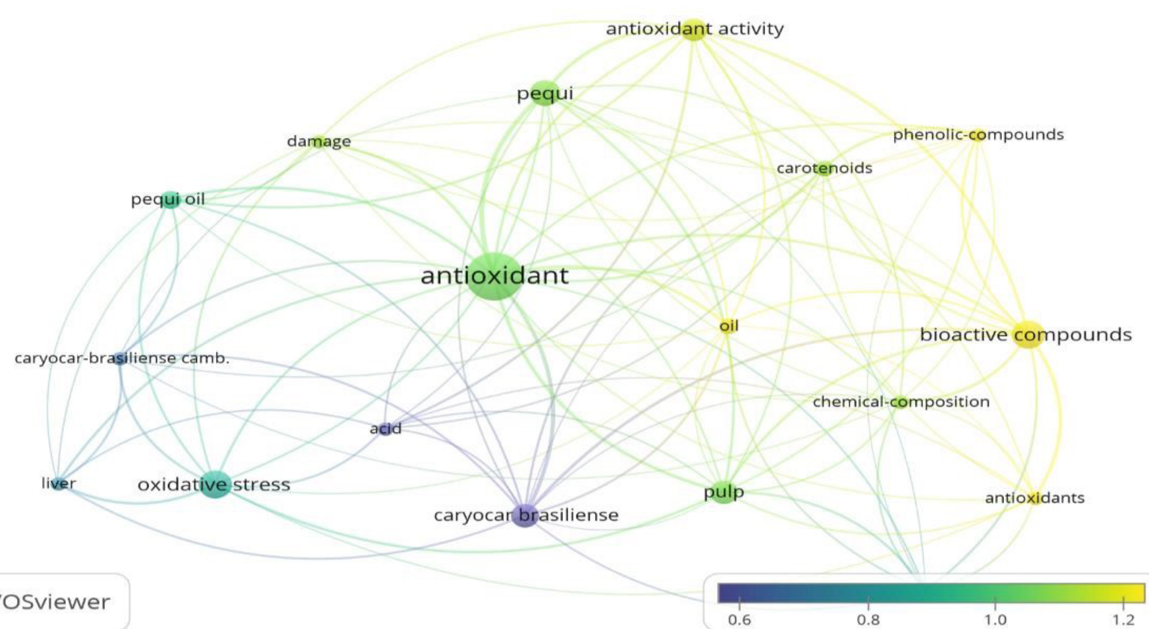


Figure 2. Keyword competition network.

Table 1. Articles collected for the systematic review, 2022.

