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REVIEW ARTICLE

An overview of the ellagic acid and proanthocyanidins' polyphenols from cambuci (*Campomanesia Phaea Berg*): Myrtaceae's family

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Abstract

Cambuci (*Campomanesia phaea Berg.)* is a native fruit to the Atlantic Forest biome of Brazil with several bioactive compounds, ascorbic acid, phenolic compounds, volatile compounds, tannins, and carotenoids and it is used mainly to produce jellies, ice cream, juices, and alcoholic beverages. This review and bibliometric analysis establish the progress, trends, and perspectives of research on this fruit. The results show an increase in publications is related to the emergence of this new research and demonstrate the potential growth of cambuci in different studies. Between 2003 and 2022, 153 articles and 22 reviews related to cambuci were published. The bibliometric analysis revealed that the main research area was Agricultural and Biological Sciences, and the main country producing research on the cambuci fruit was Brazil, with 118 articles published. Given that most publications are associated with Brazil, the foremost institutions dedicated to cambuci research are also Brazilian. The University of São Paulo spearheads the list of affiliations and comprises eight other Brazilian organizations, including seven universities and one research institution. The author's keywords revealed that phenolic compounds, antioxidant capacity, flavonoids, antioxidant activity, bioactive compounds, and osmotic dehydration are motor themes in cambuci research. Additionally, ellagic acid is a bioactive phenolic compound in tannins, and proanthocyanidins are compounds of great relevance in cambuci and have great benefit for human health with antibacterial, antifungal, antiviral, anti-inflammatory, antidiabetic, gastroprotective, and antidepressant activity. In conclusion, the review establishes that cambuci is an interesting source for its application in the food and pharmaceutical industries.

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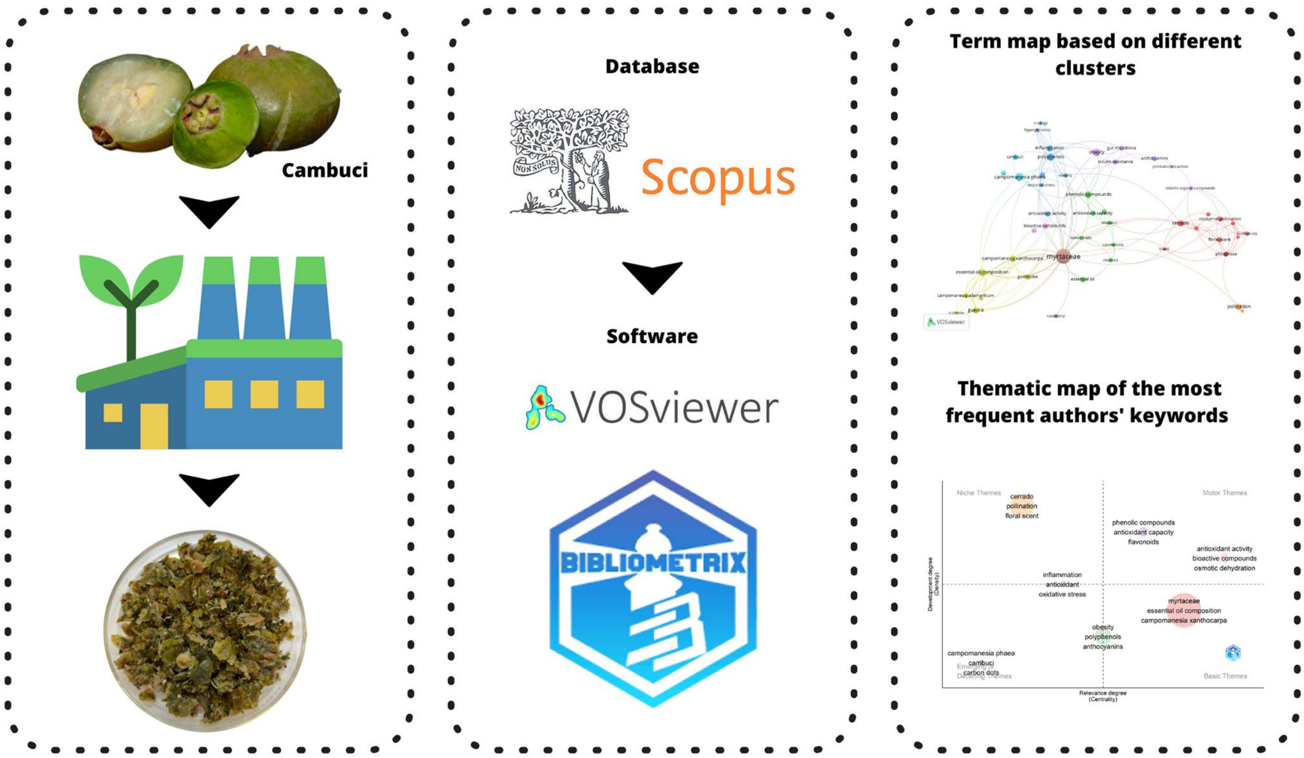
Graphical abstract



Keywords Native fruits · Natural products · Scientometrics · VOSviewer · Bioactive compounds · Food products

Introduction

Brazil is one of the most biodiverse countries in the world, with more than 40,000 different species, which equals 20% of the world's biodiversity [1]. For instance, fruit production in Brazil is 45 million tons per year, which makes Brazil the largest producer of fruit in the world. However, many fruits are unknown and explored despite having a high content of bioactive compounds [2]. Due to the large extension of the territory, it is possible to find many climates that generate many biomes that favor the appearance of different native fruits [3]. In addition, this allows the introduction and adaptation of various exotic fruits [4, 5]. The Myrtaceae family has excellent ecological and commercial importance, since it is one of the main families of fruit trees in the world, with 140 genera and approximately 5800 edible species, which are distributed in tropical and subtropical areas [6, 7]. The Myrtaceae family includes some fruits, such as *Psidium cattleianum* (araçá), *Myrciaria cauliflora*. (jabuticaba), *Eugenia uniflora* (pitanga), *Eugenia dysenterica DC.* (cagaita), *Campomanesia phaea Berg.* (cambuci), and *Myrciaria dubia McVaugh* (camu-camu), among others [3, 5].

Cambucí (*Campomanesia phaea Berg.*) is a Brazilian Atlantic Rainforest biome fruit that has a high productive potential, since it has a wide variety of attributes that allow it to follow the trends of Brazilian consumers, such as wellness and health, sustainability, ethics, and high sensory quality [8]. The cambuci tree grows mainly in Serra do Mar, Minas Gerais, and São Paulo States of Brazil [9–11]. The fruits are fleshy, succulent, and edible and have a diameter between 5 and 6 cm in the middle region and a thickness between 3 and 4.5 cm [10]. The cambuci is juicy and has a sweet smell and a somewhat acid taste, which is why it is used in small proportions for the preparation of jams, jellies, ice cream, and even liqueurs, and has a pulp yield of about 80% [3, 8, 12]. Moreover, it is an essential source of phenolic compounds [9, 13]. Its annual harvest can reach 300 tons. However, it varies each year. Also, this is an approximation, because most cambuci fruits are harvested in periods of low demand [14].

Cambuci fruit has various bioactive compounds, ascorbic acid, phenolic compounds, volatile compounds, tannins, and carotenoids [8]. In Cambuci extracts, quercetin derivatives have been identified in concentrations ranging from 3.53 to 6.44 µg/mL, free ellagic acid in the range of 9.57 to 16.98 μg/mL, and total ellagic acid between 1312 and 2400 μg/mL [14]. On the other hand, Sanchez–Azevedo et al. [9] identified rutin in concentrations ranging from 0.048 to 0.105 g/kg (dry weight) for fruits from Rio Grande da Serra, Mogi das Cruzes, Paraibuna, and Paranapiacaba. Similarly, Epigallocatechin Gallate (EGCG) was found in concentrations between 0.099 and 0.138 g/kg. Phenolic compounds in cambuci are important in counteracting metabolic complications related to obesity, as they improve glucose tolerance and reduce fasting blood glucose and insulinemia [14]. In addition, the bioactive compounds in cambuci positively affect anti-inflammatory and antimicrobial action [15].

