BRAZILIAN JOURNAL OF FOOD TECHNOLOGY

ISSN 1981-6723
Online version

ORIGINAL ARTICLE

Gabiroba (*Campomanesia pubescens*): an analysis of the evolution of bioactive, proximate, and mineral compounds during development

Gilson Gustavo Lucinda Machado[1]*, Elisângela Elena Nunes Carvalho[1], Eduardo Valério de Barros Vilas Boas[1]*

[1]Universidade Federal de Lavras (UFLA), Departamento de Ciência dos Alimentos, Lavras/MG, Brasil

***Corresponding Author:** Gilson Gustavo Lucinda Machado and Eduardo Valério de Barros Vilas Boas. Department of Food Science, School of Agricultural Sciences of Lavras, Federal University of Lavras (UFLA) – University Campus. Trevo Rotatório Professor Edmir Sá Santos, s/n, Lavras, MG, Brazil, ZIP Code: 37200-000.E-mails: gilsonguluma@gmail.com; gilson.machado1@estudante.ufla.br; evbvboas@ufla.br

Cite as: Machado, G. G. L., Carvalho, E. E. N., & Vilas Boas, E. V. B. (2026). Gabiroba (Campomanesia pubescens): an analysis of the evolution of bioactive, proximate, and mineral compounds during development. Brazilian Journal of Food Technology, 29, e2025081. https://doi.org/10.1590/1981-6723.812025

Abstract

Gabiroba (*Campomanesia pubescens* (DC.) O. Berg.) (Myrtaceae) is a fruit species native to the Brazilian Cerrado. Its fruits have a sweet and sour taste and stand out as a rich source of vitamin C and bioactive compounds. This study aimed to analyze the evolution of bioactive compounds, proximate composition, and mineral profile of the fruit throughout its development (from 9 to 63 days after anthesis). The experiment was conducted in a completely randomized design (CRD), consisting of seven evaluation periods (from 9 to 63 days after anthesis, with a 9-day harvest interval), with three replicates. Fruits harvested at each developmental stage were analyzed for chlorophyll, total carotenoids, vitamin C, total phenolics, antioxidant activity, proximate composition, and mineral profile. The results were subjected to statistical analysis using the Sisvar software at a 5% significance level. Overall, an intense synthesis of chlorophyll and carotenoids was observed in the initial stages of development, followed by degradation during ripening. Vitamin C peaked at 36 days after anthesis, with a subsequent decline. Antioxidant activity, initially high, decreased throughout ripening. Significant variations in the proximate composition were observed depending on the development stage. Mineral content decreased linearly, with 100 g of ripe gabiroba providing 4.47% of the recommended daily intake (RDI) of Ca, 6.95% of Mg, 3.20% of P, 7.1% of K, 1.54% of Zn, 22.62% of Fe, 9.56% of Mn, and 11.11% of Cu.

Keywords: Cerrado Brazilian biome; Growth; Maturation; Metabolism; Myrtaceae; Bioactive compounds.

Highlights

- The development of gabiroba is marked by the synthesis of bioactive compounds
- During gabiroba ripening, antioxidants and pigments are degraded
- Fruit development is marked by changes in its proximate and mineral composition

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1 Introduction

The Cerrado, the second-largest biome in Brazil in terms of territorial extent, is considered one of the richest biomes in the world. It holds an immeasurable renewable natural resource, especially notable for its fruit species with unique and intense sensory characteristics. It is estimated that around 50% of the original Cerrado area is currently used for agriculture (Santos et al., 2021), which contributes to the destruction of an entire ecosystem that remains largely unexplored scientifically.

Therefore, studies focused on species from this biome, particularly their fruits, can contribute significantly to the preservation of its biodiversity. Although the fruits of *Campomanesia pubescens* (DC.) O. Berg. have been studied in recent years and classified as climacteric (Machado et al., 2025; Santos et al., 2015; Balaguera-López & Arévalo, 2012; Silva et al., 2009), scientific knowledge about the development of this species is still limited. Understanding this process is essential to assessing how fruit quality is established, implement good pre- and post-harvest practices, and determine the optimal harvest time. *Campomanesia pubescens* is a native fruit species of the Cerrado biome, and its fruit is popularly known as gabiroba, guabiroba, or guabiroba-do-campo. Like other species of the same family (Myrtaceae), its fruits have a sweet flavor and can be consumed fresh or processed into juices, jams, and sweets. Fruits from various *Campomanesia* species have been reported to contain high levels of phenolic compounds, antioxidant activity, and vitamin C (Abreu et al., 2020; Verruck et al., 2020; Silva et al., 2009).

In general, fruits possess functional properties that can effectively reduce the risk of chronic diseases, such as cancer and cardiovascular conditions. Their consumption is directly associated with health benefits, mainly due to the presence of bioactive compounds, antioxidants, and dietary fiber (Bhardwaj et al., 2022). Regarding their functional potential, based on the levels of bioactive compounds such as phenolics and vitamin C, gabiroba surpasses widely consumed fruits in Brazil, including blueberry and strawberry (Liu et al., 2022; Zia & Alibas, 2021).

Silva et al. (2009) published a study on the development of gabiroba fruits from the municipality of Lavras, in southern Minas Gerais state. Considering Brazil's vast territorial size, further studies in different regions are necessary to evaluate the effects of genotype and edaphoclimatic conditions on fruit quality formation. Despite its high potential and widespread distribution in the Cerrado, there are no studies in the literature reporting the characterization of this fruit in the microregion of Campos das Vertentes, where the samples were collected. Furthermore, the determination of chlorophyll, total carotenoids, phenolics, antioxidant activity, proximate composition, and mineral profile of gabiroba at different developmental stages has not yet been described in the literature. Therefore, this study stands out for its originality, as it evaluates *C. pubescens* fruits from a scientifically unexplored region and provides a more comprehensive analytical investigation of the fruit throughout its development than previously reported.

Thus, the present study aimed to characterize the physicochemical properties of *C. pubescens* fruits from the Campos das Vertentes region in Minas Gerais state, Brazil, in order to gain a better understanding of their phenolic compounds, antioxidant activity, proximate composition, and mineral profile throughout fruit development.