References	Title	Objective	Type of Study	Outcome
Borges et al., 2022	Pequi pulp oil: effect on physical and chemical, nutritional and textural properties of cottage cheese	To produce a new cheese with added pequi pulp oil.	Experimental	The use of oil and pequi pulp emulsifier improved the texture and body of the cheese, reducing cohesiveness, hardness, gumminess, elasticity and chewiness.
Silva et al., 2022	Characterization and release of microcapsules of pequi oil for use in yogurt.	To use complex coacervation with cashew gum and chitosan to encapsulate pequi oil in enriched yogurt.	Experimental	The wall materials showed good encapsulation efficiency, with electrostatic interactions and microcapsule stability. Acid release and resistance to temperature and greater stability. The study showed potential for application in yogurts, with the addition of microcapsules carried out at the cooling stage
Cornélio-Santiago et al., 2022	Pressurized liquid extraction of pequi and *Sacha inchi* oil: Effects of variables on yield and composition	To evaluate the impact of the contact time between solvent and matrix (pequi kernels and *Sacha inchi*) in intermittent purging on the extraction of oil, free fatty acids, total phenolic content and β-sitosterol.	Experimental	*Sacha inchi* and pequi oils had high levels of β-sitosterol and TPC. The main fatty acids were linolenic in *Sacha inchi* and oleic in pequi. Extraction with pressurized isopropanol in 27 minutes resulted in high oil recovery: 92.98% for pequi and 86.55% for sacha inchi.
Cedran et al., 2022	Optimization of emulsion water-oil with *Limosilactobacillus reuteri* using pequi oil as a continuous phase	To optimize water-in-oil emulsions containing pequi oil and *Limosilactobacillus reuteri*.	Experimental	The new formulation with pequi oil showed high encapsulation efficiency, protection during storage and a slight improvement in emulsion stability, making it suitable for probiotic systems and effective for topical use.
Silva et al., 2022	Improving of functionality in women with osteoarthritis of knee gel with oil of *Caryocar coriaceum* (Pequi).	To develop a pharmaceutical hydrogel with Carbopol® nano-encapsulated with pequi oil and evaluate its effect on pain and functionality in women with knee osteoarthritis.	Experimental in vivo	The gel, without cytotoxicity or irritation, increased muscle strength and knee range of motion, reducing instability, pain and swelling in women with osteoarthritis. The treatment improved quality of life (SF-36) and was considered stable and safe.
Brito et al., 2022	Bioactive compounds from pequi pulp and oil modulate antioxidant and antiproliferative activity in mononuclear blood cells and breast cancer cells.	To identify the main hydrophilic compounds in pequi pulp and lipophilic compounds in pequi oil and to verify their modulatory effects on the oxidative stress of human peripheral blood mononuclear cells (MN) cultured with MCF-7 breast cancer cells	Experimental in vivo	The hydrophilic extract of pequi pulp had the highest content of phenolic compounds, while the lipophilic extract had the highest content of carotenoids. β-sitosterol was the main phytosterol and γ-tocopherol the main tocopherol. Extracts rich in bioactive compounds stimulated mononuclear blood cells and improved SOD activity. In addition, when evaluated against MCF-7 cells and in coculture, they showed cytotoxic activity.
Pateiro et al., 2021	Fatty acid composition, cardio-vascular functionality, thermogravimetric differentiation, calorimetric and spectroscopic behavior of pequi oil (*Caryocar villosum* Alb.)	To determine the composition and fatty acid profile of pequi oil (*Caryocar villosum*), its functionality in cardiovascular health, thermogravimetric differential, e spectroscopic behavior..	Experimental	Pequi oil: high nutritional value, 70% unsaturated fatty acids, with oleic and linoleic acids predominating their functional indices showed cardioprotective properties, with low atherogenic and thrombogenic activity, as well as a high hypocholesterolemic index. The spectral bands confirmed the predominance of unsaturated fatty acids, and the oil had high thermal and oxidative stability with low mass losses at 267 °C and 376 °C, temperatures higher than those used in food and industry.
Marangon et al., 2021	Formulation of Chitosan/Gelatin/Pequi oil: Properties Rheological, Thermal and Antimicrobials	To formulate natural chitosan/gelatine emulsions containing pequi oil and Evaluate Properties, Rheological, Thermal and Antimicrobial.	Experimental	The addition of pequi oil gave greater thermal stability to the polymeric network of chitosan and gelatine. Rheological tests showed that the emulsions were more elastic than viscous, with increase in elasticity according to concentration of pequi oil. The emulsions with pequi oil showed better antimicrobial activity against *Staphylococcus aureus* compared to those stabilized with gelatin and chitosan, as well as greater long-term storage stability.

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Table 1. Continuation.