Compounds like ellagic acid have both medicinal and nutritional applications. However, in recent years, there has been a growing industrial interest in using this compound to synthesize bioengineering materials [16]. Furthermore, in line with the suggestions of Frayne et al. [17], nanocomposites utilizing ellagic acids (EA) have the potential for applications in environmental pollutant degradation, particularly in removing toxic aromatic compounds. On the other hand, proanthocyanidins could generate interest in the food industry, because they manage to efficiently reduce acrylamide, which could increase the shelf life of foods, as suggested by Sáyago–Ayerdi et al. [18].

The composition of the cambuci fruit is approximately 80.5% pulp, 18.5% peel, and 1% seeds [10]. The pulp generates interest in the cambuci's industrial processing, since it has a high yield (fibers), total soluble solids, and titratable acidity [19]. However, the peel and seeds have not been extensively studied. 25–30% of by-products are produced and discarded while processing fruits and vegetables, mainly seeds, peel, bark, and pomace [20]. The by-products are widely produced in the world. It has dietary fiber and many bioactive compounds (organic acids, minerals, phenolic compounds, and sugars). However, most are rejected and discarded [21, 22]. Nevertheless, due to overproduction and inadequate sustainable management of by-products, they end up in landfills, associated with various social, economic, and environmental problems [23]. For instance, the environment receives Greenhouse Gas emissions, because these organic materials are disposed of in landfills or burned, contaminating water, air, soil, and other foods [24].

Bagasse or seeds could be used in nutraceutical and pharmaceutical areas or can even be used in livestock feed products [25]. However, the conventional extraction techniques for different compounds require a large volume of solvents, which can be dangerous. On the other hand, they have low selectivity extraction yields and provide short extraction times. The extraction of bioactive compounds from by-products must maximize the extraction yield, satisfy the demand of the industry, keep the bioactive compound free of impurities and toxic compounds, and avoid compound deterioration during the extraction process [26, 27].

Bibliometric analysis has become a tool to determine trends and gaps in research areas [28]. The use of this method has allowed for elucidating the trends and perspectives of research in Uvaia (*Eugenia pyriformis Cambess—Myrtaceae*) [29], jabuticaba (*Myrciaria cauliflora*) [6], bacupari (*Garcinia brasilienses*) [30], recovery of food waste by anaerobic digestion [31], and anaerobic digestion technology [28]. This study aims to identify trends in research related to Cambuci and research gaps and opportunities through bibliometric analysis. The analysis focused on review articles and research published between 2003 and 2022.

Methodology

The bibliometric analysis was carried out using as a reference the methodology described by Sganzerla & da Silva [23] and Gabriel da Rosa et al. [6]. The search was performed through the Scopus© database with words and terms: cambuci OR campomanesia AND phaea OR "O. Berg Landrum" OR "(O. Berg) Landrum" OR cambucizeiro. Furthermore, the filter by document type was used, selecting "article" and "review". The files counted were exclusively articles and reviews published between 2003 and 2022. 175 documents were found 153 articles, and 22 reviews. The data were exported and added to the VosViewer © software, thus generating graphs and tables that facilitate the evaluation of the main characteristics of the set of documents found. The graphs show the clusters of the main keywords, the main authors, the most cited articles, and their respective countries.

The dataset obtained was also inserted into the bibliometric software Bibliometrix (R language), where graphics were obtained to present the most employed authors' keywords, a thematic map of the most frequent authors' keywords in the field of cambuci research, and the top authors. The bibliometric discussion was based on the 175 documents found and evaluated the evolution of publications related to cambuci between the years 2003 and 2022, which are the main research fields, the most cited documents, the principal authors, ten main affiliations, and the main countries. Finally, the main trends related to the topic were evaluated. Figure 1 presents the stages of bibliometric analysis.

Research trends on Cambuci

Publication evolution and research areas

The progress of research of cambuci studies can be seen in Fig. 2. A total of 175 documents were found, of which 153 were articles and 22 reviews published between 2003