2 Materials and methods

2.1 Experimental design

The experiment was conducted in a completely randomized design (CRD), consisting of seven evaluation periods of gabiroba (from 9 to 63 days after anthesis, with a 9-day harvest interval), with three replicates.

2.2 Plant material

Campomanesia pubescens fruits were harvested from a native pasture area with typical Cerrado vegetation and predominance of this species, located at Fazenda Bela Vista, 7 km from the municipality of Santana do Garambéu, in the Campos das Vertentes region, Minas Gerais state, Brazil (Latitude: 21° 34' 30" South, Longitude: 44° 4' 49" West, 1044.52 m altitude). Approximately 150 C. pubescens specimens (plants) were marked with numbered tags and monitored starting from flowering, which began in August and peaked in September. The fruits were randomly harvested from all 150 marked plants, and flowering was tracked using colored wool threads to more accurately standardize the harvest dates.

Fruits were collected in September, October, and November 2021, across seven distinct developmental stages, from 9 to 63 days (Figure 1) after anthesis, with a 9-day harvest interval. Approximately 2 kg of fruits were harvested at each developmental stage, separated into three replicates, packed in polystyrene boxes containing ice, and transported to the Postharvest Laboratory of Fruits and Vegetables at the Federal University of Lavras. Fruits showing signs of pathogen or pest damage, or with defects, were discarded. The selected fruits were then frozen in liquid nitrogen, ground, packaged, and stored in an ultra-freezer (Coldlab–CL374-86V) at -80 ºC until analysis.

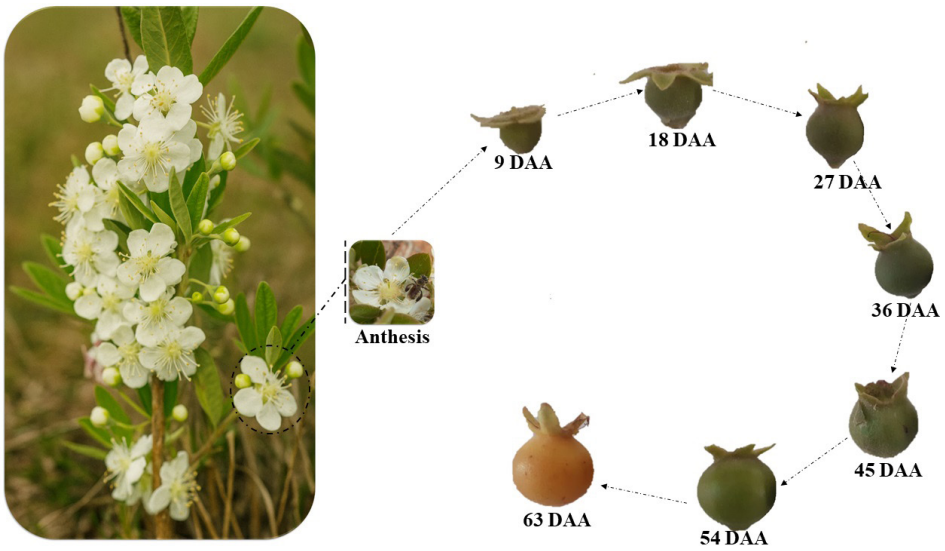


Figure 1. Developmental stages of gabiroba (*Campomanesia pubescens*) fruits. DAA: Days After Athesis.

2.3 Analyses

2.3.1 Total chlorophyll

The total chlorophyll content was determined spectrophotometrically, according to Paradiso et al. (2018).

2.3.2 Total carotenoids

Extracted and quantified using a spectrophotometric method as described by Rodriguez-Amaya (2001). Results were expressed in mg per 100 g^{-1} of fresh sample.

2.3.3 Vitamin C

Vitamin C content was determined using a colorimetric method employing 2,4-dinitrophenylhydrazine, according to Stroheker & Henning (1967). Results were expressed as mg of ascorbic acid per 100 g^{-1} of pulp.

2.3.4 Total phenolic compounds and antioxidant capacity

2.3.4.1 Extract preparation

This procedure was adapted from Rufino et al. (2010). The extracts obtained were then used for the analysis of total phenolics and antioxidant activity. The data were analyzed using Design Expert 12 software, which provided the optimal combination of extraction reagents, thus optimizing the methodology.

2.3.4.2. Total phenolics

The total phenolic content (TPC) of the fruits was determined using the Folin-Ciocalteu method, as described by Paradiso et al. (2018), and the Fast Blue method, according to Medina (2011), with some adaptations. These adaptations refer to the adjustment of reagent and sample volumes for use in a microplate. The results obtained from both methods were expressed as milligrams of gallic acid equivalents per 100 g of fresh sample mass (mg GAE/100 g^{-1} FM).

2.3.4.3 Antioxidant activity

The antioxidant activity of the fruits was determined using three different methods: the β-carotene/linoleic acid system, as described by Rufino et al. (2010); the ABTS method, following the procedure of Auzanneau et al. (2018); and the FRAP assay, according to Pulido et al. (2000). In all methods, minor adaptations were made to adjust the reagent and sample volumes for use in a microplate. The results from the β-carotene/linoleic acid system were expressed as the percentage of oxidation inhibition, those from the ABTS method as micromoles of Trolox equivalents per gram of fresh sample (μMol TE/g-1), based on a calibration curve prepared with known Trolox concentrations, and those from the FRAP assay as micromoles of ferrous sulfate per gram of fresh mass (μM FeSO4/g-1 FM), using a five-point standard curve (0–2000 μM) prepared with ferrous sulfate (FeSO4·7H2O) as reference.

2.3.5 Proximate composition

Moisture, lipids, proteins, and ash were determined according to the Association of Official Analytical Chemists (2019), and the results were expressed in g per 100 g^{-1} of fresh matter. Dietary fiber was determined using a combination of enzymatic and gravimetric methods as described. Alpha-amylase, protease (from *Bacillus licheniformis*), and amyloglucosidase were used to digest the samples under agitation and strict control of pH/temperature/time (6.0/95 °C/15 min; 7.5/60 °C/30 min; 4.3/60 °C/30 min, respectively). After digestion, the samples were left to rest overnight, treated with 95% ethanol, and vacuum-filtered using porous-bottom crucibles lined with Celite. Filtration was completed after washing the crucibles with 78% ethanol, 95% ethanol, and P.A. acetone. The crucibles plus residue obtained after filtration were dried in an air-circulation oven at 105 °C for 12 hours and weighed. This procedure was performed using three crucibles per sample, with crude protein and ash contents determined in the residues from crucibles two and three. Dietary fiber content was calculated using the following Formula 1:

$$\%TDF = \frac{R - P - A - B}{SW} . 100 \quad (1)$$

Where TDF: total dietary fiber; R: residue mass; P: protein content; A: ash mass; B: blank; SW: sample mass.