Evangelista-Silva et al., 2021	The intestinal transporters GLUT5 and FAT/CD36 and blood glucose are reduced by a carotenoid-rich oil/MUF A in high-fat fed mice	To investigate the effects of pequi oil (PO) on intestinal nutrient transporters, intestinal morphology and biomarkers.	Experimental In vivo	Pequi oil increased calorie intake without altering fat. In the high-fat diet group, it reduced fasting glycemia and villus width. There was no impact on GLUT2, L-FABP or FATP4 levels, NPC1L1, NHE3 or PEPT1, but GLUT5 and FAT/CD36 reduced. The oil seems to have reduced the absorption of monosaccharides and fatty acids, contributing to lower fasting glycemia without altering body weight or visceral fat.
Pires et al., 2020	Dermal wound healing properties of lipid-core polymeric nano-capsules loaded with *Caryocar brasiliense* oil: formulation and in vivo evaluation	To report on the improved activity of nanostructured CBC (LNCCBC and LNCCBC+) on dermal wounds in vivo	Experimental In vivo	The oil had physicochemical characteristics suitable for use, with adequate moisture and acidity and a higher % of oleic acid. The nano-emulsions were around 200 nm in size. The nanostructured oil showed superior efficacy in dermal healing in vivo compared to the free oil. The formulation showed the best results, with a greater increase in the production of type 1 collagen, which is essential for scar repair.
Comunian et al., 2020	Reduced loss of carotenoids during storage by co-encapsulation of pequi and buriti oils in oil/water emulsions followed by freeze-drying: use of unheated whey protein isolates as emulsifiers.	To encapsulate pequi oil and co-encapsulate pequi oil and buriti by emulsification with whey protein isolate (WPI) as an emulsifier in two forms, natural (unheated) and heated, followed by freeze-drying.	Experimental	The emulsions showed good stability, with droplet sizes varying between 0.88 and 2.33 μm. The formulations showed the lowest instability indices. The co-encapsulated oils showed greater retention of carotenoids compared to the free oils after 30 days, as well as better oxidative stability indices. Formulations with an oil to aqueous phase ratio of 1:3, regardless of WPI heating, stood out for their better carotenoid retention and oxidative stability.
Ombredane et al., 2020	Systems based on nano-emulsions with a promising approach to improve the antitumor effect and activity of pequi oil (*Caryocar Cambess.*) in breast cancer cells.	To elaborate and characterize a nano-emulsion based on pequi oil and evaluate its anticancer effects.	Experimental	Significant anti-tumor dose and time dependent effects against breast cancer cells (4T1) after 24 and 48 hours, along with lower cytotoxicity against non-tumor cells (NIH/3T3) after 24 and 34 hours
Coutinho et al., 2020	Pequi nano-emulsion (*Caryocar brasiliense Cambess*) - administered orally, modulated Inflammation in acute lung injury induced by LPS in rats	To develop nano-emulsions containing pequi oil (pequi-NE) and evaluate their effects in a model of lung injury induced by lipopolysaccharide (LPS)..	Experimental In vivo	The pequi nano-emulsion had particles with an average diameter of 174-223 nm and favorable physicochemical properties. Pretreatment with free pequi oil reduced the influx of inflammatory cells, while the nano-emulsion completely abolished the accumulation of leukocytes. The nano-emulsions potentiate the anti-inflammatory properties of pequi oil, attributed to the high levels of oleic acid in the oil
Castelo et al., 2020. Estudo Experimental	Development and Characterization of Microparticles of Pequi Oil (*Caryocar coriaceum* wittm.) Encapsulation by vibration nozzle.	To analyze the physicochemical characteristics and evaluate the effects supplementation with *C. brasiliense* oil in an animal model.	Experimental	The oil showed excellent oxidative stability, with a predominance of oleic 3.56%) and palmitic (37%) fatty acids. Supplementation reduced total cholesterol, LDL-c and non-HDL-c, and was most effective when combined with olive oil and *C. brasiliense* oil. This resulted in significant benefits in the lipid profile.
Silva et al., 2020	*Caryocar brasiliense Cambess* pulp oil supplementation reduces total cholesterol, LDL-c and non-HDL cholesterol	To analyze the physicochemical characteristics and evaluate the effects supplementation with *C. brasiliense* oil in an animal model.	Experimental In vivo	The oil showed excellent oxidative stability, with a predominance of oleic 3.56%) and palmitic (37%) fatty acids. Supplementation reduced total cholesterol, LDL-c and non-HDL-c, and was most effective when combined with olive oil and *C. brasiliense* oil. This resulted in significant benefits in the lipid profile.
Nascimento et al., 2019	In vitro release and antioxidant potential of pequi oil biopolymers (*Caryocar Brasiliense* Cambess)	To synthesize Oil-based biopolymers (*Caryocar brasiliense* Cambess) to be implemented as drugs	Experimental	The polymers under study showed good sensitivity to pH. None have oxidative potential. However, they have significant potential to reduce growth inhibition and increase survival of the *Saccharomyces cerevisiae* strains tested. The lowest concentration (100 μg mL-1) is considered the most effective and can be used as biomaterials.

Continue...

Table 1. Continuation.