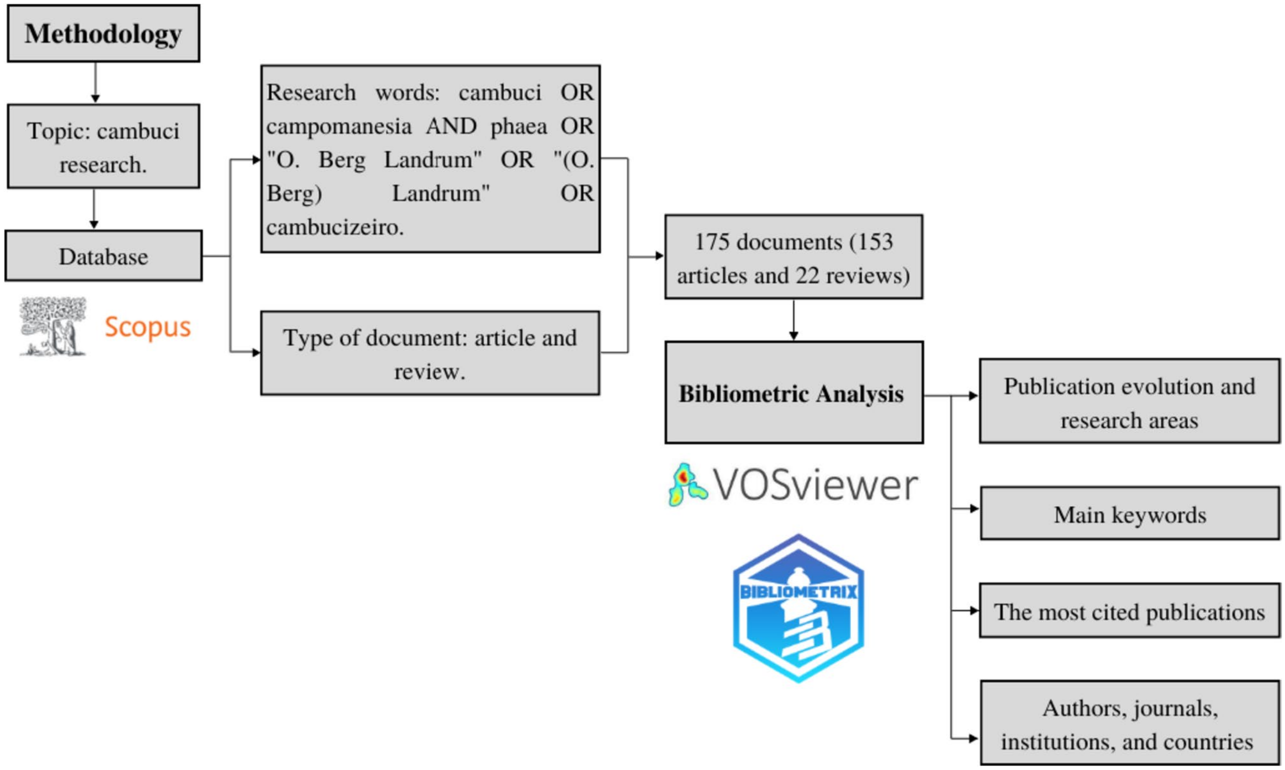


Fig. 1 Methodological steps for the bibliometric analysis

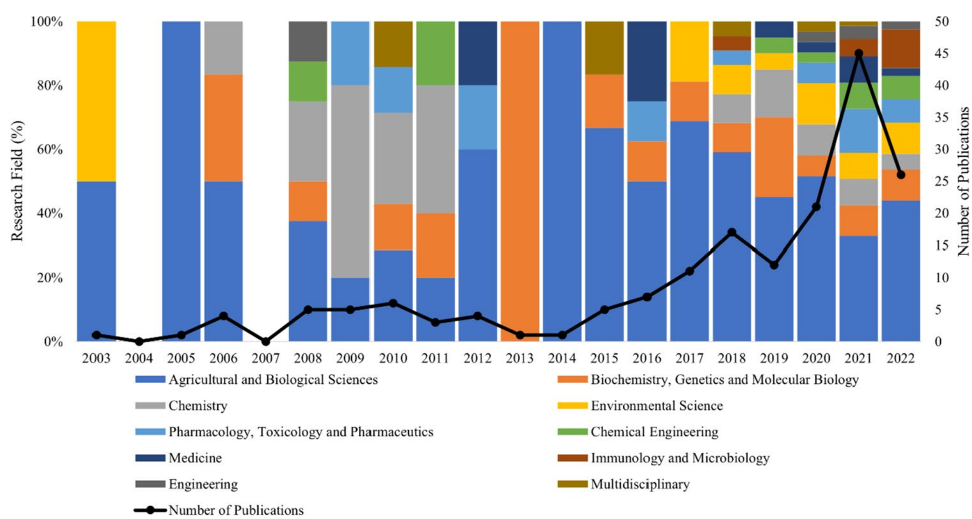


Fig. 2 Progress of the number of publications over the years (2003–2022) in the field of cambuci research

and 2022 in the Scopus database. In 2003, the first publication was founded. In 2004 and 2007, publications ceased, returning to occur in 2005, 2006, and 2008, with 1, 4, and 5 documents being published, respectively. The number of publications remained below 7 for 13 years until 2016, when a growing interest in cambuci began, demonstrated by the growth of publications between 2019 and 2021, the latter being the year that presented the highest number of publications, reaching the mark of 45 documents. The increase in publications is related to the emergence of new research areas. Until 2017, research areas alternated, reaching a maximum of 4 per year, which changed in 2019 with the publication of documents by new research areas. The emergence of these new research areas demonstrates the potential growth of cambuci in different studies and its multidisciplinary character.

Table 1 describes the ten main areas of publications in the research period. The main publication area is Agriculture

Table 1 Ranking ten top publication areas, affiliations, countries, and journals

Ranking	Research areas	Number	%[a]
1st	Agricultural and biological sciences	115	67.65
2nd	Biochemistry, genetics and molecular biology	30	17.65
3rd	Chemistry	25	14.71
4th	Environmental science	21	12.35
5th	Pharmacology, toxicology and pharmaceutics	21	12.35
6th	Chemical engineering	12	7.06
7th	Medicine	12	7.06
8th	Immunology and microbiology	10	5.88
9th	Engineering	6	3.53
10th	Materials science	5	2.94
Ranking	Affiliations (institution)	Number	%
1st	Universidade de São Paulo	40	23.53
2nd	Universidade Federal de Minas Gerais	13	7.65
3rd	Universitat Salzburg	11	6.47
4th	Universidade Federal de Lavras	11	6.47
5th	Universidade Federal de Mato Grosso do Sul	9	5.29
6th	Universidade Estadual de Mato Grosso do Sul	9	5.29
7th	Universidade Federal de Santa Catarina	9	5.29
8th	Universidade Estadual de Campinas	6	3.53
9th	Universidade Federal do Rio de Janeiro	5	2.94
10th	Empresa Brasileira de Pesquisa Agropecuária–Embrapa	5	2.94
Ranking	Countries	Number	%
1st	Brazil	118	69.41
2nd	China	13	7.65
3rd	Austria	11	6.47
4th	United States	10	5.88
5th	India	7	4.12
6th	Italy	6	3.53
7th	Canada	4	2.35
8th	Spain	4	2.35
9th	Sweden	4	2.35
10th	Mozambique	3	1.76
Ranking	Journals	Number	%
1st	Food Research International	9	5.29
2nd	Journal of Essential Oil Research	9	5.29
3rd	Arthropod-plant Interactions	6	3.53
4th	Foods	4	2.35
5th	Journal of Ethnopharmacology	4	2.35
6th	Acta Botanica Brasilica	3	1.76
7th	Anais da Academia Brasileira de Ciências	3	1.76
8th	Ciência e Tecnologia de Alimentos	3	1.76
9th	Journal of Food Process Engineering	3	1.76
10th	Molecules	3	1.76

[a]Percentage of 175 documents (automatically calculated in Scopus). Search conducted on January 1st, 2023; *In Portuguese

and Biological Sciences, and a total of 115 articles were published, corresponding to 67.65% of all publications found in the Scopus database. The difference between the number of documents opened by the first and second areas is 50%, thus demonstrating the great interest in cambuci. The second main area is Biochemistry, Genetics, and Molecular Biology, with 30 documents, followed by Chemistry, Environmental Science and Pharmacology, and Toxicology and Pharmaceuticals, with 21 documents. The results showed that studies referring to cambuci were scarce until 2017. Over the years, this fruit has become the subject of several publications, especially in Agricultural and Biological Sciences, which was predominant among cambuci publications.

Research areas and keywords for potential impact

The study of the co-occurrence of the main keywords was performed to assess the hot spots and frontiers around cambuci studies, aiming to identify which research areas are of potential impact [32]. Figure 3a presents the grouping of the 48 main keywords addressed by the authors corresponding to the information of each study**.** It is possible to see clusters based on closely interrelated keywords, grouping similar topics identified by colors. The items are connected by lines of different widths, which are proportional to the link strength among them. Figure 3b presents the evolution of publications between 2012 and 2022 based on analyzing the authors' keywords.

From the search implemented on Scopus, covering all publications related to cambuci, 175 studies were found and 641 author keywords. Ranking keywords by the total link strength, the top position is occupied by "*Myrtaceae*", followed by "*essential oil composition*", "*Campomanesia xanthocarpa*", "*guavira*", and "*Campomanesia adamantium*". This set of words is interesting, since Myrtaceae is a family comprehending 121 genera with many species, with considerable potential for obtaining carotenoids, volatile compounds, and phenolic compounds [7]. In addition to the family name, the keywords "*Campomanesia xanthocarpa*" and "*Campomanesia adamantium*" represent other species that are closely related to cambuci, since they belong to the same genera (*Campomanesia*). In the present study, 9 (nine) clusters were formed, and their items are presented in Table 2. In addition, Table 3 ranks the top 20 keywords according to the number of occurrences.

It is possible to notice the family's name Myrtaceae is placed between the clusters presented in blue and yellow, which are related to three different species of fruits, respectively, *Campomanesia phaea*, *C. xanthocarpa*, and *C. adamantium*. Each of these clusters presents research topics around bioactive compounds of the correspondent specific fruit and are linked to words representing its potential applications. The clusters in violet and green do not present a species name. However, they present keywords related to diseases against which cambuci may be useful, such as "obesity" and "insulin resistance", and present attractive traits of the fruit, such as "antioxidant capacity" and "vitamin C". The red cluster presents words that comprehend some agricultural and biological aspects linked to the fruits given by the words: "biodiversity", "floral traits", and "nocturnal pollination", for example. On the other hand, the antioxidant activity, osmotic dehydration, pollination, and oxidative stress of cambuci are some topics that have begun to study as of 2020.

Figure 4 presents a thematic map, and the keywords are placed according to the development degree of the research field and its relevance. The thematic map contains four quadrants, namely motor themes (up-right), niche themes (up-left), emerging or declining themes (down-left), and basic themes (down-right). The thematic map presents the formation of 7 (seven) clusters distributed in the diagram, showing the development degree (or density) and the relevance degree (or centrality) of the research fields. According to Fig. 4, the keywords "*myritaceae*", "*essential oil composition*", and "*Campomanesia xanthocarpa*" are basic themes with a high relevance degree, which means that the research field is important but not well-developed yet, requiring more research and analysis, consisting of an interesting area for the development of new research. Also, the keywords "bioactive compounds", "antioxidant capacity", "flavonoids", "antioxidant activity", "phenolic compounds", and "osmotic dehydration" are motor themes, indicating research fields that are well-developed and considered great importance. It is relevant to highlight that among the terms pointed as motor themes, the cluster containing the later three keywords (i.e., "antioxidant activity", "bioactive compounds", and "osmotic dehydration") presents the highest level of relevance. This fact, together with the few publications around cambuci, may indicate the possibility of developing even more research themes already indicated as "motor themes".

