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Research article

Spondias purpurea L. (Anacardiaceae) fruits flours at different maturation stages: Drying kinetics, mathematical modelling, characterization and correlation analysis

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ABSTRACT

The aim of this study was to examine the drying kinetics of *Spondias purpurea* L. fruits at various maturation stages (I to V) using a range of mathematical models (Henderson and Pabis, Lewis, Logarithmic, Midilli, and Page). Additionally, an assessment of the resulting flours' quality was conducted. The stabilization phase of *S. purpurea* fruit drying kinetics commenced at 420 min for maturation stages I and III, and at 480 min for the remaining stages. All employed mathematical models effectively characterized the drying process, exhibiting R^2 values exceeding 0.99, MSD below 0.03, and X^2 below 0.0009. Flours demonstrated increased color intensity with higher levels of flavonoids and anthocyanins, showing a positive correlation. Immature fruits yielded flours with elevated titratable acidity, total chlorophylls, phenolic compounds, and density. In contrast, fruits in the final maturation stages produced flours with higher yield, levels of reducing sugars, total carotenoids, flavonoids, and anthocyanins. The results indicate that flours derived from ripe fruits exhibited higher yield, moisture content, pH, soluble solids, and reducing sugars, while titratable acidity was higher in green fruits. Bioactive compounds such as total chlorophyll, ascorbic acid, and phenolic compounds decreased with ripening, whereas total carotenoids increased due to chlorophyll degradation and carotenoid biosynthesis. Anthocyanin and total flavonoid levels increased in the final stages of ripening. Thus, the developmental stage directly influences the physicochemical and functional characteristics of *S. purpurea* fruit flours. This comprehensive analysis offers valuable insights into the drying kinetics of *S. purpurea* fruits and underscores the influence of maturation stages on the quality attributes of the resultant flours.

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1. Introduction

Spondias purpurea L. (Anacardiaceae) is native to several countries, including Mexico, Guatemala, the Caribbean, and Brazil [1]. The fruits of *S. purpurea* exhibit diverse shapes, such as round, oblong, or ovoid drupes, with a finely textured epicarp displaying a range of colors from green and red to yellow, reddish-brown, orange, or purple. Notably, the endocarp is thick and fibrous, while the mesocarp comprises the edible portion [2,3]. These fruits are rich in carbohydrates (11.8–19.1 g 100 g^{-1}), starch (2.47 g 100 g^{-1}), dietary fiber (0.5–1.7 g 100 g^{-1}), and a variety of essential vitamins and minerals, including potassium, phosphorus, zinc, calcium, magnesium, carotene, thiamine, riboflavin, and ascorbic acid [4]. The volatile compounds found in the pulp primarily include hexanal, trans-2-hexenal, 3-hexen-1-ol, 2-hexen-1-ol, ethyl acetate, and hexyl acetate [5]. Although initial investigations suggested a low phytochemical content in the pulp, Engels et al. [6] conducted a detailed analysis of the peel's phytochemical profile, identifying 21 phenolic compounds in less than 20 min using UHPLC–DAD–ESI-MS^n [6]. Additionally, Silva Júnior et al. [7] verified the biological activity of *S. purpurea* through its ability to scavenge free radicals using the stable radical 2,2-diphenyl-1-picrylhydrazyl (DPPH) and ferric reducing antioxidant power (FRAP). These findings underscore the nutritional richness and potential health benefits of *S. purpurea*, highlighting its distinctive fruit characteristics and valuable phytochemical composition [8].

Nonetheless, the elevated water content remains a significant contributor to the perishability of fruits, resulting in diminished post-harvest resilience and rapid degradation characterized by softening, wrinkling, browning, loss of texture, flavor, and marketable weight [9,10]. The drying process of agricultural products plays a pivotal role as a fundamental unit operation capable of addressing these challenges. By reducing the free water content, drying extends the shelf life of fruits, reduces weight for transportation and storage, and manages microbiological and enzymatic degradation reactions [11].

Studies have explored the drying processes of various fruits and their by-products, offering valuable insights into their preservation and utilization. For instance, investigations have focused in amla (*Emblica officinalis*; [12]), cabya (*Piper retrofractum*; [13]), red dragon fruit (*Hylocereus species*; [14]), kadam (*Neolamarckia cadamba*; [15]), and pomegranate fruit peel (cv. Wonderful; [16]). Within the Anacardiaceae family and *Spondias* genus, prior research has primarily addressed the drying and mathematical modeling of fruits. Notably, studies have investigated the hot air convective drying of hog plum fruit (*Spondias mombin*; [17]), shedding light on the optimization of drying processes and product quality. Despite the extensive exploration of different applications of *S. purpurea* in existing literature [3,5–7,18], there remains a conspicuous gap in research that comprehensively evaluates the fruits at all stages of development. This underscores the need for further investigations aimed at providing a holistic understanding of the drying kinetics and quality attributes throughout the entire maturation process of *S. purpurea* fruits. Such research endeavors would contribute significantly to enhancing the utilization and value addition of this important fruit species.

Dehydrated fruits play a pivotal role in bolstering human nutrition by providing essential nutrients, thereby contributing to the intake of vital elements often lacking in diets [19,20]. The nutritional richness of dried fruits exceeds that of their fresh counterparts, primarily due to the concentration of nutrients following the removal of water [21]. These dehydrated fruits serve as versatile ingredients in a myriad of products, including yogurt, baby food, bakery items, breakfast cereals [22], and even as sources for flour production [23].

Flour, defined as the product derived from grinding edible parts of various cereal species, legumes, fruits, seeds, tubers, and rhizomes through safe technological processes for food production [24], holds significant potential for integrating perishable fruits. This innovative approach not only results in products with extended shelf life and improved commercial viability but also contributes to diversifying the food sector. As flour constitutes a fundamental ingredient in countless food formulations, it becomes imperative to consider the influence of fruit maturation stages on flour quality. Such considerations highlight the importance of investigating the impact of maturation stages on flour characteristics, thereby optimizing the production process and enhancing the overall quality of the final products.