The Non-fiber carbohydrates (NFC) were determined by difference, using the following formula: CF = 100 – (moisture + lipids + proteins + fiber + ash).

2.3.6 Minerals

Samples were dried in an oven at 60 ºC for 72 hours until constant weight, subjected to nitroperchloric digestion, and analyzed for mineral composition, namely phosphorus, potassium, calcium, magnesium, sulfur, boron, copper, manganese, zinc, and iron, according to the methodology of Malavolta et al. (1997). Results were expressed in mg per 100 g^{-1} of fresh matter.

2.4 Statistical analysis

The obtained data were subjected to analysis of variance (ANOVA) and, when the F-test was significant, polynomial regression was performed. Models were selected based on the F-test and the coefficient of determination. Statistical analyses were carried out using the SISVAR software (Ferreira, 2010).

3 Results and discussion

3.1 Chlorophyll, carotenoids, vitamin C, phenolic compounds, and antioxidant activity

A quadratic trend was observed for total chlorophyll throughout the development of gabiroba (Figure 2A), similar to what was reported for a* and hº (Machado et al., 2024). The first 18 days of fruit development were marked by chlorophyll synthesis, while a consistent reduction in pigment levels was noted by 36 days, when the fruits reached the green-mature stage, continuing until full ripening.

As observed for chlorophyll, the initial growth phase of gabiroba was marked by carotenoid synthesis (Figure 2 A), while ripening was characterized by significant degradation. The presence of carotenoids in young fruits suggests that the yellowing observed during ripening is due to the unmasking of these pigments as a result of chlorophyll degradation, rather than their synthesis. The carotenoid levels found in *C. pubescens* gabiroba were higher than those observed in *C. rufa* fruits by Abreu et al. (2020), but lower than those reported by Verruck et al. (2020) in fruits of *C. eugenioides* (Cambess.) D. Legrand ex Landrum (25.68 mg 100 g^{-1}), *C. xanthocarpa* (Berg) (32.03 mg 100 g^{-1}), and *C. xanthocarpa* var. *littoralis* (D. Legrand) Landrum (61.48 mg 100 g^{-1}). In any case, the fruits of *Campomanesia* species are not generally recognized as significant sources of carotenoids when compared to other fruits known for their high carotenoid content.

An increase in vitamin C concentration was observed during the first 36 days after anthesis, a growth phase preceding ripening, followed by a decline coinciding with fruit maturation (Figure 2B), and these results were similar to those reported by Silva et al. (2009). Indeed, fruits are important sources of vitamin C for humans, and this compound tends to accumulate mainly during the growth phase, as observed in gabiroba. The reduction in vitamin C during ripening may be associated with the action of enzymes such as ascorbate oxidase, peroxidases, catalases, and superoxide dismutase (Mellidou et al., 2012).

The maximum vitamin C content in gabiroba, around 750 mg 100 g^{-1}, was observed between 36 and 45 days after anthesis, when the fruits were at the green-mature stage. Few fruits accumulate as much vitamin C as gabiroba, with exceptions such as camu-camu (1882 ±43.2 mg 100 g^{-1}), an Amazonian fruit, and acerola (1.18 to 2.43 g 100 g^{-1}) (García-Chacon et al., 2023; Olędzki & Harasym, 2024). Therefore, green-mature gabiroba fruits have potential for use by the pharmaceutical industry as sources of vitamin C. Even with the decline in vitamin C levels during ripening, fully ripe gabiroba fruits still contain high amounts of the vitamin, around 400 mg 100 g^{-1}. Thus, consuming just 10 to 15 g of the fruit would be enough to meet the daily vitamin C requirement for humans (Monsen, 2000).