The most relevant publications

Table 4 shows ten most cited articles in the research area related to cambuci; it creates a perspective of the determined branch of study. The article about bioactive compounds and antioxidant capacity of fruits written by Genovese et al. [29], and published in Food Science and Technology International was the most cited (129 citations). The study analyzed the antioxidant capacity and bioactive compounds of some exotic Brazilian fruits, such as jaracatia, cambuci frozen araçá, camu-camu, and cagaita pulps. Genovese et al. [29] determined that fruits and pulps were significant sources of bioactive compounds with antioxidant capacity, which, although cambuci did not stand out, presented considerable amounts of bioactive compounds.

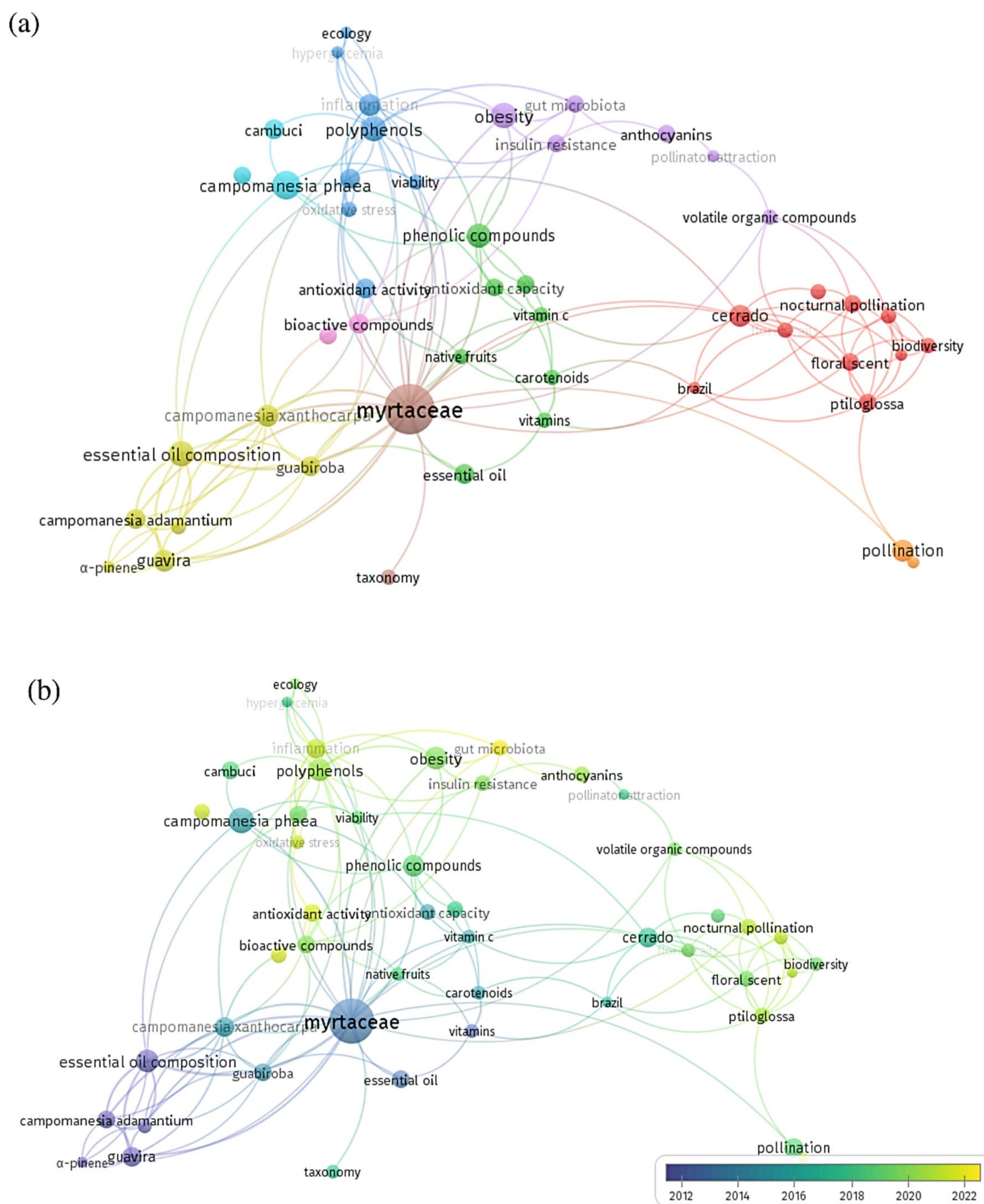


Fig. 3 The most used authors' keywords. **a** Term map based on different clusters; **b** map of the evolution of the authors' keywords by year

Gressler et al. [30] published the second most cited research about Brazilian Myrtaceae in the Brazilian Journal of Botany (122 citations). The study aimed to synthesize all information regarding the reproductive ecology of Myrtaceae in Brazil, grouping data related to pollinators and seed dispersers of different species. The results showed that dispersal and pollination in Myrtaceae from Brazil were mainly carried out by bees and frugivorous vertebrates, respectively. The work about the chemical and biological properties of Mirthaceas developed by Stefanello et al. [31] and published in the Journal Chemistry & Biodiversity was the third most mentioned work (118 citations). It concluded that the neotropical Myrtaceae species has a lot of sources of bioactive compounds, because its products have relevant antioxidant

Table 2 Identification of the clusters based on the analysis of keywords

Cluster	Number of items	Keywords on VOSviewer network
1	10	Biodiversity, Brazil, cerrado, conservation, crepuscular bees, floral scent, floral traits, megalopta, nocturnal pollination, and ptiloglossa
2	8	Antioxidant capacity, carotenoids, essential oil, flavonoids, native fruits, phenolic compounds, vitamin C, and vitamins
3	8	Antioxidant, antioxidant activity, ecology, hyperglycemia, inflammation, oxidative stress, polyphenols, and viability
4	7	Campomanesia adamantium, campomanesia xanthocarpa, essential oil composition, guabiroba, guavira, ledol, and α-pinene
5	6	Anthocyanins, gut microbiota, insulin resistance, obesity, pollinator attraction, and volatile organic compounds
6	3	Cambuci, campomanesia phaea, and carbon dots
7	4	Lepidoptera, and pollination
8	3	Myrtaceae, and taxonomy
9	2	Bioactive compounds and osmotic dehydration

Table 3 The top 20 keywords in the field of cambuci research (rank based on the occurrences)

Ranking	Keyword	Occurrences	Total link strength
1	Myrtaceae	31	48
2	Campomanesia phaea	10	9
3	Essential oil composition	8	26
4	Polyphenols	8	17
5	Obesity	8	10
6	Phenolic compounds	7	12
7	Campomanesia xanthocarpa	6	19
8	Cerrado	6	11
9	Guavira	6	18
10	Inflammation	6	9
11	Pollination	6	3
12	Antioxidant	5	6
13	Antioxidant activity	5	4
14	Bioactive compounds	5	9
15	Cambuci	5	2
16	Campomanesia adamantium	5	18
17	Essential oil	5	4
18	Guabiroba	5	11
19	Anthocyanins	4	3
20	Antioxidant capacity	4	6

and anti-inflammatory activities. The project published by Seraglio et al. [32] evaluated jambolan, guabiju, and jabuticaba about capacity, phenolic compounds, sugars, total monomeric anthocyanin, and minerals present during ripening, pointing out that, as well as research described by Stefanello et al. [31] about maturation and differing, since the previous study used neotropical Myrtaceae.