In Mexico, the harvesting of *S. purpurea* fruits primarily occurs when they reach the green or semi-ripe stage, resulting in an uneven maturation process. On the other hand, in Brazil, the harvesting practice involves collecting fruits that are either semi-ripe or fully ripe. These harvested fruits are then stored in containers such as baskets, boxes, or bags at ambient temperature, often utilizing plastic containers, until they are prepared for marketing or transportation to other agro-industries [18]. The harvesting of fruits at different stages of maturation highlights the diversity in harvesting techniques across regions. However, this practice also underscores the necessity for further research to understand how the fruit's maturation stage influences the quality of its co-products. Such investigations would provide valuable insights into optimizing harvesting practices and enhancing the overall quality of *S. purpurea*-derived products.

The evaluation of *S. purpurea* fruit flours at various maturation stages underwent a comprehensive analysis encompassing physicochemical, bioactive, colorimetric, and physical characterization. Utilizing a Pearson's correlation matrix, interactions between bioactive and colorimetric parameters were scrutinized, offering a comprehensive understanding of the interrelationships among the variables under study. This study seeks to provide significant contributions to the understanding of both the drying process and the quality attributes inherent in *S. purpurea* fruit flours, with particular emphasis on elucidating the impact of different maturation stages. The hypothesis of this study is that the different maturation stages of *S. purpurea* fruits directly influence the drying kinetics, physicochemical parameters, and composition of bioactive compounds in the resulting flours, resulting in flours useful for different applications. Therefore, the objective of this study was to analyze the drying kinetics of *S. purpurea* fruits and assess the impact of different maturation stages using mathematical modeling.

2. Material and methods

2.1. Material and preparation of S. purpurea fruits

Fruits of *S. purpurea* were obtained from a rural area in Sousa, Paraíba, Brazil (6° 46′ 4″ S and 38° 12’ 36” W). These fruits were carefully selected at five distinct maturation stages (Fig. 1A). The five ripening stages were defined based on the visual appearance of the fruits: I (green fruits), II (predominantly green with slight yellowish hues), III (intermediate transition from green to yellow-orange), IV (yellow-orange fruits), and V (red fruits). The sampling process involved the procurement of fruits from at least two different lots, with harvests conducted at various locations within the rural area. Each collection comprised a minimum of 100 fruit units, spread over a week and gathered on alternating days. Following the harvest, the fruits underwent a meticulous cleaning procedure. They were thoroughly washed and subjected to sanitation in a solution of sodium dichloroisocyanurate dihydrate ($C_3Cl_2N_3NaO_3$) at a concentration of 100 mg L^{-1} for a duration of 15 min. After sanitation, the fruits were rinsed, and the epicarp and mesocarp were meticulously removed using stainless-steel knives. This rigorous preparation ensured the uniformity and cleanliness of the fruit samples, essential for subsequent analyses.

2.2. Drying kinetics

The epicarp and mesocarp of the fruits (200 g), underwent uniform perforation and were meticulously arranged in aluminum forms measuring 25 × 15 cm. To maintain consistent shapes, the fruits were sliced to a standardized thickness, resulting in a 1 cm layer. These prepared forms were then placed randomly in a forced circulation oven (Solab®, Ar SL 102, Piracicaba, São Paulo, Brazil) set at a temperature of 60 °C. To ensure the uniformity of the drying process, the slices were periodically weighed at specific intervals: 0, 5, 10, 15, 30, 60, 120, 180, 240, 300, 360, 420, 480, 520, and 600 min. This monitoring continued until three consecutive weighings indicated a constant mass, indicating the completion of the drying process.

The selected drying conditions adhere to the guidelines established by Martinsen et al. [25] and Sahoo et al. [26] for maintaining the functional, colorimetric, and sensory properties of dried products. This careful approach to the drying process facilitates the accurate analysis of drying kinetics and enables the evaluation of quality attributes in the slices of *S. purpurea* fruits.

2.3. Mathematical modelling

The moisture ratio (MR) was calculated using Equation (1), and various mathematical models were employed to analyze the drying kinetics. These models included the Henderson and Pabis [27] model (Equation (2)), Lewis [28] model (Equation (3)), Logarithmic model proposed by Chandra and Singh [29] (Equation (4)), Midilli model [30] (Equation (5)), and Page model [31] (Equation (6)). The determination coefficient (R^2) (Equation (7)), Mean Square Deviation (MSD) (Equation (8)), and chi-square (X^2) (Equation (9)) were utilized as criteria to evaluate the suitability of these models in fitting the experimental data.

$$MR = \frac{(X_t - X_e)}{(X_0 - X_e)} \tag{1}$$

$$MR = a \times \exp(-kt) \tag{2}$$

$$MR = \exp(-kt) \tag{3}$$

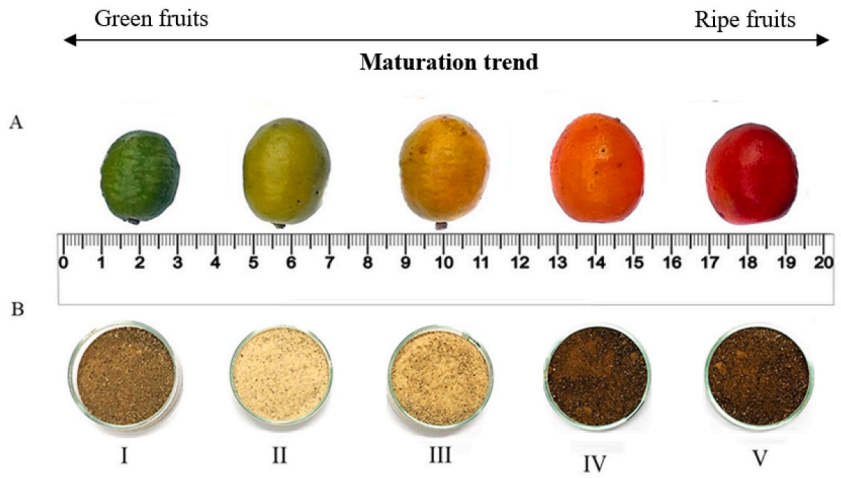

Fig. 1. Fruits (A) and flours (B) of *S. purpurea* at different maturation stages.