Nascimento Silva and Naves, 2019	Potential of the whole pequi fruit (Caryocar spp.) - pulp, kernel, oil and bark - as a medicinal food.	. To develop a phyto-cosmetic with antioxidants and photo-protectants properties from pequi oil	Experimental	The polymers under study showed good sensitivity to pH and no oxidative potential, but they were effective in reducing growth inhibition and increasing survival of *Saccharomyces cerevisiae* strains. The lowest concentration (100 mL-1) was the most effective, indicating its potential for use in specific applications.
Oliveira et al., 2018	Study of the partial replacement of whey protein isolate (WPI) by Pequi Oil maltodextrin (MD) and Spray Dry insulin (IN) on the Stability of Bioactive Compounds	To evaluate the effect of different wall matrix biopolymers on the properties of spray-dried pequi oil and the degradation of its bioactive compounds	Experimental	The particles showed amorphous characteristics, with the WPI and WPI/IN treatments showing spherical morphology. WPI and WPI/MD exhibited greater thermal stability and better protection, antioxidant capacity. The WPI system had better protection for β-carotene, δ-carotene and lycopene, while WPI/MD protected γ-carotene better, and WPI/IN also showed good protection
Pereira et al., 2020	Characterization, antibacterial activity and antibiotic-modifying action of the fixed oil of pulp and almond (*Caryocar coriaceum* Wittm).	To carry out physicochemical characterization of pequi pulp and kernel oil; its antibacterial activity and modifying action on aminoglycoside antibiotics.	Experimental	The oils had a high content of unsaturated fatty acids: oleic and palmitic acids. In the antibacterial test, the results were more significant against *Escherichia coli*, while other standard and multidrug-resistant strains showed MICs ≥ 1024 μg/mL. In addition, the oils associated with antibiotics improved the antibacterial activity against *Staphylococcus aureus*, reducing the MICs.
Roll et al., 2018	Oil from pequi pulp (*Caryocar brasiliense* Camb.) related to aging, inflammation and oxidative stress in older Swiss mice, especially females.	To carry out physicochemical characterization of pequi pulp and kernel oil; its antibacterial activity and modifying action on aminoglycoside antibiotics.	Experimental In vivo	The treatment with pequi oil improved hemoglobin and hematocrit, with no genotoxic or clastogenic effects. It increased lymphocytes and reduced neutrophils and monocytes in 11-12 month old females, eliminating significant differences compared to younger controls. Supplementation can protect against anemia, inflammation and oxidative stress related to aging, especially in females..
Horn et al., 2018	Development and characterization of films and gels of collagen/gelatin incorporated with pequi oil.	To develop and characterize films and gels of collagen/gelatin incorporated with pequi oil to improve their properties.	Experimental	The addition of pequi oil (PO) reduced the contact angle due to the carboxylic groups of palmitic and oleic acids. The roughness observed in the SEM images resulted from good homogenization. The OP reduced the tensile and elongation forces of the films, and increased the thermal stability, indicating good compatibility between the PO and the biopolymers, suggesting potential application in the wound healing process.
Silva et al., 2018	Optimization of cashew gum and chitosan for microencapsulation of pequi oil by complex coacervation.	To evaluate the optimized conditions of cashew gum (CG) and chitosan (CT) for encapsulation of pequi oil by complex coacervation	Experimental	The PO was released in greater quantities at acidic pH for the GA/CT and CG/CT complexes, respectively. The yield of microparticles was 60%, with sizes of 4.8 μm (CG/CT) and 2.7 μm (GA/CT). The encapsulation efficiency was high, 86% (CG/CT) and 89% (GA/CT). CG formed an effective complex with CT at pH 4.5.
Cicero et al., 2018	Chemical characterization of a variety of cold-pressed gourmet oils available on the Brazilian market	To chemically characterize, the different special extra virgin oils produced by cold pressing fruits/nuts (olive, pequi, palm, avocado, coconut, macadamia and Brazil nut) and seeds (grape and canola), traded in the region region of Minas Gerais		Olive oil stood out for its high oleic acid (MUFA) content, while grape seed oil, horse chestnut oil and Brazil nut and canola had significant levels of PUFA. Coconut oil had the highest content of saturated fatty acids (lauric acid). Gourmet palm, pequi, coconut and canola oils had high levels of phenolic acids, while olive oil had antioxidants such as tyrosyl..
Traesel et al., 2017	Evaluation of embryotoxic oxic and teratogenic effects of oil extracted from pulp of *Caryocar brasiliense* Cambess in rat and teratogenic effects of oil extracted from pulp of *Caryocar brasiliense* Cambess in rats	To evaluate the maternal, embryotoxic and teratogenic effects of *Caryocar brasiliense* pulp oil (CBPO).	Experimental in vivo	The oil showed no maternal toxicity, with no impact on the weight, behavior or hematological and biochemical data of the pregnant females. Reproductive rates and the number of corpora lutea were similar between the groups, indicating a low embryotoxic effect. External and skeletal abnormalities were observed in all groups, including the control

TPC: total phenolic content; SF-36: Short-Form Health Survey (36 items); SOD: superoxide dismutases; GLUT: glucose transporter, MUFA: monounsaturated fatty acids; PUFA: polyunsaturated fatty acids; L-FABP: liver fatty acid binding protein; FATP: fatty acid transport protein; NPC1L1: Niemann–Pick C1-Like 1 polytopic transmembruane protein; NHE: sodium--hydrogen exchanger isoform; PEPT: peptide transporter; FAT/CD: fatty acid translocase/cluster of differentiation; LCN: lipid-core nanocapsules; CBC: *Caryocar brasiliense* Cambess; WPI: whey protein isolate; MD: pequi oil maltodextrin; IN: spray dry insulin; NIH/3T3: National Institutes of Health 3-day transfer, inoculum 3 x 10^5 cells; LPS: lipopolysaccharide; FTIR: Fourier Transform Infrared Spectroscopy; LDL: low-density lipoprotein; HDL: high-density lipoprotein; pH: potential of hydrogen; MIC: minimal inhibitory concentration; DNA: deoxyribonucleic acid; GA/CT: ?; CG/CT: cashew gum and chitosan; EC50: effective concentration 50%.