Vallilo et al. [33] developed the article published in the journal Food Science and Technology to analyze the nutritional constitution of the fruits of C. adamantium, which is part of the Myrtaceae family. The study showed that these fruits had relevant characteristics for application in the beverage industry (such as flavoring) and food (in nature), such as minerals, ascorbic acid, and dietary fiber. The search for evaluation of antioxidant and antimicrobial activities of the essential oil of cambuci developed by [41] characterized the components of essential oils from leaves of *Campomanesia adamantium* (Cambess.). According to the results, during the reproductive phase, the composition was mainly monoterpenes, while in the vegetative phase, it was composed of sesquiterpenes. The results also showed that the reproductive phase of the essential oil had high antimicrobial activity against Candida albicans and Staphylococcus aureus, for instance.

Moura et al. [35] wrote a project about jaboticaba published in the journal Food Research International to evaluate two different Sabara jabuticaba extracts regarding their anti-obesogenic characteristics and whether the tannin content present in the extract can influence the body weight gain and mitigation of hyperglycemia, hyperinsulinemia, total cholesterol, and hepatic triacylglycerol levels. Sabara jabuticaba is a species that belongs to the Myrtaceae family, as well as *Campomanesia phaea Berg*. This study proved that the tannin extracts considerably influenced these aspects and confirmed their anti-obesogenic characteristic. On the other hand, the article about the nocturnal pollination system was to portray a pioneering pollination system mediated between a plant and its nocturnal bee pollinators. And they conclude that the combination of the most substantial compounds is responsible for attracting nocturnal pollinating bees. In addition, olfactory suggestions are possibly linked to the attraction of daytime bees, since the main components of cambuci attract honeybees.

In a nutshell, the most relevant publications about cambuci (*Campomanesia phaea Berg.*) and other species belonging to the Myrtaceae family show that they could be a substantial source of bioactive compounds with great relevance

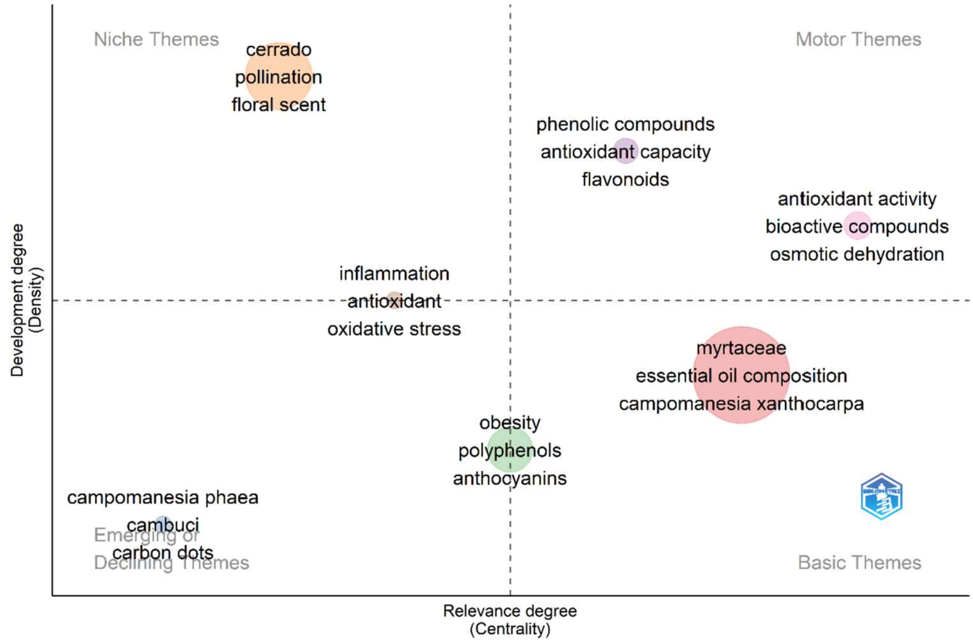


Fig. 4 Thematic map of the most frequent authors' keywords in the field of cambuci research

Table 4 Top ten most cited articles in the field of cambuci research

Ranking	Journal	Publication year	Total citations	Average citation per year	References
1st	Food Science and Technology International	2008	129	8.06	[33]
2nd	Brazilian Journal of Botany	2006	122	6.78	[34]
3rd	Chemistry & Biodiversity	2011	118	9.08	[35]
4th	Food Chemistry	2018	63	10.50	[36]
5th	Food Science and Technology	2006	56	3.11	[37]
6th	Food Research International	2019	45	9.00	[38]
7th	Austral Entomology	2017	42	6.00	[39]
8th	Food Research International	2018	36	6.00	[40]
9th	Brazilian Journal of Pharmaceutical Sciences	2009	34	2.27	[41]
10th	Plant Biology	2017	33	4.71	[42]

to the different industries, and they have a high research and development potential.

Review of the number of articles, citations, and areas

Figure 5 presents the authors' production over time, indicating the number of articles each author has published per year and the citations each author received (color of circles) from 2008 to 2022. The most productive authors in the whole period are Dötterl, S. (11 publications, mainly about agricultural and biological sciences, and environmental science), Genovese, M. I. (11, agricultural and biological sciences, and biochemistry, genetics, and molecular biology), and Jacomino, A. P. (10, agricultural and biological sciences, and biochemistry, genetics, and molecular biology).

Dötterl, S. is affiliated with the Paris-London University of Salzburg, Austria, and has been developing research around cambuci fruit in partnership with several Brazilian institutions, as well as some institutions from Italy and Germany. Genovese, M. I. is a Brazilian researcher, developing most of her studies only with national contribution and one study with the University of Laval from Canada. Jacomino, A. P. is affiliated with the University of São Paulo, Brazil, presenting most studies around cambuci with other Brazilian partners and one study with Michigan State University from the United States of America.

Table 1 indicates the publication areas on the number of publications. Brazil is the absolute leader in the number of publications, responsible for 118 documents related to biochemistry, chemistry, agriculture, biological sciences, genetics, and molecular biology. In the second position is

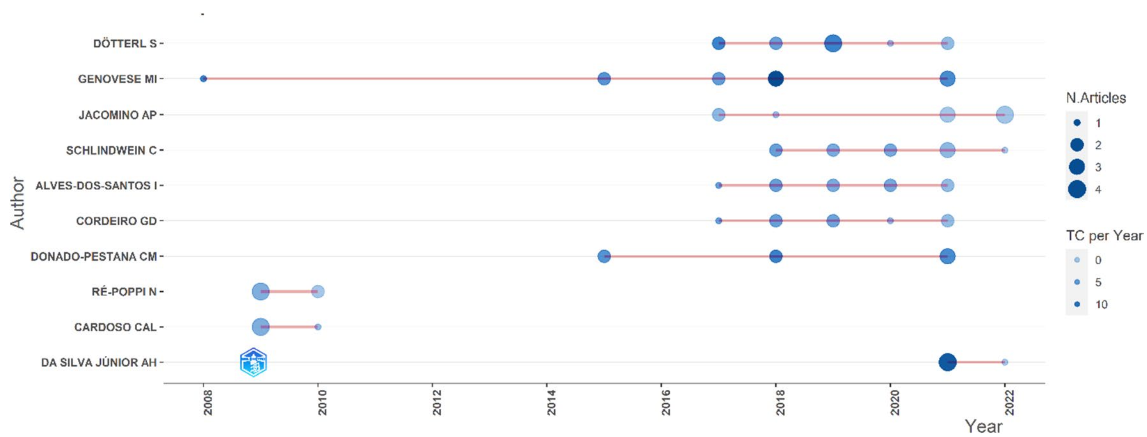


Fig. 5 Bibliometric analysis of the top authors in the field of cambuci research

China (13 documents), with genetics, biochemistry, agricultural, biological sciences, environmental sciences, and molecular biology research. The third place corresponds to Austria (11).