$$MR = a \times exp(-kt) + c \tag{4}$$

$$MR = a \times exp(-kt^n) + b \times t \tag{5}$$

$$MR = a \times exp(-k \times t^n) \tag{6}$$

$$R^2 = \frac{\sum_{i=1}^{N} \left[\left(MR_{exp} - \overline{MR_{pre}} \right) \left(MR_{pre} - \overline{MR_{pre}} \right) \right]^2}{\sum_{i=1}^{N} \left(MR_{exp} - \overline{MR_{pre}} \right)^2 \sum_{i=1}^{N} \left(MR_{pre} - \overline{MR_{exp}} \right)^2} \tag{7}$$

$$MSD = \sqrt{\frac{\sum \left(MR_{pre} - MR_{exp} \right)^2}{N}} \tag{8}$$

$$X^2 = \frac{1}{N-n} \sum_{i=1}^{N} \left(MR_{pre} - MR_{exp} \right)^2 \tag{9}$$

where (1): *Xt*, *Xe* and X_0 are the moisture content at time *t*, the equilibrium moisture content (after drying is complete) and the initial moisture content in $t = 0$, respectively. (2–6): *t* is the drying time (min); *k* is the drying constant (min^{-1}); *n*, *b*, *c* and *a* are constant in the models. (7–9): MR_{exp} and $\overline{MR_{exp}}$ are the ratio of the experimental moisture content in the times and its average, respectively; MR_{pre} and $\overline{MR_{pre}}$ are the ratio of the moisture content predicted by the equation in the times and its average, respectively; *N* is the observations number made during the experiment and *n* is the constants number in the model.

2.4. *S. purpurea fruit flour processing and quality characterization analysis*

After the drying process, the fruits underwent further processing by being crushed in a blender (Mondial®, Turbo Power L-77, Conceição do Jacuípe, Bahia, Brazil) and subsequently sieved using a nylon sieve with a 1 mm mesh to obtain the flour (Fig. 1B). The resulting flours were packed in high-density polypropylene packaging, covered with aluminum foil, and then stored at ambient temperature (27 ± 2 °C). The quality assessment of the flours was conducted in five replications and followed the standards outlined by the Institute Adolfo Lutz [32] and the Analysis Methods of the Association of Official Analytical Chemists [33].

2.4.1. *Physicochemical parameters*

Analyzed parameters were: yield (%), determined by the ratio between the epicarp and mesocarp mass after and before drying; moisture (%), determined by dehydration of 5 g of sample in an forced circulation oven at 105 °C until constant mass; titratable acidity (TTA, % citric acid), determined by titrating 0.5 g of a sample diluted in distilled water with 0.1 M sodium hydroxide (NaOH) and 1 % phenolphthalein alcoholic solution ($C_{20}H_{14}O_4$) as an indicator; hydrogenionic potential (pH), determined using a digital pH meter (Tecnal®, TEC-2, São Paulo, São Paulo, Brazil); and soluble solids (SS, °Brix), determined by reading on a digital refractometer (Hanna®, HI96801, Woonsocket, Rhode Island, USA) of 1 g of the sample diluted and macerated in 7 mL of distilled water.

For the determination of reducing sugars (RS, mg 100 g^{-1}), the 3,5-dinitrosalicylic acid ($C_7H_4N_2O_7$) method described by Miller [34] was employed. An extract was prepared by diluting 0.25 g of the sample in 100 mL of distilled water. Subsequently, a solution was prepared in test tubes containing 0.5 mL of the extract, 0.5 mL of distilled water, and 0.5 mL of the 3,5-dinitrosalicylic acid solution.

The tubes were vigorously agitated in a stirrer (Novainstruments®, NI 1058, Piracicaba, São Paulo, Brazil) and then placed in a thermostatic bath (Hemoquímica®, HM 0128, Sabará, Minas Gerais, Brazil) set at 100 °C for 15 min. The content of reducing sugars was determined by spectrophotometry (Spectrum®, 560 UV, Maharashtra, India) at a wavelength (λ) of 540 nm. Glucose ($C_6H_{12}O_6$) was used as a reference to establish the standard curve ($y = 0.5657x$ - 0.0225; $R^2 = 0.9917$), enabling the quantification of reducing sugars in the samples.

2.4.2. *Bioactive parameters*

The determination of total chlorophylls (TCh, mg 100 g^{-1}) and carotenoids (TCa, μg 100 g^{-1}) contents followed the method described by Lichtenthaler [35]. An extract was prepared by macerating and diluting 0.25 g of sample (for maturation stage I) or 0.5 g of sample (for maturation stages II, III, IV, and V) with 0.2 g of calcium carbonate ($CaCO_3$) and 5 mL of 80 % acetone (C_3H_6O) in a dark environment. The extract was then subjected to centrifugation in a refrigerated centrifuge (Cientec®, CT-4000, Piracicaba, São Paulo, Brazil) at 10 °C and 8.8 × 103 *g* for 10 min. The supernatant was read on a spectrophotometer at wavelengths (λ) of 663 nm and 646 nm for total chlorophylls (TCh) and 470 nm for carotenoids (TCa). Additionally, the content of ascorbic acid (AsA, mg 100 g^{-1}) was determined by titrating 0.5 g of the sample, diluted in 5 % oxalic acid ($C_2H_2O_4$), with a 0.2 % solution of 2,6-dichlorophenolindophenol ($C_{20}H_{14}O_4$), following the protocols outlined by [36], and Association of Official Analytical Chemist [33].