bioactive compounds and add them to food. In addition, 18% of the studies (5 articles) carried out in 2018 investigated the development of biopolymers, films, and gels with pequi oil, evaluating their antioxidant and preservation properties.

The studies published in 2019 and 2021 (11%, 3 articles per year) evaluated the anti-inflammatory and analgesic effects of pequi oil, its antioxidant potential, and the use of biopolymers and nanoencapsulation to treat breast cancer and attenuate glucose absorption. In 2017, only one study was published, which examined the embryotoxic and teratogenic effects of pequi oil.

Figure 4 presents the impact factor of the journals used in the research, highlighting 26 journals. Among the most influential are Fuel (Journal Citation Reports [JCR]: 8.03), Food Research International (JCR: 7.425), Biomedicine & Pharmacotherapy (JCR: 7.419), and Life Sciences (JCR: 6.78), while national journals such as Brazilian Archives of Biology and Technology (JCR: 1.18) and Natural Product Research (JCR: 2.2) had a lower impact factor. International journals had greater visibility and number of citations when compared to national journals.

The impact factor is a crucial measure for assessing the influence and reputation of journals and is calculated based on the number of citations in the current year and the number of publications in the previous two years (Rodrigues, 2024). The journals used in the study had considerable impact factors, indicating high-quality content.

The majority of studies used *Caryocar brasiliense* Cambess for experimental research, which is the most studied species,

Figure 4. Impact factor (Journal Citation Reports) of the journals included in the systematic review, 2022.

as corroborated by Nascimento et al. (2019), due to its wide distribution in Brazil.

The meta-analysis of the 14 articles was carried out in two stages, using fixed-effect and random-effect models, which showed consistent results. At the first stage, the outcomes analyzed included anemia, inflammation, antioxidant, antitumor, nutritional, embryotoxic, teratogenic, and osteoarthritis effects. At the second stage, the outcomes included healing, glucose and cholesterol reduction, lung inflammation, modulation of breast cancer cells (MCF-7), antibacterial and antioxidant effects, as demonstrated in Figures 5 and 6.

The results of the meta-analysis showed the therapeutic effects of pequi oil, highlighting its effectiveness in various interventions. Meta-analysis 1 (Figure 6) revealed a 49% proportion of positive therapeutic effects, with $p < .01$ and 95%CI of 0.37–0.64. The main bioactive compounds identified were polyphenols, carotenoids, and phytosterols such as β-sitosterol and γ-tocopherol. Among the studies, four stood out, such as Oliveira et al. (2018), who reported a proportion of 84% (95%CI 0.75–0.91) for antioxidant effect and Roll et al. (2018) with 80% (95%CI 0.71–0.87) in relation to anemia and inflammation. Besides Silva et al. (2022), who observed a significant improvement in pain and functionality in women with knee osteoarthritis, with a proportion of 75% (95%CI 0.65–0.83) and Ombredane et al. (2020) who showed an antitumor effect on breast cancer cells with 60% effect (95%CI 0.50–0.70).

Some studies, with less weight, showed embryotoxic and teratogenic effects (10%, 95%CI 0.05–0.18) and effects on physicochemical and nutritional properties (13%, 95%CI 0.07–0.21); however, these did not significantly affect the overall results.

In Meta-analysis 2 (Figure 6), the total effect was 73% (95%CI 0.67–0.79), with a significant p-value and moderate heterogeneity ($I^2 = 95\%$, $p < .1009$). Pires et al. (2020) reported a proportion of 85% (95%CI 0.76–0.91) for healing, and Horn et al. (2018) found 80% (95%CI 0.71–0.87) for the same outcome. The study of Coutinho et al. (2020) demonstrated a significant anti-inflammatory effect (75%, 95%CI 0.65–0.83), while Silva et al. (2020) found an anti-inflammatory and proliferative effect against breast cancer, with a ratio of 70% (95%CI 0.60–0.79). Nascimento et al. (2019) observed an antioxidant effect of 74% (95%CI 0.64–0.82). Silva et al. (2020) found cholesterol reduction with 65% effect (95%CI 0.55–0.74), and Evangelista-Silva et al. (2021) reported glucose reduction with 70% effect (95%CI 0.60–0.79). The study of Marangon et al. (2021) on the antimicrobial activity of pequi oil against *Staphylococcus aureus* showed an effect of 60% (95%CI 0.50–0.70), with statistical significance. These results reinforce the potential therapeutic benefits of pequi oil, particularly in the areas of healing, inflammation, antioxidants, and combating conditions such as cancer and cardiovascular disease.