Since most publications are linked to Brazil, the most important organizations researching cambuci fruit are also Brazilian. The affiliation ranking is led by the University of São Paulo and features eight other Brazilian institutions, among which there are seven universities and one research organization (Embrapa). The second place in the affiliations' ranking is also a Brazilian institution. In third place is the University of Salzburg, Austria, with 11 papers, 10 of which are by Dötterl, S. Regarding the ranking of journals, the impact factor ranges from 2.409 (Arthropod-Plant Interactions) to 7.425 (Food Research International) with an average value of 4.211 (considering only the eight journals that present an impact factor score). These journals deal with food chemistry, microbiology, and safety, aspects related to essential oils, interactions of insects and other arthropods with plants, and the use of plants for pharmacological effects. Figure 6 shows the main keywords of the top 5 articles published regarding cambuci.

Review of cambuci fruit and waste

Source

Cambuci fruit (*Campomanesia phaea Berg.*) is also known as cambuchi, cambucy, cambuhi, cambucizeiro, camote, camuci, and camucim [43]. It is native to Brazil's Atlantic Forest biome [44, 45]. Mainly, this fruit is found in the State of São Paulo, Brazil. However, it has also been observed in Minas Gerais and Rio de Janeiro States [46]. Due to its short useful life, high moisture content (88% wet base), and

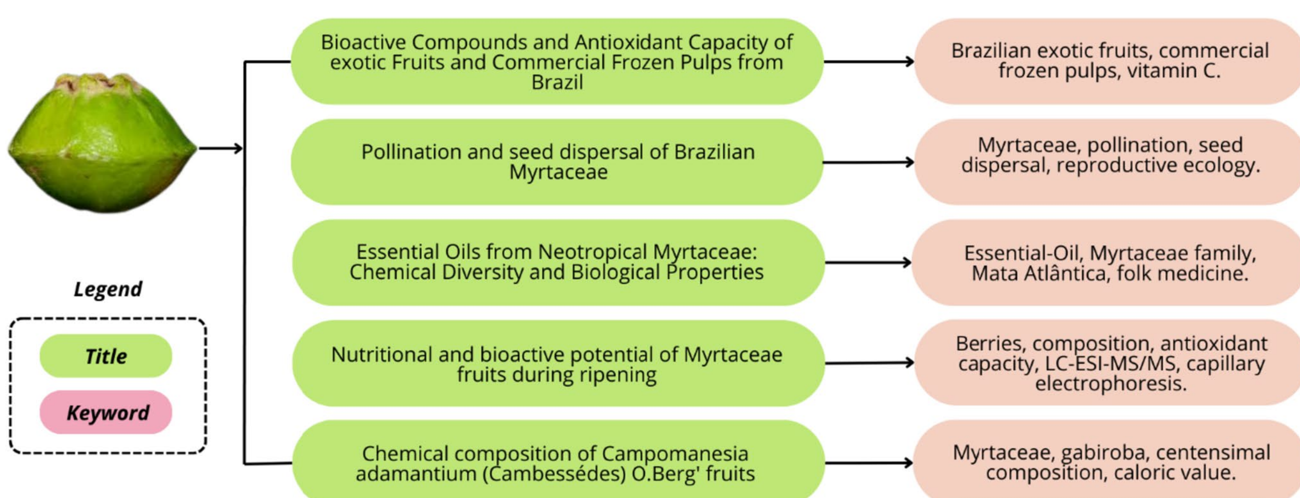


Fig. 6 Keywords of the most relevant articles on cambuci

consumption in places close to the harvest [10, 47]. Cambuci trees can be found in backyards, nature reserves, and small commercial orchards responsible for meeting the needs of the emerging market. On the other hand, this species can grow in acidic soils with high organic matter and aluminum content and low potassium and magnesium [43]. The trees have a height between 3 and 5 m, and the trunks have a diameter of 20 to 30 cm [10].

Cambuci is a green berry and ovoid-rhomboidal fruit with an acid-astringent taste [8], which measures approximately 6 cm in diameter in the central part and a thickness that varies between 3 and 4.5 cm [10]. Cambuci fruits have a high pulp yield and contain approximately 9 to 13 seeds, of which 30% are fertile. The seeds are white, flat, and orbicular [43, 48]. The flowering of the cambuci tree occurs in 4 and 5 months [49]. It occurs mainly between October and January, with the maximum intensity between November and December. Nonetheless, throughout the year, there is reduced extemporaneous flowering [43]. Ripe cambuci fruits are characterized by maintaining the green color of the peel, but they become more opaque and less intense. In addition, there is a reduction in the firmness of the fruits, and a natural detachment of the trees is evident. Traditionally, the harvest of these fruits consists of the manual collection of the fruits on the ground [43], which leads to loss of quality, contamination, and fruit dehydration [50].

Physicochemical characterization

Table 5 shows the composition of the cambuci pulp according to various authors. In general, cambuci has a high moisture content (greater than 80%) and insoluble fiber, which is related to the promotion of gastrointestinal health, anti-obesity, as well as the reduction of suffering from diabetes and cardiovascular disease [51]. However, it is essential to note that its composition may also vary according to the area of origin. Sanches [48] analyzed the fruits from four regions: Rio Grande da Serra, Mogi das Cruzes, Paraibuna, and Paranapiacaba, obtaining a high concentration of lipids, ashes, protein, carbohydrates, and fiber. Moreover, the value of soluble solids can vary between 9.37 and 10.61, according to the investigations carried out by Tokairin [15] and Sanches [48]. On the other hand, the pH value varies from 2.4 to 2.91, as reported by Tokairin et al. [36] and Sanches [48].

Table 5 Physicochemical characterization of the cambuci pulp

Composition	[52]	[9]	[43]	[19]
Moisture (%)	84.41	88.8	84.68	86.80
Ash (%)	2.30	2.60	2.64	2.20
Lipids (%)	1.44	4.60	3.16	2.89
Proteins (%)	3.00	3.00	8.86	1.17
Insoluble fiber (%)	–	–	33.12	30.68
Soluble fiber (%)	–	–	5.50	6.51
Carbohydrates (%)	11.62	8.44	–	–

Cambuci is a fruit with high phenolic compound levels and high antioxidant capacity, which can reduce the risk of developing metabolic diseases or obesity [8, 14]. For instance, Donado-Pestana et al. [14] reported values of 4.0 mg GAE/mL for total polyphenols in cambuci pulp [12] obtained 4.4 mg GAE/mL, [53] reported 3.4 mg GAE/mL and Genovese et al. [50] obtained 2.4 mg GAE/mL.

Moreover, Donado-Pestana et al. [12] established that the major polyphenols present in cambuci extracts are ellagic acid (4333 µg/100 mL), digalloyl-HHDP-glucose (Tellimagrandin II), *p*–coumaric acid hexoside, quercetin-O-(O-galloyl)-pentoside (1862 µg/100 mL), quercetin rhamnose, and quercetin pentoside. Figure 7 shows the chemical structure of these compounds. Besides, Taver et al. [47] established that cambuci antioxidant capacity was between 9.23 and 12.2 µmol g^{-1}. Donado-Pestana et al. [14] established the antioxidant capacity of cambuci by different methods. They found that the antioxidant capacity by the oxygen radical absorbance capacity assay and by the ferric reducing antioxidant power assay, the antioxidant capacity was 13.87 µmol Trolox mL^{-1}.

Ellagic acid is a bioactive phenolic compound in tannins [16, 54]. This compound is found naturally in fruits and vegetables (Table 6). It has an excellent benefit for human health due to its antibacterial, antifungal, antiviral, anti-inflammatory, antidiabetic, gastroprotective, and antidepressant activity [16, 55, 56]. Among the functions of ellagic acid is the inhibition of liver damage induced by alcohol, since it increases the levels of antioxidants, eliminates free radicals, and stabilizes cell membranes [57]. Ellagic acid is insoluble in water and slightly soluble in alcohol. It is also a thermostable compound, with a melting point of 350 °C and a molecular weight of 302.197 g/mol, which can be soluble in basic solvents [58].