The determination of phenolic compounds (CPh, mg 100 g^{-1}) followed the Folin-Ciocateau method [37]. Initially, phenolic compounds were extracted from 3 g of the sample, which was macerated and diluted in 50 mL of distilled water and allowed to rest for 30 min. Subsequently, a solution was prepared in test tubes containing 10 μL of the extract, 2115 μL of distilled water, and 125 μL of

Folin-Ciocateau reagent. The tubes were vigorously shaken and left to stand for 5 min. Following this, 250 μL of 20 % sodium carbonate (Na_2CO_3) solution was added to the tubes, which were then stirred again and placed in a water bath (Marconi®, MA470, Piracicaba, São Paulo, Brazil) set at 40 °C for 30 min. The quantification of phenolic compounds was achieved by measuring the resulting solution's absorbance in a spectrophotometer (Genesys®, 10S UV–VIS, Thermo Scientific, USA) at a wavelength (λ) of 765 nm. Gallic acid ($C_7H_6O_5$) served as a reference to establish the standard curve ($y = 0.0451x + 0.0055$; $R^2 = 0.999$), enabling the determination of phenolic compound concentrations in the samples.

2.4.3. Colorimetric parameters

Colorimetric analyses were performed at a controlled ambient temperature of 27 ± 2 °C. The samples were directly evaluated using a colorimeter (Konica Minolta®, CR-10, Osaka, Japan) that had been calibrated on a white surface, as outlined by [38]. In the CIE L*a*b* color space, which represents colors in rectangular coordinates, several parameters were examined: Lightness (L^*), which ranges from 0 (black) to 100 (white); a^* representing the red-green axis, with positive values indicating redness and negative values indicating greenness; and b^* representing the yellow-blue axis, with positive values indicating yellowness and negative values indicating blueness. Additionally, in the CIE L*C*h color space, which represents color intensity in cylindrical coordinates, two parameters were assessed: Chroma (C^*), indicating color purity, with higher values suggesting more intense color, and hue angle (h°), which defines the color appearance within the cylindrical color space.

$$C^* = \left[(a^*)^2 + (b^*)^2\right]^{\frac{1}{2}} \tag{10}$$

$$h^\circ = \text{arctg}\left(\frac{b^*}{a^*}\right) \tag{11}$$

From these primary data, it was calculated a^*/b^*, $(a^*/b^*)^2$, browning index (BI), yellowing index (YI), and color index (CI) (Eqs. (12)–(15), respectively) [39,40].

$$X = \frac{a^* + 1.75L^*}{5.64L^* + a^* - 3.01b^*} \tag{12}$$

$$\text{BI} = \frac{100 \times (X - 0.31)}{0.172} \tag{13}$$

$$\text{YI} = \frac{142.86 \times b^*}{L^*} \tag{14}$$

$$\text{CI} = \frac{2000 \times a^*}{L^* \times \left[(a^*)^2 + (b^*)^2\right]^{\frac{1}{2}}} \tag{15}$$

2.4.4. Physical parameters

Apparent density (ρA, g cm^{-3}) were determined by the ratio between the mass (w_s, g) and the total volume (V_t, mL) [41] (Eq. (16)). Compacted density (ρC, g cm^{-3}) were determined from the ratio between the w_s and the volume occupied by it (V_c, cm^3), after compaction for 50 consecutive beats at a height of 10 cm [41] (Eq. (17)). Carr index (CIn, %) were determined by comparing the ρA and the ρC [42] (Eq. (18)). Hausner ratio (HR, dimensionless) were determined by means of the ratio between ρA and the ρC [42] (Eq. (19)).

$$\rho A = \frac{w_s}{V_t} \tag{16}$$

$$\rho C = \frac{w_s}{V_c} \tag{17}$$

$$\text{CI}\ (\%) = \left(\frac{\rho C - \rho A}{\rho A}\right) \times 100 \tag{18}$$

$$\text{HR} = \frac{\rho C}{\rho A} \tag{19}$$

2.5. Statistical analysis

Mathematical modeling was conducted using the Statistica 7.0 software (StatSoft, USA). To assess the normality of the data, the Shapiro–Wilk test was applied. Analysis of variance (ANOVA) was performed using Assistat software version 7.7 beta [43]. In cases where ANOVA indicated a significant effect, means were compared using Tukey's test at a significance level of $p < 0.05$. The results of bioactive compounds were processed and visualized using SigmaPlot 4.0 software [44]. Simple correlations between variables

(bioactive and colorimetric parameters) were determined by calculating Pearson's correlation coefficient (Equation (20)). Additionally, means were compared using Student's t-test at significance levels of $p < 0.05$ and $p < 0.01$ to assess the significance of differences between groups.

$$r = \frac{\sum_i (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_i (x_i - \overline{x})^2 \sum_i (y_i - \overline{y})^2}} \tag{20}$$

where i is the number of replications ($i = 1, \ldots, n$), x_i represents the values of the dataset ($x_1, x_2, \ldots, x_n$), $\overline{x}$ is the mean of the dataset, y_i represents the values of another corresponding dataset ($y_1, y_2, \ldots, y_n$), and $\overline{y}$ is the mean of the other corresponding dataset.

3. Results and discussion

3.1. Drying kinetics of S. purpurea fruits

Initially, the MR is notably higher as a result of the abundant water content present in the fruits. This high moisture content facilitates the absorption of thermal energy, thereby enhancing water diffusion to the surface [45]. In the first 15–60 min, surface water evaporates without encountering significant resistance, indicating a constant drying phase [46]. This phase persists until reaching the critical moisture level, typically around the 60-min mark, which signals the beginning of increased internal resistance to further drying processes (Fig. 2).

The resistance to water passage within fruits is influenced by a range of external factors, including slice size, drying temperature, as well as internal factors such as superficial pores diameter, micro-cracks, roughness, respiration rate, and cuticular moisture permeability [9]. An increase in internal resistance leads to inadequate water diffusion towards the surface, failing to compensate for the liquid evaporation, thereby initiating the declining drying phase (60–300 min). Stabilization is achieved when the product's moisture content reaches equilibrium with the surrounding air [47]. In the context of *S. purpurea* fruits, the stabilization phase of drying kinetics began at 420 min for fruits in maturation stages I and III, and at 480 min for others (Fig. 2). The extended stabilization time for fruits in advanced maturation stages is likely due to their higher water content, leading to increased internal resistance during the declining drying phase.