Information on the analysis of publication bias in the meta-analysis studies was not present at a specific point in the funnel graphs, indicating the studies did not have any suspicions of publication bias (Figure 7).

The results and discussion of the studies were organized considering the potential and applications of pequi oil in various areas, highlighting research in the food, pharmaceutical, and cosmetics industries as well as its therapeutic effects.

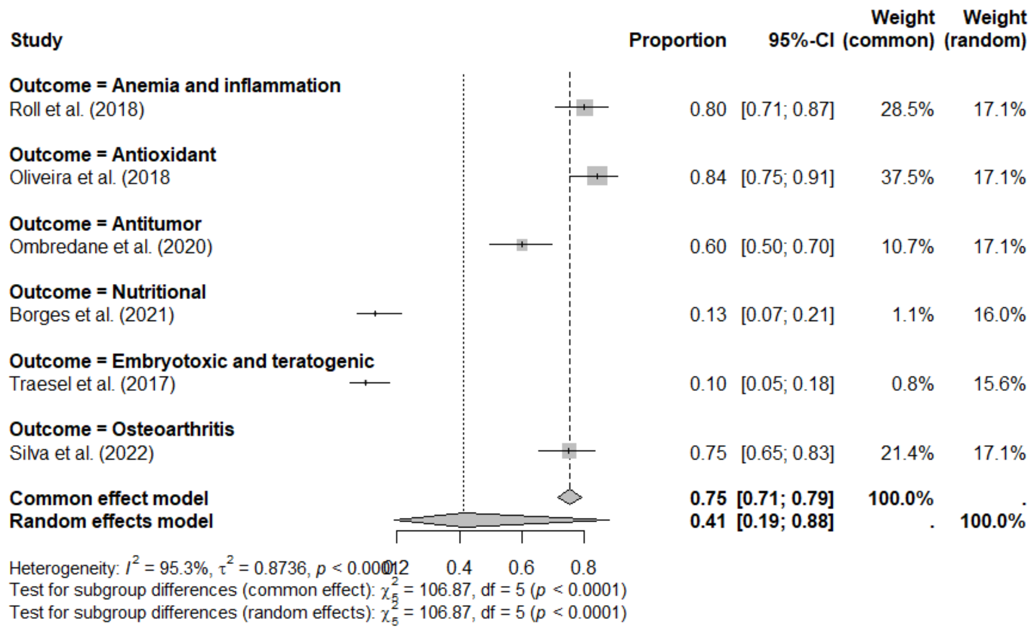
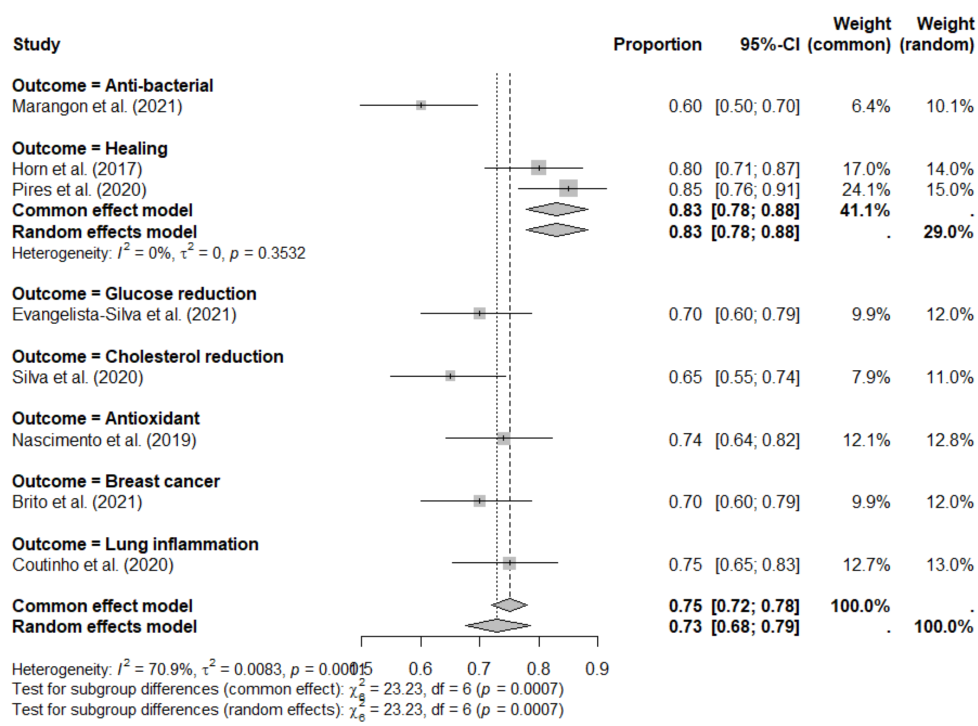