Other compounds in cambuci are proanthocyanidins, phenolic compounds, responsible for the astringency and acid taste [52, 71]. The proanthocyanidins present in cambuci are tannins resulting from the polymerization of polyphenolic compounds called flavonoids. This compound can be found in various specimens of the plant kingdom, such as flowers, fruits, and bark, among others [72]. Its presence promotes bitterness, acidity, aroma, and astringency in the fruits, the latter characteristic of the cambuci [14, 52]. Proanthocyanidins have numerous bioactive activities, such as antioxidant capacity, which is more significant than the antioxidant activity presented by vitamin E and greater than vitamin C [73]. They also exhibit anti-inflammatory and antimicrobial activity [74]. When ingested, these tannins promote several health benefits due to their easy absorption, presenting a bioavailability of more than 90% [75]. Among the benefits,

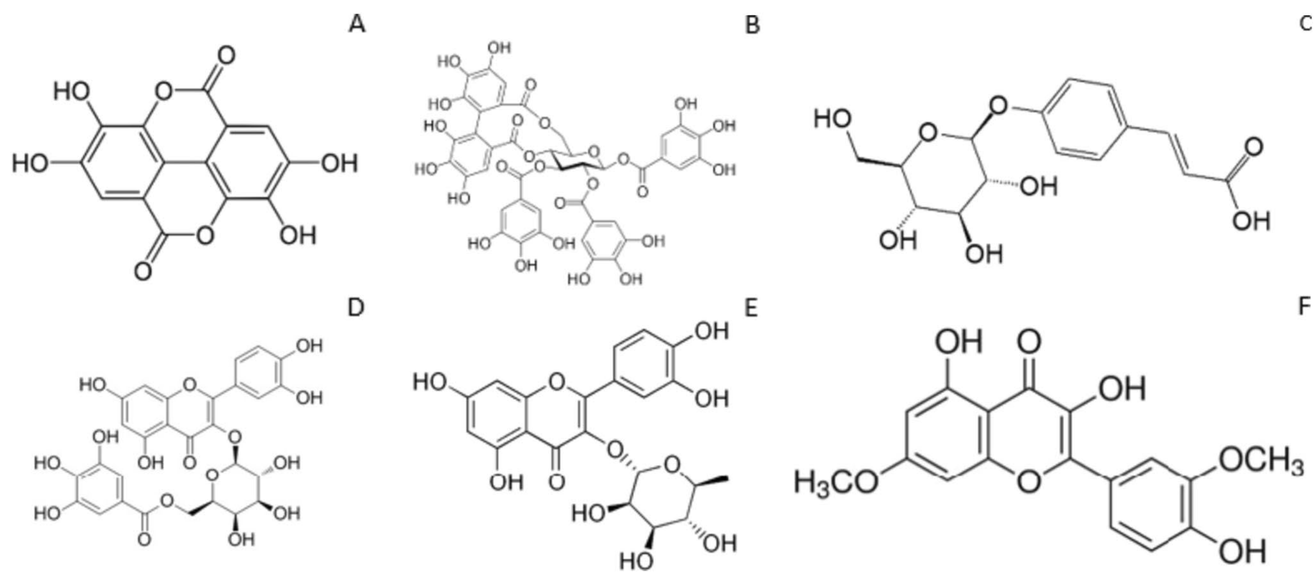


Fig. 7 Structures of the main polyphenols obtained from cambuci fruit. **A** ellagic acid, **B** digalloyl-HHDP-glucose (Tellimagrandin II), **C** p-coumaric acid hexoside, **D** quercetin-O-(O-galloyl)-pentoside, **E** quercetin rhamnose, and **F** quercetin pentoside

Table 6 Ellagic acid concentration in pulp extracts

Fruit	Concentration	Extraction method	References
Blueberry (*Vaccinium corymbosum L.*)	3–8.4 mg/g FW	Enzymatic hydrolysis combined with ultrasonic-assisted organic solvent extraction	[59]
	0.97–2.1 mg/g FW	Enzymatic hydrolysis extraction	[59]
Kakadu plum (*Terminalia ferdinandiana*)	1214–1726 mg/100g DW	100% methanol	[60]
Camu-camu (*myrciaria dubia*)	490 mg/100g DW	–	[61]
Cambuci (*Campomanesia phaea Berg.*)	240 mg/100g DW	–	[62]
	480 mg/100g DW	70% methanol for 1 min, and centrifugated for 10 min (20 °C)	[52]
Feijoa (*Acca sellowiana (O. Berg) Burret*)	9.2 mg/g DW	70% ethanol, material to solvent ratio of 1:30, at 50 °C for 30 min	[63]
Strawberry (*Fragaria × ananassa)*	0.95–1.77 mg/g FW	80% ethanol, extract centrifuged at 6000 rpm and 4 °C for 10 min	[64]
Raspberry (*Rubus chingii Hu*)	9.46–30.70 mg/100g FW	55% ethanol with ultrasonic treatment for 30 min	[65]
Jabuticaba (*Myrciaria jaboticaba (Vell.) O.Berg*)	3.88 mg/100g DW	35 °C for 50 h, extraction at 45 °C with water and propanone (52:48 v/v) using a 1:20 w/v ratio	[66]
Guava (*Psidium guajava* L.)	5.72–30.60 mg/100 g DW	100% methanol	[67]
Buriti (*Mauritia flexuosa* L.)	0.13 mg/100 g DW	Ethanol and a supramolecular solvent system (SUPRAS) formed by octanoic acid aggregates	[68]
Psidium cattleianum	2213–3818 µg/g	100% ethanol. Solvent ratio of 1:10 (w/v) and magnetic stirring, for 4 h, at 25 °C	[69]
Araçá (*Psidium cattleianum* Sabine)	29.1 µg/mL	Samples (250 mg) were mixed with methanol (1:40, w/v) and stirred for 5 min	[70]

DW Dry weight, *FW* fresh weight

cardioprotective, neuroprotective, immunomodulatory, antidiabetic, and anticancer effects can be mentioned [76]. In addition, they have metabolic effects, since they decrease triglyceride levels, the number of foam cells, atherosclerosis, and lipogenesis [77].

When proanthocyanidins are in an acidic medium in the presence of heat, it promotes the formation of anthocyanidins, a property that can be further explored [75]. Several residues are used as a source of proanthocyanidins, mainly grape seeds [78, 79]. Given its numerous benefits

Table 7 Proanthocyanidin concentration in some fruits

Fruit	Concentration	Units	References
Cambuci	11.5–52.2	Mg CAT/100g FW	[8]
Kiwi fruit	13.3	Mg/100 g FW	[80]
Avocado	17.8		
Strawberry Honeoye	49.2		
Strawberry Jonsok	34.2		
Apple Lobo	43.3		
Cherry	26.8		
Peach	37.7		
Nectarine	21.6		
Pear	20.7		
Cloudberry	31.9		
Grape red	32.6		
Grape green	54.0		

CAT Catechin equivalent, *FW* fresh weight

and properties, this compound shows great promise. The concentration of proanthocyanidins present in Cambuci varies according to the method of analysis used and the harvest period. Studies show that the proanthocyanidin content in cambuci ranges from 11.5 to 52.2 mg CAT/100g [8]. Furthermore, fruits of the cambuci trees harvested in different localities also presented variations in the concentration of this compound. However, the concentration is significant [14]. Table 7 shows proanthocyanidin concentration in some fruits. The higher concentration of proanthocyanidins in cambuci is like that presented by the green grape. It is higher than most other fruits, demonstrating that Cambuci is a promising raw material for obtaining proanthocyanidins.