3.2. Mathematical modelling

The parameters derived from the equations fitted to the drying curves of *S. purpurea* fruits across varying maturation stages are detailed in Table 1.

All mathematical models employed effectively characterized the drying process, exhibiting R^2 values exceeding 0.99, MSD below 0.03, and X^2 below 0.0009. Notably, the Midilli ($R^2 \geq 0{,}998$, MSD $\leq 0{,}016$, and $X^2 \leq 0{,}0008$) and Logarithm ($R^2 \geq 0{,}997$, MSD $\leq 0{,}026$, and $X^2 \leq 0{,}0003$) models demonstrated superior fits, making them the most suitable for forecasting the drying kinetics of *S. purpurea* fruits across the five maturation stages under the experimental drying conditions. While there was no distinct correlation observed between the constants of the models and the maturation stages, the parameter k in the Midilli model exhibited a maturation-related increase. According to Goneli et al. [48], parameter k represents the drying speed constant, crucial for effective diffusivity in the drying process during the declining period, influencing liquid diffusion, and controlling the overall process.

The drying process in this study was carried out using small, standardized cuts of the mesocarp and epicarp of the fruits, arranged in a 1 cm layer and dried at a mild temperature of 60 °C to minimize significant losses in the bioactive compounds. It is important to

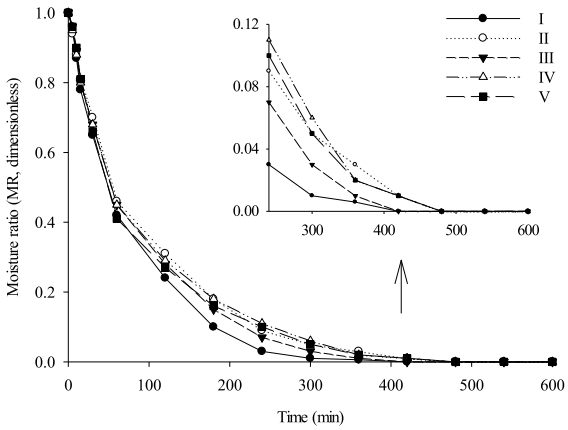

Fig. 2. Drying kinetics of *S. purpurea* fruits at different maturation stages.

Table 1
Parameters of the equations adjusted to the drying curves of *S. purpurea* fruits at different maturation stages.

Model	Maturation stages	Constants					R^2	MSD	X^2
		a	*b*	*k*	*n*	*c*			
Henderson and Pabis	I	0.9928	–	0.0134	–	–	0.9990	0.017	0.0003
	II	0.9764	–	0.0105	–	–	0.9981	0.023	0.0006
	III	0.9883	–	0.0116	–	–	0.9986	0.020	0.0005
	IV	0.9732	–	0.0107	–	–	0.9974	0.027	0.0009
	V	0.9870	–	0.0119	–	–	0.9967	0.019	0.0004
Lewis	I	–	–	0.0136	–	–	0.9990	0.017	0.0003
	II	–	–	0.0110	–	–	0.9977	0.025	0.0007
	III	–	–	0.0118	–	–	0.9985	0.021	0.0005
	IV	–	–	0.0112	–	–	0.9967	0.030	0.0010
	V	–	–	0.0122	–	–	0.9967	0.021	0.0005
Logarithmic	I	0.9915	–	0.0135	–	0.0018	0.9990	0.014	0.0003
	II	0.9696	–	0.0109	–	0.0099	0.9982	0.016	0.0006
	III	0.9845	–	0.0118	–	0.0049	0.9986	0.015	0.0005
	IV	0.9645	–	0.0111	–	0.0131	0.9975	0.017	0.0008
	V	0.9770	–	0.0126	–	0.0155	0.9973	0.009	0.0005
Midilli	I	1.0131	−0.00001	0.0196	0.9168	–	0.9993	0.017	0.0002
	II	1.0128	−0.00003	0.0209	0.8577	–	0.9990	0.023	0.0003
	III	1.0173	−0.00001	0.0200	0.8840	–	0.9992	0.020	0.0003
	IV	1.0199	−0.00002	0.0249	0.8226	–	0.9989	0.026	0.0003
	V	1.0295	−0.00001	0.0253	0.8389	–	0.9984	0.020	0.0001
Page	I	–	–	0.0172	0.9440	–	0.9992	0.015	0.0003
	II	–	–	0.0181	0.8889	–	0.9989	0.017	0.0003
	III	–	–	0.0167	0.9211	–	0.9990	0.016	0.0003
	IV	–	–	0.0202	0.8667	–	0.9988	0.019	0.0004
	V	–	–	0.0198	0.8874	–	0.9981	0.011	0.0001

Parameters of the equations (*a*, *b*, *k*, *n* and *c*), coefficient of determination (R^2), Mean Square Deviation (MSD), and chi-square (X^2).

emphasize that the adjustment to the obtained mathematical models is closely related to the drying conditions employed in the study. Processes involving higher temperatures would alter the mathematical parameters studied (such as the constant 'k', associated with effective diffusivity). Internal factors, such as surface pore diameter, microcracks, roughness, and respiration rate [9], as well as the fruit's ripening stage, are also crucial and strongly influence both the drying kinetics and the adjustment to the mathematical models.

3.3. Quality characterization analysis of S. purpurea fruit flour

3.3.1. Physicochemical parameters

The physicochemical attributes assessed in the *S. purpurea* fruit flours exhibited significant differences ($p < 0.05$) across maturation stages (Table 2). Flours derived from ripe fruits displayed elevated levels of yield, moisture, pH, SS, and RS. Notably, TTA was notably higher in fruit flour from maturation stage I. The majority of the evaluated characteristics demonstrated a strong fit to a simple linear regression model.

The higher yield and moisture content observed in ripe fruit flours, recorded at 30.7 % and 15.6 % (dry basis), respectively, can be attributed to the natural phenomenon of water absorption and accumulation in vacuoles during fruit development. This process is vital for osmoregulation and nutrient homeostasis within the fruit [49]. Water content in fruits exists in two forms: free water within intracellular spaces and linked water in capillaries or intercellular spaces bound to solid constituents [50]. The distribution of water in fruits is influenced by cell membrane rigidity. These membranes maintain structural integrity until a certain temperature threshold, after which they collapse, releasing bound water during drying. Understanding these dynamics enhances our insight into physiological processes during fruit development and drying stages.