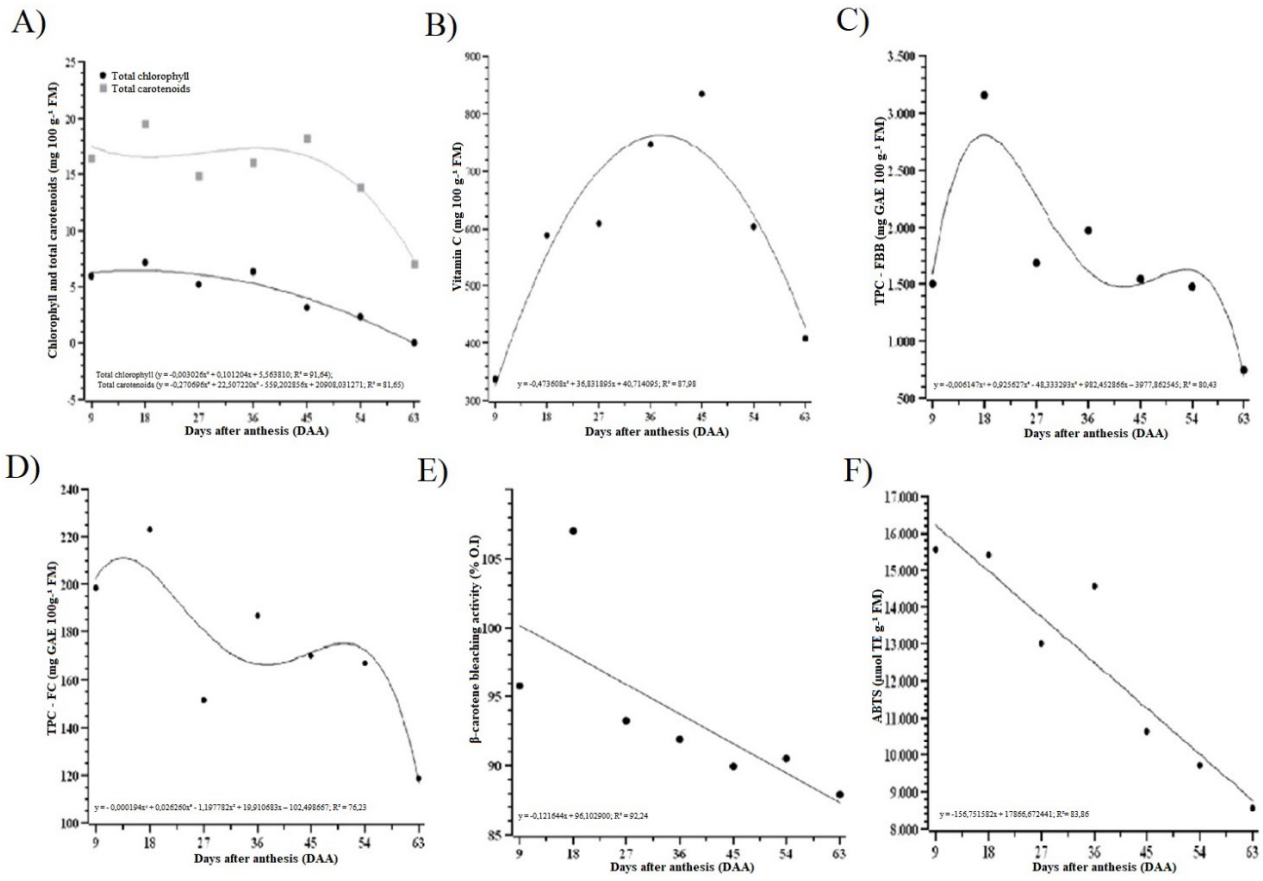


Figure 2. (A) Clorofila and Carotenoides Totais, (B) vitamin C, (C) TPC-FBB, (D) TPC-FC, (E) β-carotene, (F) ABTS in gabiroba fruits during development.
Note: TPC-FBB: total phenolic compounds measured by Fast Blue BB, TPC-FC: total phenolic compounds measured by Folin-Ciocalteu.

The TPC increased during the first 18 days of development, the phase with the highest growth rate, and subsequently decreased (Figure 2C and D). During the early ripening stage, total phenolic levels remained stable but dropped considerably during full maturation. Although the behavior of phenolics determined by two different methods was similar, it is important to note that the values obtained differed depending on the method used.

The phenolic contents determined by the Fast Blue method were substantially higher than those obtained using the Folin-Ciocalteu method. According to Medina (2011), the difference in phenolic levels determined by the methods used in this study can be explained by the fact that the Fast Blue salt contains diazonium groups (-+N=N-), which retain nitrogen and couple it to a reactive activating group (-OH) of the phenolic compound. This coupling occurs mainly with phenolic activating groups, and unless that position is already occupied, substitution typically occurs at the ortho position relative to the activating group. Phenols couple more readily in a slightly alkaline solution, where they can be converted into more reactive phenoxide ions. Another explanation for the variation is that each reagent interacts differently with the phenolic compounds present in the fruits (Guimarães et al., 2020). In a study conducted by Pico et al. (2020), it was reported that the Folin-Ciocalteu reaction exhibited over 75% interference in the analyzed samples, mainly due to the presence of reducing sugars and enediols (ascorbic acid and dehydroascorbic acid). In contrast, the Fast Blue method showed no interference in fruits and cereals and demonstrated approximately 1.5 times greater sensitivity than the Folin method, an effect likely observed in gabiroba due to its high ascorbic acid content.

The reduction in phenolic content observed in Figures 2C and D suggests their involvement in the biosynthesis of secondary compounds derived from phenylpropanoids and, particularly during ripening, their possible association with tannin polymerization and the reduction of fruit astringency (Watkins, 2019). The decrease observed during ripening is consistent with that reported for camu-camu, a fruit from the same family as gabiroba. The high phenolic levels found exceeding 698 mg 100 g^{-1} throughout fruit development are greater than those reported for fruits considered excellent sources of phenolics, such as strawberry (Huang et al., 2022), and grape (Vo et al., 2022).

The antioxidant activity of gabiroba was evaluated using the β-carotene/linoleic acid, ABTS, and FRAP methods. Antioxidant activity measured by the first two methods decreased linearly throughout fruit development, from 95.20 to 87.92 and from 15570.36 to 8564.03, respectively (Figure 2E and F). However, the antioxidant activity measured by the FRAP method did not change significantly, with an average of 9461.39 (µM of ferrous sulfate g^{-1}) (data not shown). The reduction in antioxidant activity may be associated with the decrease in carotenoid, vitamin C, and phenolic contents (Figure 2A, B, C, and D), which are well-known natural antioxidants in fruits. A decrease in antioxidant activity during fruit development, especially during ripening, has been reported for a variety of fruits, such as pitaya (Zitha et al., 2022) and Chinese raspberry (*Rubus chingii* Hu) (Li et al., 2021).

The protection ranging from 88 - 95% inhibition of free radicals generated during linoleic acid peroxidation, as detected by the β-carotene/linoleic acid method (Figure 2E), is higher than the 40 - 70% protection reported for *Eugenia leitonii* D. Legrand (Infante, 2013), as well as other fruits from the Cerrado biome such as araçá-boi (12.6%), bacaba (72.7%), and bacupari (6%) (Borges et al., 2022). It is also superior to the values found in seeds of baru (66.5%), marolo (90.7%), and pequi (89.4%) (Barros et al., 2021).

Regarding the antioxidant activity measured by the ABTS method (Figure 2F), the values observed in fully ripe fruits (63 days) were lower than those reported for ripe fruits of *C. eugenioides* (9515.30 µmol Trolox g^{-1}) and higher than those reported for ripe fruits of *C. xanthocarpa* (Berg) (5342.44 µmol Trolox g^{-1}), *Campomanesia xanthocarpa var. littoralis* (6741.14 µmol Trolox g^{-1}), *C. rufa* (O. Berg) Nied. (1862.81 µmol Trolox g^{-1}), and *C. xanthocarpa* O. Berg (507.49 µmol Trolox g^{-1}) (Abreu et al., 2020; Pereira et al., 2012; Verruck et al., 2020. The differences observed among the methods can be explained by the distinct affinities of antioxidants for oxidative substances, as well as their mechanisms of action and the composition of the reaction medium (Infante, 2013).