Industrial processing of cambuci and perspectives

The annual production average of cambuci fruits is approximately 300 tons per year in Brazil [9]. Figure 8 shows the agro-industrial processing of cambuci, which allows visualizing the research opportunities on the

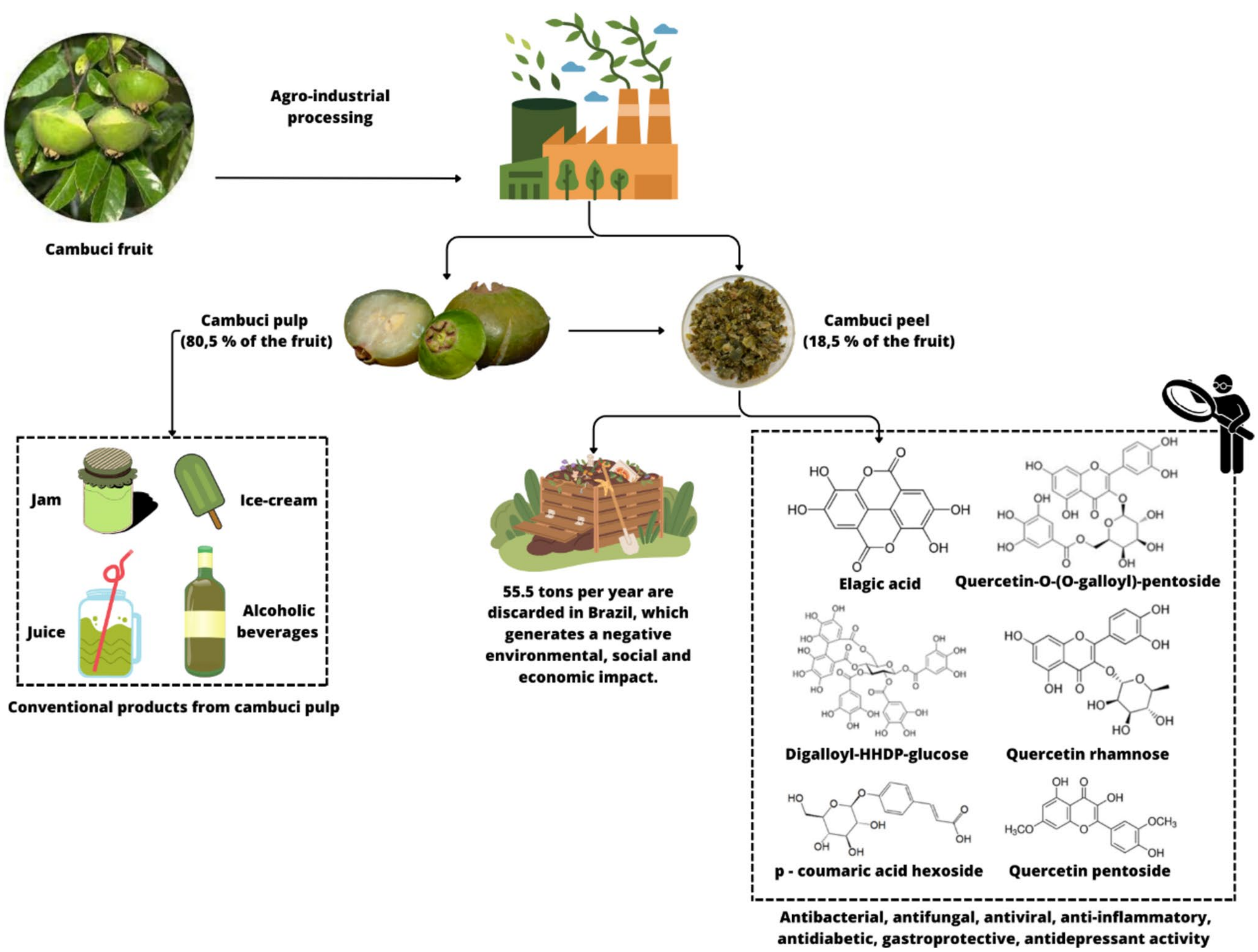


Fig. 8 Agro-industrial processing of cambuci fruit

by-products of the fruit. The cambuci fruit is mainly used to prepare juices, jellies, and ice creams [3, 9]. However, it can also be consumed in nature [8]. The cambuci is receiving more attention from consumers due to its attributes for industrialization, such as high fiber and soluble solids, pulp yield, titratable acidity, and especially the high amount of pectin. The high concentration of pectin has increased gelling capacity, a significant characteristic of certain proteins in industrialized products, such as candies, jellies, and gelatine [46, 81]. In addition, cambuci has phenolic and bioactive compounds in its structure that have anti-inflammatory, antioxidant, and antimicrobial characteristics [53, 82–85].

In Brazil, the primary consumers of this fruit are haute cuisine restaurants, juices, and a wide variety of recipes [43]. The versatility of cambuci fruit allows it to be prepared with sweet or savory products that can be served in meals from breakfast to dinner [50]. In addition, its peel is sold at fairs, emphasizing its vitamin C content [50] and its potential for treating diabetes [3]. *Campomanesia phaea* (cambuci) extracts showed remarkable results when evaluated concerning the ability to eliminate reactive oxygen, aging, inflammation, and neurodegenerative diseases [82]. Research has shown that phenolic compounds in cambuci have antidiabetic properties, since it contains ellagitannin derivatives in their composition, which is responsible for significantly lowering postprandial glucose levels [3, 86]. Furthermore, these polyphenols are relevant in attenuating obesity-related metabolic disorders, such as lowering insulinemia and preventing dyslipidaemia by raising HDL cholesterol and lowering LDL cholesterol [12, 14].

Silva Júnior et al. [83] proved that the use of cambuci juice as a precursor of carbon dots (a modern class of materials that has several advantages, such as low cytotoxicity) for the detection of zinc ions (an essential micronutrient in biological pathways) is considered feasible, and that is one of the reasons for using cambuci juice on research, because conventional methods have several disadvantages, such as high-cost reagents. On the other hand, cambuci is extremely rich in water, which makes it very perishable, thus limiting its production and commercialization. Thus, developed studies have proven that drying processes aligned with pre-treatments (using sorbitol and ethanol combined with freezing) is an effective alternative to increase the stability of cambuci due to the higher amount of fiber, pulp yield, total titratable acidity, and pectin [47, 87, 88]. Spricigo et al. [86] developed the work that showed that there are different types of amino acids in cambuci, such as glutamic acid, that collaborate with neural development, promoting the improvement of cognitive functionalities, such as memory.

Conclusions

The bibliometric analysis gave us the research trends and perspectives on a native Brazilian fruit (cambuci) between 2003 and 2022. The analysis indicated that 153 articles and 22 reviews were published, and the predominant research area was agriculture and biological sciences. In addition, it was possible to establish that issues, such as phenolic compounds, antioxidant capacity, flavonoids, antioxidant activity, bioactive compounds, and osmotic dehydration, are driving issues considered of significant importance, and it is suggested that future research be related to these issues to develop knowledge of this native fruit. Besides, it was possible to determine that Brazil is the country that has developed the most research on cambuci (118 documents) with topics related to genetics, agriculture, chemistry, biological sciences, biochemistry, and molecular biology. Cambuci is a fruit with great potential for the food and pharmacy industry, since it has compounds, such as ellagic acid and proanthocyanidins, which have anti-inflammatory, antioxidant, and antimicrobial effect that significantly favors healthy subjects. In conclusion, this study showed the progress of research, trends, and updates on the valuation of cambuci, and suggests continuing to develop research on this native Brazilian fruit that has a high industrial potential.

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Author contributions JAJM: methodology, data curation, formal analysis, and writing–original draft preparation. LCA: formal analysis, and writing—reviewing and editing. VCF: formal analysis, and writing—reviewing and editing. LFM: formal analysis, and writing—reviewing and editing. MAR: supervision. TFC: conceptualization, methodology, writing—reviewing and editing, and supervision.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

Compliance with ethics requirements This article does not contain any studies with human or animal subject.

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