Table 2
Physicochemical parameters of *S. purpurea* fruits flours at different maturation stages.

Parameters	Maturation stages					*p*-value	Equation	R^2
	I	II	III	IV	V			
Yield (%)	$22.2^{d} \pm 1.0$	$28.7^{b} \pm 1.4$	$28.2^{b} \pm 1.3$	$27.1^{c} \pm 1.2$	$30.7^{a} \pm 1.5$	0.1253	$y = 1.54x + 22.74$	0.60
Moisture (%)	$8.7^{d} \pm 0.4$	$9.2^{d} \pm 0.6$	$11.1^{c} \pm 0.6$	$12.6^{b} \pm 0.5$	$15.6^{a} \pm 0.9$	0.0053	$y = 1.72x + 6.28$	0.95
TTA (%)	$10.6^{a} \pm 0.1$	$2.4^{c} \pm 0.1$	$2.2^{c} \pm 0.1$	$2.7^{b} \pm 0.1$	$2.3^{c} \pm 0.1$	0.1883	$y = -1.62x + 8.92$	0.49
pH	$2.8^{c} \pm 0.2$	$3.3^{b} \pm 0.1$	$3.6^{a} \pm 0.1$	$3.7^{a} \pm 0.1$	$3.7^{a} \pm 0.1$	0.0343	$y = 0.22x + 2.77$	0.82
SS (°Brix)	$33.0^{c} \pm 0.9$	$21.3^{e} \pm 0.8$	$26.7^{d} \pm 1.0$	$48.4^{b} \pm 0.6$	$57.3^{a} \pm 0.8$	0.1095	$y = 7.56x + 14.67$	0.63
RS (mg 100 g^{-1})	$126.8^{d} \pm 8.9$	$231.4^{c} \pm 4.6$	$370.4^{b} \pm 6.9$	$813.0^{a} \pm 8.7$	$865.9^{a} \pm 8.9$	0.0088	$y = 205.97x - 136.42$	0.93

Results expressed as mean ± standard deviation. Means followed by equal letters on the line do not differ by Tukey's test ($p < 0.05$). Coefficient of determination (R^2), titratable acidity (TTA, % citric acid), hydrogenionic potential (pH), soluble solids (SS), and reducing sugars (RS).

Research suggests that around 50 °C, cell integrity remains preserved, indicating a consistent conversion of bound (intracellular) water to free water during drying [51]. However, the temperature (105 °C) used to assess flour moisture content could potentially harm cell membranes, prompting the release of water bound to solid constituents of ripe fruits into the extracellular medium. This occurrence elucidates the elevated moisture levels detected in flours from ripe fruits.

The analysis presented in Table 2 highlights a decline in TTA and an elevation in pH within the flours of ripe fruits. This transformation can be linked to the utilization of organic acids as substrates during cellular respiration [52]. Despite the concentration of remaining acids during drying, TTA decreased (from 2.3 % to 2.7 % citric acid). Furthermore, the ripening process spurred the hydrolysis of long-chain carbohydrates into simple sugars, culminating in augmented levels of SS and RS in ripe fruit flours (ranging from 48.4 to 57.3 °Bx and 813.0–865.9 mg 100 g^{-1}, respectively).

3.3.2. Bioactive parameters

Significant differences ($p < 0.05$) were evident in all assessed bioactive compounds across various maturation stages. Contents of TCh (Fig. 3A), AsA (Fig. 3C), and CPh (Fig. 3D) exhibited notably lower levels in flours derived from *S. purpurea* fruits in advanced developmental stages. This underscores the impact of maturation on these bioactive compounds, indicating a decline in more mature fruits. The fluctuation in bioactive compound content underscores the necessity of considering maturation stage when evaluating the nutritional and functional aspects of *S. purpurea* fruit flours (Alia-Tejacal et al., 2023).

The decline in TCh levels in fruit flours during advanced ripeness stages (Fig. 3A) can be linked to the increased ethylene release during fruit ripening [53]. Ethylene, emitted by fresh fruits, stimulates the expression and enzymatic activity responsible for chlorophyll breakdown [54]. The degradation pathway of chlorophyll commences with the removal of chlorophyll A phytol by chlorophyllase, leading to chlorophyll formation. Subsequently, Mg decelatase eliminates the Mg atom from the central nucleus of chlorophyll, producing a phaphobide A. The enzyme pheophorbide oxygenase (PAO) catalyzes the conversion of pheophorbide A into