The reduction in antioxidant activity observed during the development of gabiroba is likely related to the loss of membrane permeability, especially during ripening and senescence, possibly due to the oxidation of existing membrane components, such as in lipid peroxidation. Thus, the decrease in antioxidant activity, that is, the impairment of free radical scavenging systems, results in a greater accumulation of reactive oxygen species, such as superoxide and hydrogen peroxide (Awad, 2011).

3.2 Proximate composition

A large variation in the proximate composition of gabiroba was observed, with all analyzed variables showing a cubic behavior throughout development ($p < 0.05$; Figure 3). An increase in moisture content was noted during the first 27 days of gabiroba development, followed by a decrease until 54 days, and a slight increase at the end of ripening (Figure 3A).

These changes suggest a high water demand by the fruits during the period of the highest growth rate and throughout ripening. Indeed, metabolism during these stages tends to be higher, requiring a greater water supply. However, moisture variations may also be related to climatic fluctuations during fruit development. Periods of water deficit and high temperatures are associated with reductions in fruit moisture, while when the soil's field capacity is close to 100%, due to rainfall, fruits tend to absorb more water and increase their moisture content.

Climatological data collected during gabiroba development are shown in Figure 3G. Fruit growth occurred mainly between September and October, a period marked by increased precipitation and temperature. Fruit ripening was concentrated in November, coinciding with a drop in rainfall levels but without significant changes in average temperature. The higher the temperature is, the greater the evapotranspiration will be, which affects the reduction of fruit moisture if water is not naturally replenished by rain or irrigation systems. Thus, changes in fruit moisture can be associated, at least in part, with climatic variations.

An increase in the ethereal extract content of gabiroba was observed during the 54 days following anthesis, coinciding with its growth, followed by a decline during ripening (Figure 3B). It is noteworthy, however, that the maximum ethereal extract content did not exceed 1%. Indeed, fruits are generally not considered significant sources of lipids. Nonetheless, fruit growth was marked by lipid synthesis, while ripening was characterized by lipid degradation. This degradation may be associated with the hydrolysis of oils and the use of resulting fatty acids in biosynthetic pathways of volatiles that confer aroma to gabiroba, as occurs in other fruits (Chabalala et al., 2022). Fatty acids themselves can contribute to the fruit's aroma or give rise to esters, which are common in ripe fruits after their fusion with alcohols. Additionally, ripening is marked by increased membrane permeability, leading to greater interaction between enzymes and substrates, intensifying fatty acid metabolism (Watkins, 2019), which may result in their reduction.

Crude protein levels ranged from 0.58% to 0.83% during fruit growth, decreasing to 0.35% during ripening (Figure 3C). Therefore, gabiroba cannot be considered a source of protein, similar to most fruits. Growth was marked by protein turnover, while ripening was characterized by predominance of degradation reactions. Changes in protein content, even at a low scale, may be associated with the specific role of proteins at each stage of fruit development. They regulate a series of metabolic reactions through enzymatic functions in the cytoplasm, membranes, and cell walls, leading to alterations during fruit development (Watkins, 2019).