Figure 5. Meta-analysis 1 of studies on pequi oil categorized according to outcomes.



Quantifying heterogeneity: tau^2 = 0.0085 [0.0016; 0.0477]; tau = 0.0923 [0.0405; 0.2185]; I^2 = 70.9% [39.9%; 85.9%];
H = 1.86 [1.29; 2.67]. Test of heterogeneity: Q d.f. p-value 24.09 7 0.0011.

Figure 6. Meta-analysis 2 of studies on pequi oil categorized according to outcomes.

4 DISCUSSION

4.1 Applications and potential of Pequi Oil in food technology and industry

The food industry has become increasingly interested in natural ingredients with functional properties with focus on pequi oil, which is valued for its physicochemical and nutritional properties, such as high levels of unsaturated fatty acids and carotenoids. The study by Lorenzo et al. (2021) revealed that pequi oil has 70% unsaturated fatty acids, with a predominance of oleic (52.67%) and linoleic acid (15.20%).

The functionality indices suggested cardiovascular protective properties, with low atherogenic (0.38) and thrombogenic (0.75) indices and a high hypocholesterolemic index (2.58).

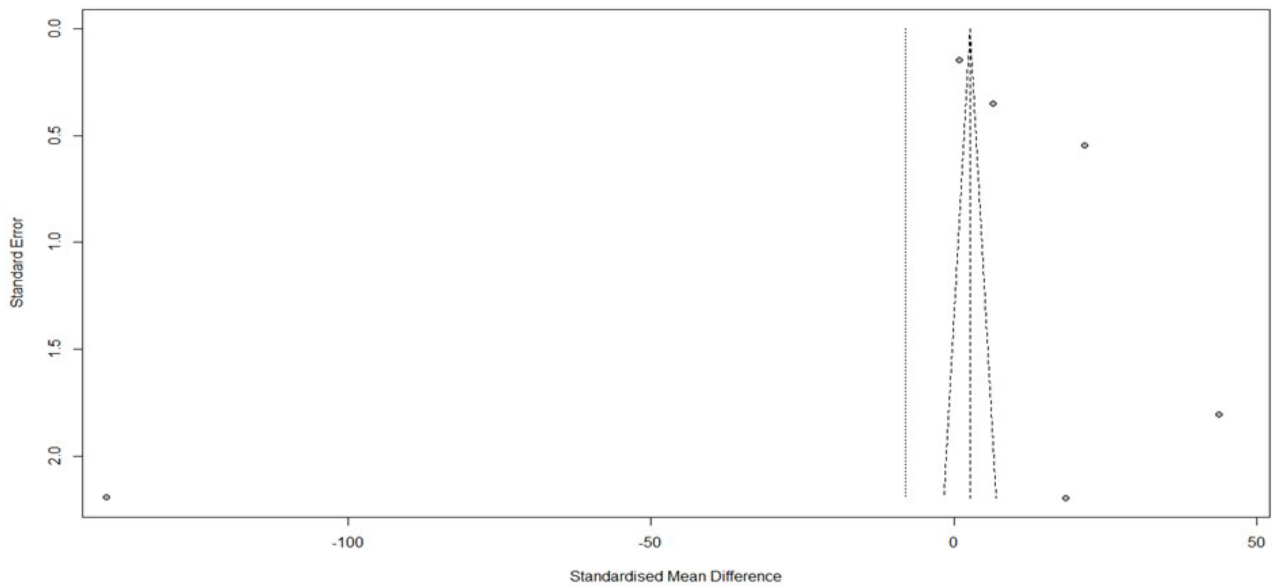


Figure 7. Publication bias analysis of categorized studies (2022).