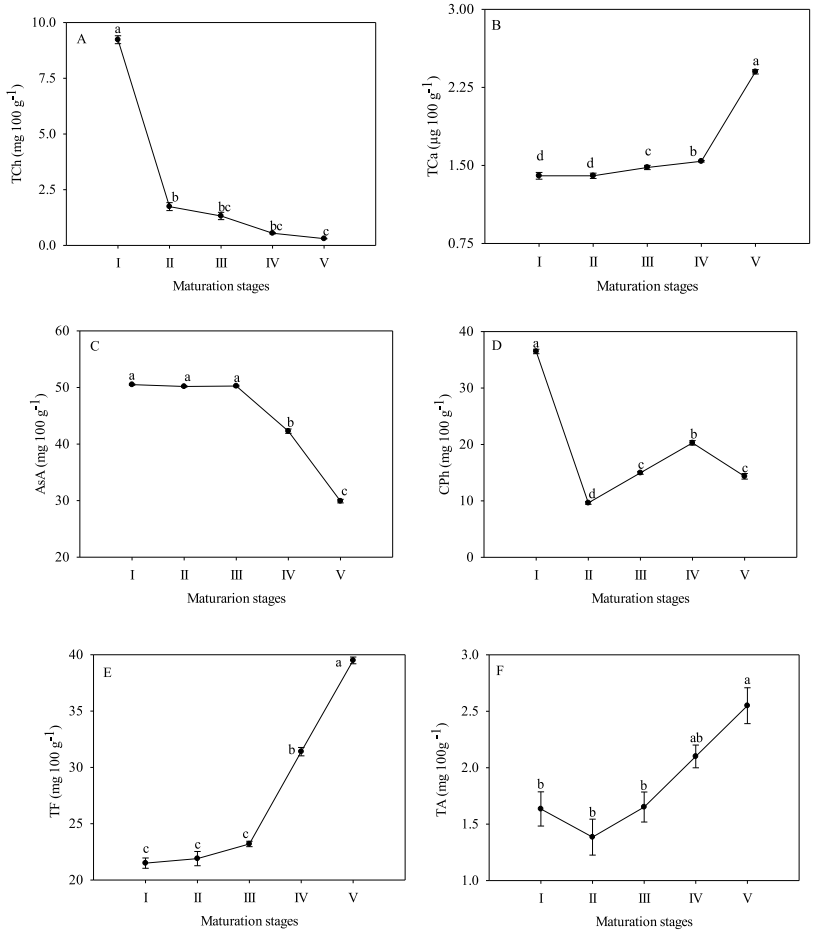

Fig. 3. Bioactive parameters of *S. purpurea* fruits flours at different maturation stages. Equal letters do not differ by Tukey's test ($p > 0.05$). Total chlorophylls (TCh, A), total carotenoids (TCa, B), ascorbic acid (AsA, C), phenolic compounds (CPh, D), total flavonoids (TF, E), and total anthocyanins (TA, F).

a red chlorophyll catabolite, resulting in the alteration of the tetrapyrrolic structure of chlorophyll and the loss of green color [55] in ripe fruits. This biochemical cascade explains the decrease in chlorophyll levels observed in flours from fruits at advanced ripeness stages.

The levels of TCa (Fig. 3B) were notably higher in flours derived from ripe fruits, a phenomenon attributed to the concurrent processes of chlorophyll degradation and carotenoid biosynthesis during ripening. Conversely, the levels of AsA (Fig. 3C) exhibited a decrease, primarily associated with the fruit's growth process [56]. However, the decline in AsA levels during later stages of maturation might have been facilitated by elevated moisture content (Table 2). Given that AsA is water-soluble, it can be transported by water during the drying diffusion process, potentially amplifying oxidative reactions induced by temperature and oxygen on the fruit's surface. Furthermore, it is noteworthy that the ascorbic acid content in *S. purpurea*, as documented by Maldonado-Astudillo et al. [18], ranges between 7.36 and 88.1 mg 100 g^{-1} of fresh weight, which surpasses the levels found in many other tropical fruits. This variation in AsA content underscores the diverse biochemical composition of *S. purpurea* and its significance in nutritional contexts.

The levels of CPh (Fig. 3D) display a notable tendency to be higher in flours derived from green fruits, gradually diminishing as the fruits mature. This decline is likely due to their oxidation by polyphenol oxidase and/or in response to the decrease in TTA (Table 2). It is established that a portion of the acids consumed in respiration can serve as a carbon source for the synthesis of phenolic compounds [57]. The anomalous behavior observed in stages III and IV, where CPh levels increased, might be influenced by harvesting and storage practices. The synthesis of these compounds tends to escalate under stress conditions, and the fluctuations in CPh levels during these maturation stages may result from stressors introduced during harvesting and storage processes. This underscores the sensitivity of phenolic compound synthesis to environmental factors and post-harvest handling techniques.

The levels of TA (Fig. 3F) remained constant in the fruit flours during the initial three stages of development and showed an increase in subsequent stages, aligning with the onset of maturation and ripening processes. Studies suggest that exogenous abscisic acid (ABA), a hormone that regulates maturation and ripening, positively regulates the expression levels of various genes responsible for anthocyanin biosynthesis, such as *FcPAL*, *FcCHS2*, *FcCHI*, *FcF3H*, *FcDFR*, *FcANS*, *FcUFGT*, and *Fc3RT* [58]. The interaction of these genes with other proteins, such as *FabHLH*, intensifies the biosynthesis and color development of anthocyanins [59].

Similarly, the levels of TF (Fig. 3E) increased with maturation, as they share practically the same biosynthetic pathway as anthocyanins. Engels et al. [6] conducted an extraction and characterization of 21 phenolic compounds from the epicarp of *S. purpurea*, identifying phenolic acids and flavonoids, including *O*-glycosides of quercetin, kaempferol, kaempferide, and rhamnetin. These findings offer valuable insights into the biochemical processes underlying the accumulation of anthocyanins and flavonoids during the maturation of *S. purpurea* fruits.

3.3.3. Colorimetric parameters

The L* values displayed an increase in the fruit flours during maturation stages I and decreased after reaching maturation stage III (Table 3). Maturation stage II presented higher L^* values due to the lower concentration of pigments at this stage, characterized by the degradation of chlorophyll and the initial appearance of carotenoids and flavonoids. Moreover, moisture content might have influenced the L^* values by inducing greater swelling of the granules, consequently reducing the contact surface area (Table 2). This reduction in contact surface area diminishes light reflection, resulting in a darker appearance of the flours derived from ripe fruits [60].

The parameters a^*, b^*, and C^* of the flours displayed an increase with progressing maturation stages. This trend stems from the degradation of chlorophylls and the biosynthesis of carotenoids and flavonoids, leading to a decline in green coloration and an elevation in yellow and red hues (Fig. 1). The elevation in C^* values signifies a shift in the color saturation of the flours from neutrality towards a more intense state as maturation progresses [61,62]. Moreover, the h° values decreased initially and then increased after stage IV. The rise in the h° values of the flours corresponds with the changes observed in the a^* and b^* coordinates, indicating a transition from greenish to yellowish or reddish tones.