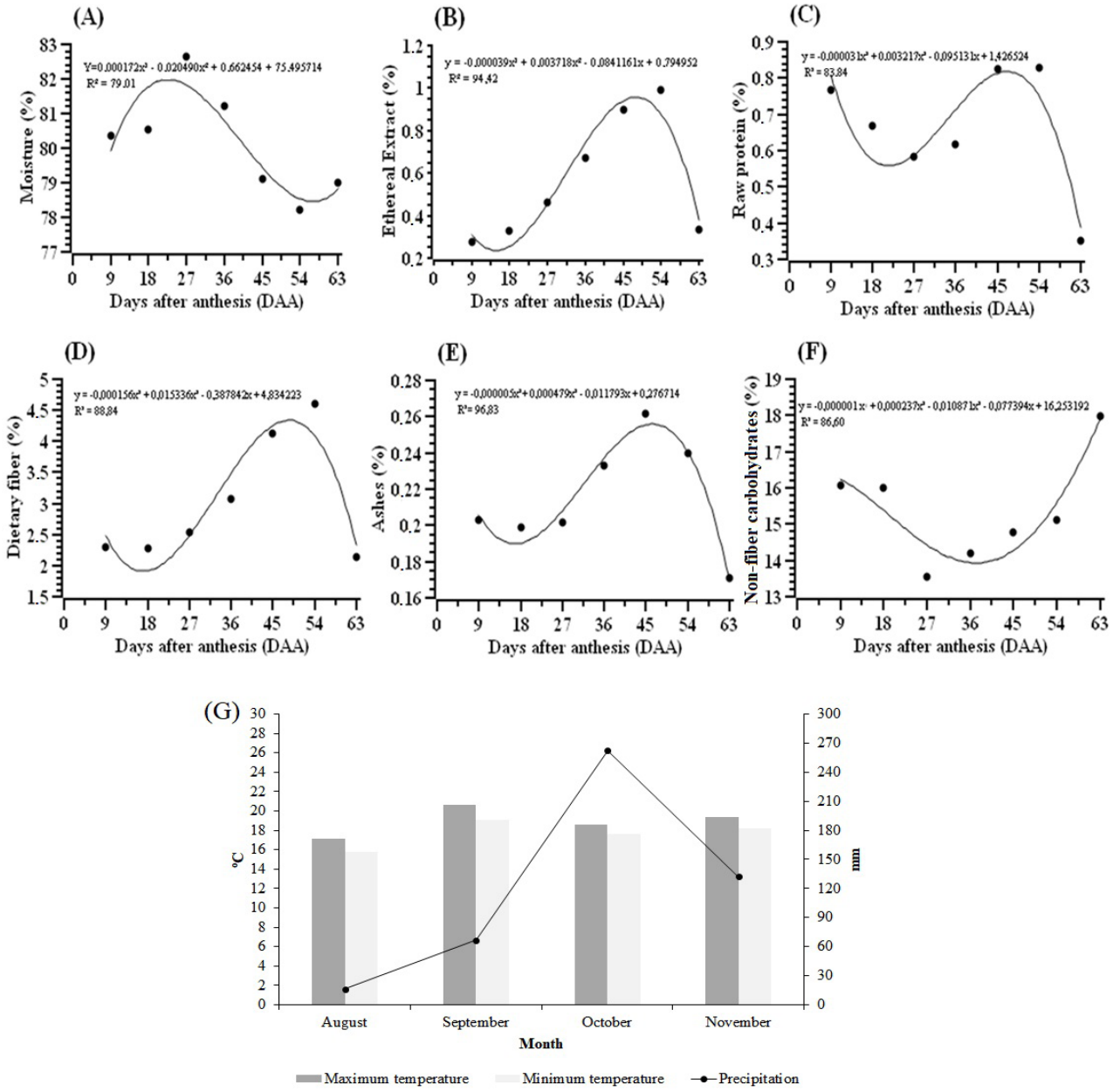


Figure 3. Proximate composition of gabiroba at different stages of development (g 100 g^{-1} whole matter). (A) Moisture, (B) Ethereal extract, (C) Crude protein, (D) Dietary fiber, (E) Ash, (F) Non-fiber carbohydrates (G) Data referring to the monthly averages of precipitation, maximum and minimum temperatures on the gabiroba harvest dates.
Legend: The graph data refer to the Barbacena, MG region, the closest location to the sample collection area.
Source: adapted from the National Institute of Meteorology (Instituto Nacional de Meteorologia, 2021).

Gabiroba growth was marked by an increase in dietary fiber content, reaching a peak of 4.61% at 54 days, when the fruits were green-ripe, followed by a decrease to 2.14% in ripe fruits (Figure 3D). The increase in dietary fiber is associated with the synthesis of cell wall compounds such as pectin, hemicellulose, and cellulose, polysaccharides that can be depolymerized, solubilized, and metabolized during ripening (Zhang et al., 2021). The recommended daily intake of fiber is around 30 g. Thus, the consumption of gabiroba and its products can significantly contribute to meeting the recommended intake. Consuming 100 g of gabiroba would provide about 7% of the recommended daily fiber intake (World Health Organization, 2005).

The ash content increased up to 0.26% during the first 45 days after anthesis, the period of highest fruit growth rate, then decreased to 0.17% in ripe fruits (Figure 3E). Since ash corresponds to the fixed mineral residue of a food, its accumulation during growth is associated with its transport from absorption by the mother plant's root system. The reduction observed, especially during ripening, can be related, at least in part, to mineral dilution due to the increase in fruit moisture during this period (Figure 2G).

The NFC, which was 16.08% at nine days after anthesis, decreased to 13.55% at 27 days, then increased to 17.99% in ripe fruits (Figure 3F). The carbohydrate fraction, determined by difference, mainly refers to sugars and starch in most fruits. Its accumulation reflects the translocation of photoassimilates from the leaves to the fruits. The reduction observed between 9 and 27 days after anthesis suggests its use as an energy source at a rate higher than the accumulation of photoassimilates. The increase from 15.11% to 17.99% during ripening may be associated with sugar metabolism, related or unrelated to starch hydrolysis. Nevertheless, the presence of starch in gabiroba needs to be confirmed. Sugar accumulation is directly associated with the sweetening of the fruits, common during ripening.

The proximate composition data of gabiroba reported in the present study fall within the range of values reported for fruits of the genus *Campomanesia* (Abreu et al., 2020; Verruck et al., 2020). Proximate composition is influenced by genotypes, environmental factors, and the stage of fruit development (Goldoni et al., 2019), which supports the reported data.

Although the ash content, determined along with other proximate composition variables, provides a general idea of the mineral value of the food, a detailed analysis is essential to understand its true mineral content. Furthermore, ash determination is subject to errors, such as mineral volatilization due to the high temperature used during sample incineration, or interactions with other compounds, which can lead to an underestimated value of ash or total mineral content. With this in mind, the mineral profile of gabiroba was determined.

3.3 Mineral profile

All evaluated minerals showed a linear decrease in their concentrations throughout gabiroba development ($p < 0.05$; Figure 4).