Recent research, such as that by Borges et al. (2022), explored the use of pequi oil in cheeses, with additions of between 7.00–13.00%, resulting in total unsaturated fatty acids ranging from 58.68–81.06%, with oleic acid being the main component (62.61%). In cheese, the inclusion of pequi oil altered the texture, decreasing cohesiveness, hardness, elasticity, and chewiness by 13% (95%CI 0.07–0.21). Murtaza et al. (2017) observed similar effects when adding pequi oil to cheddar cheese.

Marangon et al. (2021) studied the use of pequi oil as an emulsion stabilizer, observing improvements in viscosity, elasticity, and temperature stability, as well as an antimicrobial effect of 60% (95%CI 0.50–0.70), suggesting its potential application as a preservative. Pereira et al. (2020) also found significant antimicrobial effects against *Escherichia coli* and *Staphylococcus aureus* when the oil was combined with antibiotics.

Microencapsulation technology has been applied to preserve the bioactive compounds in pequi oil, as demonstrated by Castelo et al. (2020), who obtained 96.17% encapsulation efficiency using sodium alginate and chitosan. Silva et al. (2022) used coacervation to encapsulate pequi oil in cashew gum and chitosan, with a good release rate and increase in the percentage of oleic acid (25.00 to 33.00%) in the enriched yogurts.

Cornelio-Santiago et al. (2022) evaluated the extraction process with pressurized isopropanol solvent and identified pequi oil with 57.22 mg/100 g of β-sitosterol and 589.46 mg GAE/kg of total phenolic content, with oleic acid (48.28–50.77%) and linolenic acid (44.03–47.13%) being the main fatty acids present. Oil recovery was 92.98% higher than the 55.00% obtained with cold handmade extraction (Van Hoed, 2010).

4.2 Applications in the pharmaceutical and cosmetic industry and their therapeutic effects

Pequi oil has demonstrated therapeutic, nutritional, and sensory value, with research seeking to elucidate its efficacy. The technologies used, such as encapsulation, have shown good results, according to the meta-analysis (Figures 5 and 6).

Comunian et al. (2020) encapsulated and co-encapsulated pequi and buriti oil with whey protein isolate, increasing carotenoid retention. Silva et al. (2022) developed a hydrogel with nano-encapsulated pequi oil, obtaining a 75% reduction (95%CI 0.65–0.83) in osteoarthritis symptoms. Silva et al. (2018) used cashew gum and chitosan to microencapsulate the oil, applying it to cosmetics and nutraceuticals.

Nano-capsule formulations with pequi oil have shown efficacy in dermal healing *in vivo*, increasing the production of type 1 collagen (Pires et al., 2020) with a positive effect of 70% (95%CI 0.60–0.79). Anti-inflammatory and proliferative effects have also been observed in breast cancer and lung lesions, with a 75% reduction in side effects (95%CI 0.65–0.83) (Costa et al., 2011; Coutinho et al., 2020; Ombredane et al., 2020).

Junior et al. (2020) investigated the analgesic and anti-inflammatory effects of pequi oil, observing leukocyte and edema inhibition, as well as embryotoxic and teratogenic effects in rats (Traesel et al., 2017). The oil also reduced fasting glycemia and controlled the low-density lipoproteins (LDL) fraction of cholesterol (Evangelista-Silva et al., 2021; Silva et al., 2020).

Three studies synthesized biopolymers to protect the oil's bioactive compounds, applying them in gels and films for tissue healing (Horn et al., 2018; Nascimento et al., 2019; Oliveira et al., 2018). Pires et al. (2020) and Horn et al. (2018) reported ratios of 85% and 80%, respectively, demonstrating that nanostructured oil induced dermal healing in rats by increasing the production of type I collagen.

In addition, Nascimento-Silva and Naves (2019) developed a phyto-cosmetic with pequi oil, demonstrating antioxidant and photoprotective properties, with a high concentration of phenolic compounds.

5 CONCLUSIONS

The results elucidated and proved the importance of the application of pequi oil, as it is a natural ingredient and mainly due to the presence of bioactive compounds and unsaturated fatty acids, which are considered beneficial to health. This can be seen in the meta-analysis, attesting to the possibility of 73% of the practical application of pequi oil in many therapies, as well as the effect on physicochemical, nutritional, and sensory properties in food and antimicrobial activity, which can be applied as a preservative in food.

It was also found that pequi oil is a renewable and promising alternative for nanoencapsulation and emulsion technology, for the synthesis of biopolymers, and in the production of gels and films for tissue healing processes.

Thus, pequi oil has shown great potential for boosting product development in many industrial sectors. However, it is essential to look for new alternatives for its exploitation, which will allow for more practical applications and the development of new products.

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