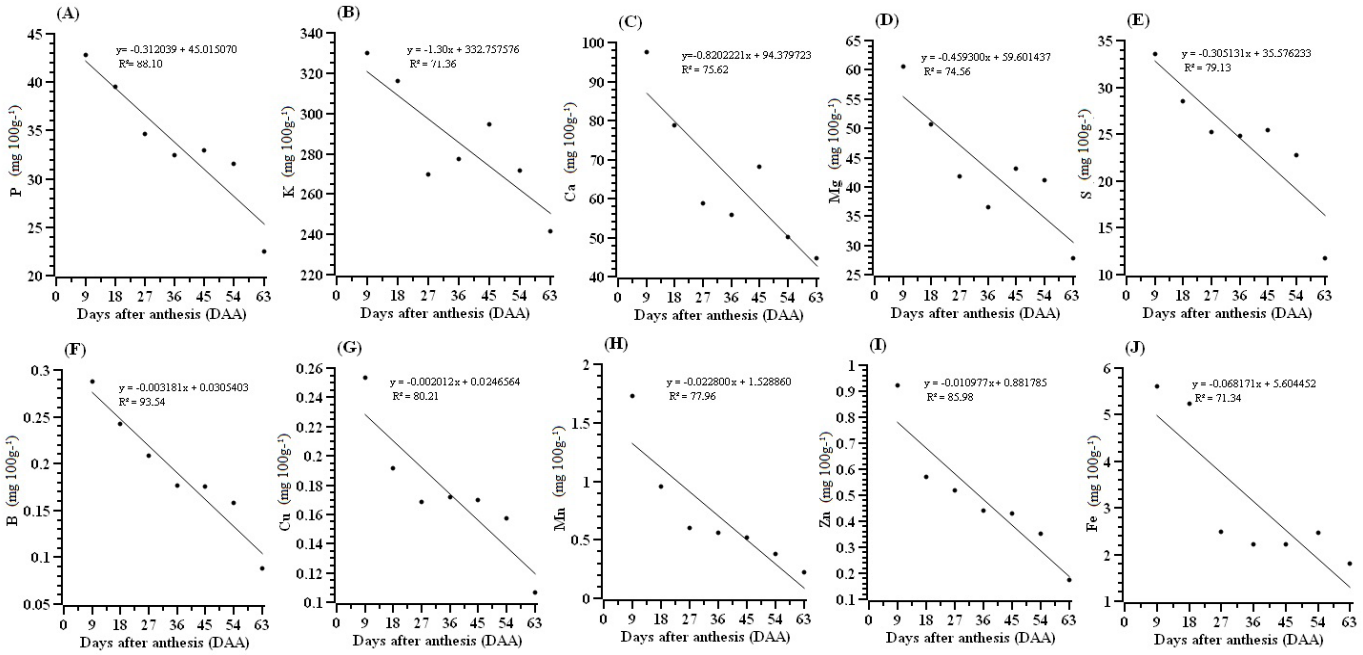


Figure 4. Minerals in gabiroba at different stages of development (mg 100 g^{-1} of whole matter). (A) Phosphorus, (B) Potassium, (C) Calcium, (D) Magnesium, (E) Sulfur, (F) Boron, (G) Copper, (H) Manganese, (I) Zinc, and (J) Iron.

Based on the mineral profile, potassium was found to be the predominant mineral in ripe gabiroba, followed by calcium and magnesium.

The phosphorus concentration (Figure 4A) in ripe gabiroba was about 22.44 mg 100 g^{-1}, lower than the values observed in blueberries (67.15 mg 100 g^{-1}) (Yildirim et al., 2015), native wild fruits from Southern Africa, such as *Phoenix reclinata* Jacquin (Arecaceae) (88 mg 100 g^{-1}), *Parinari curatellifolia* Planch. ex Benth. (Chrysobalanceae) (50.9 mg 100 g^{-1}), *Cordyla africana* Lour. (Fabaceae) (82.6 mg 100 g^{-1}), *Carpobrotus edulis* (L.) N.E.Br. (Mesembryanthemaceae) (84.4 mg 100 g^{-1}) (Sibiya et al., 2020), and fruits of wild *Oroxylum indicum* (L.) Kurz from Thailand (31 mg 100 g^{-1}) (Punchay et al., 2020). Phosphorus is necessary for protein production by the body, supporting growth, maintenance, and cellular repair, ATP, and energy production. It is also important for maintaining healthy bones and teeth, and it works together with B-complex vitamins to assist kidney function, muscle contractions, regular heartbeats, and nerve signaling (Gharibzahedi & Jafari, 2017).

Ripe gabiroba proved to be an excellent source of potassium (Figure 4B) (241.38 mg 100 g^{-1}), surpassing bananas, which are well known as a source of this mineral. Devarajan et al. (2021) reported potassium values in bananas ranging from 20.98 to 129.3 mg 100 g^{-1}, while Oyeyinka and Afolayan (2019) reported levels as high as 350.39 mg 100 g^{-1} in banana pulp. Potassium is important for helping reduce cardiovascular diseases, blood pressure, and urinary calcium excretion. It plays a key role in controlling hypercalciuria and kidney stones, also lowering the risk of osteoporosis, and is necessary for proper fluid balance (Gharibzahedi & Jafari, 2017; He & MacGregor, 2008).

Ripe gabiroba showed a calcium content (Figure 4C) of 44.68 mg 100 g^{-1}, a value higher than that found in other fruits such as banana (4.64 mg 100 g^{-1}; 18–33 mg 100 g^{-1}) (Oyeyinka & Afolayan, 2019; Maseko et al., 2022), pequi almonds (180 mg 100 g^{-1}), murici (2 mg 100 g^{-1}), and sweet passion fruit seeds (190.2 mg 100 g^{-1}) (Araújo et al., 2018). Calcium is important for promoting the health of bones and teeth, aiding muscle relaxation and contraction, and is essential for the functioning of the nervous system, immune system, blood clotting, and regulation of blood pressure (Gharibzahedi & Jafari, 2017).

The magnesium content found in ripe gabiroba was 27.83 mg 100 g^{-1} (Figure 4D), higher than that reported for murici almonds (1.8 mg 100 g^{-1}) (Araújo et al., 2018) and fruits of *C. eugenioides* (21.74 mg 100 g^{-1}), *C. xanthocarpa* (Berg) (14.35 mg 100 g^{-1}), and *C. xanthocarpa* var. *littoralis* (23.59 mg 100 g^{-1}) (Verruck et al., 2020), varying widely among species of the same genus. This mineral has a multitude of roles in the human body, including serving as a cofactor for more than 300 enzymatic reactions. Research suggests a positive effect of magnesium on the recovery of people who have had a stroke, making it extremely important in the diet for stroke prevention (Kirkland et al., 2018).

Among the macronutrients, the one found in the lowest concentration in ripe gabiroba was sulfur (S) (11.70 mg 100 g^{-1}) (Figure 4E). The concentration found is higher than that reported for guava (0.14 mg 100 g^{-1}) (Chiveu et al., 2019). Studies indicate that sulfur has an impact on oxidative stress, inflammation, immunity, and even the perception of muscle pain; although there are still no established dietary requirements for its daily intake, its impact on health should be emphasized (Hewlings & Kalman, 2019).

The concentration of boron in the ripe fruit was 0.087 mg 100 g^{-1} (Figure 4F), lower than that found in guava (0.27 mg 100 g^{-1}) (Chiveu et al., 2019) and blueberry (5.25 mg 100 g^{-1}) (Yildirim et al., 2015). Studies indicate that boron, at optimal concentrations, helps boost immunity, has antioxidant effects, and is important for embryonic growth and development. It also aids brain function, combats osteoporosis, and is used in cancer therapy and wound healing (Khaliq et al., 2018); however, excessive consumption can lead to effects opposite to those reported.

The copper content observed in ripe gabiroba was 0.10 mg 100 g^{-1} (Figure 4G), lower than that found in fruits of the same genus, such as *C. eugenioides* (< 5.5 mg 100 g^{-1}), *C. xanthocarpa* (Berg) (< 5.5 mg 100 g^{-1}), and *C. xanthocarpa* var. *littoralis* (< 5.5 mg 100 g^{-1}) (Verruck et al., 2020), as well as in banana (0.4 mg 100 g^{-1}), and papaya (0.5 mg 100 g^{-1}) (Morais et al., 2017). The absence of copper can lead to Menkes syndrome or kinky hair disease, although excessive amounts can cause Wilson's disease (Avram et al., 2021).

Ripe gabiroba showed a manganese content of 0.22 mg 100 g^{-1} (Figure 4H), lower than that reported for other fruits of the same species, such as *C. eugenioides* (< 2.5 mg 100 g^{-1}), *C. xanthocarpa* (< 2.5 mg 100 g^{-1}), and *C. xanthocarpa* var. *littoralis* (< 2.5 mg 100 g^{-1}) (Verruck et al., 2020). However, it presented a higher value than that found in fruits of *Solanum sessiliflorum* Dunal (0.04 mg 100 g^{-1}) (Sereno et al., 2018) and papaya pulp (0.05 mg 100 g^{-1}) (Morais et al., 2017). Consumption of manganese at optimal concentrations has been shown to play a significant role in carbohydrate metabolism, affecting the liver, heart, kidney, central nervous system, and other physiological regulatory functions (Gandhi et al., 2018).

The ripe gabiroba showed a zinc content of 0.17 mg 100 g^{-1} (Figure 4I), higher than that reported for guava (0.09 mg 100 g^{-1}) (Chiveu et al., 2019), similar to that reported for fruits of *C. xanthocarpa* (0.18 mg 100 g^{-1}), and lower than that reported for other fruits such as *C. eugenioides* (0.40 mg 100 g^{-1}), *C. xanthocarpa* var. *littoralis* (0.31 mg 100 g^{-1}) (Verruck et al., 2020), blueberry (0.25 mg 100 g^{-1}) (Yildirim et al., 2015), araçá (0.48 mg 100 g^{-1}), uvaia (6.05 mg 100 g), açaí (2.82 mg 100 g^{-1}), and jatobá (1.14 mg 100 g^{-1}) (Pasta et al., 2019). Intake of this trace mineral in concentrations below or above the recommended range may lead to alterations in enzymatic activity, directly affecting the occurrence and development of diseases (Cheng & Chen, 2021).

The iron concentration found in ripe gabiroba (1.81 mg 100 g^{-1}) (Figure 4J) is higher than that reported for fruits of the same genus, such as *C. eugenioides* (1.40 mg 100 g^{-1}), *C. xanthocarpa* (1.25 mg 100 g-^{1}), and *C. xanthocarpa* var. *littoralis* (1.72 mg 100 g^{-1}) (Verruck et al., 2020), as well as higher than that found in other fruits of the Brazilian flora, such as marolo (0.59 mg 100 g^{-1}), murici (0.17 mg 100 g^{-1}), araçá (1.10 mg 100 g^{-1}), and jatobá (1.50 mg 100 g^{-1}), but lower than reported for uvaia (2.13 mg 100 g^{-1}) and açaí (4.50 mg 100 g^{-1}) (Pasta et al., 2019). Iron is vital for oxygen transport in the hemoglobin of red blood cells and the myoglobin of muscles. It is also an essential component of cytochrome and other proteins and cofactors involved in critical systemic biochemical reactions (Chen et al., 2022).

Of the 10 minerals evaluated, nine are considered essential for humans, with the exception of boron. The recommended daily intake of essential minerals for adult men, as well as the concentration of these minerals in ripe gabiroba, can be seen in Table 1. Thus, according to Table 1, the consumption of 100 g of ripe gabiroba would contribute the following percentages of the recommended daily intake (RDI) of minerals: Ca (4.47%); Mg (6.95%); P (3.20%); K (7.1%); Zn (1.54%); Fe (22.62%); Mn (9.56%); and Cu (11.11%). Therefore, gabiroba can be used as an important source of minerals, contributing to the necessary intake in the daily diet.

Table 1. Mineral contents in ripe gabiroba and recommended daily intake (RDI) of essential minerals (mg) for adult men (World Health Organization, 2005).

	Ca	Mg	P	K	S	Zn	Fe	Mn	Cu
RDI (mg)	1000	400	700	3400	*	11	8	2.3	0.9
Ripe Gabiroba (mg $100g^{-1}$)	44.68	27.83	22.44	241.38	11.70	0.17	1.81	0.22	0.1
% ID	4.47	6.95	3.20	7.1	---	1.54	22.62	9.56	11.11

*intake of recommended levels of sulfur-containing amino acids. Based on WHO/FAO/UNU Expert Consultation (World Health Organization, 2005).

4 Conclusion

The early stages of gabiroba development are characterized by intense synthesis of pigments (carotenoids and chlorophylls), vitamin C, total phenolics, and antioxidant activity. Maturation, on the other hand, is marked by a sudden reduction in chlorophyll, vitamin C, total phenolics, and antioxidant activity, alongside an increase in the synthesis and/or unmasking of carotenoids, the pigment responsible for the fruit's orange coloration.

Gabiroba development showed significant variations in its proximate composition.

The individual contents of the minerals studied decrease linearly throughout gabiroba development. Consumption of 100 g of ripe gabiroba can contribute 4.47%, 6.95%, 3.20%, 7.1%, 1.54%, 22.62%, 9.56%, and 11.11% of the recommended daily intake for Ca, Mg, P, K, Zn, Fe, Mn, and Cu, respectively.

Future studies should investigate the influence of environmental and genotypic factors on the chemical and functional composition of the fruit. Additionally, research on bioaccessibility, post-harvest conservation, the development of functional products, and potential health effects, including interactions with the gut microbiota, could support the importance of genetic improvement programs for the species. Such studies would help make gabiroba a commercially viable fruit, enhancing its utilization and value.

Data Availability Statement

The data supporting this study are not publicly available, but can be requested from the corresponding author upon reasonable request.

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Funding: National Council of Technological and Scientific Development (CNPq: 04413/2016-0; 302699/2019-8; 404716/2021-0; 307157/2022-9), Minas Gerais Research Support Foundation (FAPEMIG: PPM-00458-15; PPM-00355-17), and Higher Education Personnel Improvement Coordination (CAPES: 88881.068456/2014-01).

Received: July 31, 2025; **Accepted:** Jan. 19, 2026
Section Editor: Mateus Petrarca.