The parameters a^*/b^* and $(a^*/b^*)^2$ play a crucial role in providing a realistic estimate of consumer perception [39], exhibiting significant variations ($p < 0.05$) across different maturation stages. An exception was noted between the initial maturation stages of green fruits (I and II) and the final stages of ripe fruits (IV and V). Nonetheless, despite this exception, the values of the relationship increased with the highest percentage of red color, indicating distinct color categories in terms of human visual perception. In a review by Maldonado-Astudillo et al. [18], it was emphasized that *S. purpurea* fruits undergo color changes in Brazil: (i) from dark green to

Table 3
Colorimetric parameters of *S. purpurea* fruits flours at different maturation stages.

Parameters	Maturation stages					*p*-value	Equation	R^2
	I	II	III	IV	V			
L^*	$51.4^{d} \pm 0.7$	$68.5^{a} \pm 1.2$	$67.7^{a} \pm 1.4$	$61.8^{b} \pm 0.6$	$56.5^{c} \pm 1.3$	0.0407	$y = -3.56x^2 + 21.71x + 35.19$	0.84
$+a^*$	$4.5^{c} \pm 0.3$	$5.0^{c} \pm 0.8$	$8.1^{b} \pm 0.7$	$12.6^{a} \pm 0.8$	$13.5^{a} \pm 0.5$	0.0065	$y = 2.56x + 1.04$	0.94
$+b^*$	$31.2^{c} \pm 0.5$	$32.5^{d} \pm 0.9$	$36.6^{c} \pm 0.4$	$38.0^{b} \pm 0.1$	$39.4^{a} \pm 0.8$	0.0037	$y = 2.19x + 28.97$	0.96
C^*	$31.6^{e} \pm 0.6$	$33.2^{d} \pm 0.3$	$37.4^{c} \pm 0.4$	$39.5^{b} \pm 0.3$	$51.7^{a} \pm 0.8$	0.0011	$y = 2.64x + 28.77$	0.98
h°	$81.8^{a} \pm 0.4$	$81.7^{a} \pm 1.2$	$77.5^{b} \pm 1.1$	$66.9^{d} \pm 1.0$	$70.9^{c} \pm 0.8$	0.0556	$y = -3.65x + 86.74$	0.76
a^*/b^*	$0.14^{c} \pm 0,0$	$0.16^{c} \pm 0,0$	$0.22^{b} \pm 0,0$	$0.33^{a} \pm 0,0$	$0.34^{a} \pm 0,0$	0.0078	$y = 0.06x + 0.07$	0.93
$(a^*/b^*)^2$	$0.02^{c} \pm 0,0$	$0.02^{c} \pm 0,0$	$0.04^{b} \pm 0,0$	$0.11^{a} \pm 0,0$	$0.12^{a} \pm 0,0$	0.0210	$y = 0.03x$ - 0.03	0.87

Results expressed as mean ± standard deviation. Means followed by equal letters on the line do not differ by Tukey's test ($p < 0.05$). Coefficient of determination (R^2), lightness (L^*), redness ($+a^*$), yellowness ($+b^*$), chroma (C^*), and hue angle (h°).

light green during the pre-climacteric phase; (ii) a transition from light green to yellow-orange during the climacteric ascent; and (iii) a development of reddish-purple coloration at the climacteric peak. These observations align with the color variations observed in the study, further substantiating the dynamic visual changes in *S. purpurea* fruits during different maturation stages.

3.3.4. Physical parameters

The ρA and ρC values were higher in the flours during the initial maturation stages. No significant differences ($p > 0.05$) were observed in the CIn and the HR (Table 4). Consistently, the ρC surpassed the ρA due to the reduced number of empty spaces resulting from compaction [63]. However, the ρA and ρC values of flours from advanced maturation stages were lower than the others, possibly due to higher moisture content, which promotes the swelling of the granules (Table 2), occupying a larger volume. In this context, the costs associated with storage tanks and packaging could potentially be reduced for flours from early maturation stages, given their higher ρA and ρC values (more product in less space/volume). This observation underscores the economic implications of considering the physical characteristics of flours at different maturation stages in terms of storage and packaging efficiency.

CIn and HR are methods used to indirectly assess the flow properties of powdered products, including flow capacity and cohesiveness, determined by the ratio of ρA to ρC. A CIn range of 0.12–0.16 indicates excellent fluidity, while a range of 0.23–0.35 suggests poor fluidity [64]. An HR value less than 1.25 indicates easy flow [63]. The flour from fruits in maturation stage V exhibited excellent fluidity, while the others demonstrated poor fluidity. Despite these differences in fluidity, all the flours displayed good flow rates. These findings shed light on the powder flow characteristics of *S. purpurea* fruit flours at various maturation stages, offering valuable insights for optimizing processing and handling during production and packaging.

3.4. Correlation analysis (bioactive and colorimetric parameters)

Pearson's correlations are shown in Table 5. Only very strong and significant positive and negative correlations were considered ($r \geq 0.95$ or $r \leq -0.95$).

Significant positive correlations ($p < 0.01$) were observed between BI and YI ($r = 0.9860$), and TA ($r = 0.9657$), demonstrating the influence of browning on the spectrum of yellowness. The CI was positively correlated ($p < 0.01$) with TF and TA, showing greater color intensity with increasing levels of this group and class of bioactive compounds. Only a significant negative correlation ($p < 0.01$) of AsA with TF and TA was noted, indicating an inversely proportional behavior, but a positive correlation with TCa ($p < 0.05$). According to Souza et al. [65], the contribution of AsA to the antioxidant activity of fruits varies, not always exhibiting a significant positive correlation.

4. Conclusion

The stabilization phase of *S. purpurea* fruit drying kinetics commenced at 420 min for fruits in maturation stages I and III, and at 480 min for the others. Among the mathematical models employed, the Midilli and Logarithmic models proved to be the most effective in representing the drying process of *S. purpurea* fruits. Notably, immature fruits yielded flours with shorter drying times and higher levels of TTA, TCh, CPh, and higher density (useful for incorporation into functional, healthy bakery products that can increase satiety). On the other hand, fruits from the final maturation stages resulted in flours with higher yield and elevated levels of RS, TCa, TF, and TA (ideal for incorporating bakery products, concentrated beverages, jams, and functional sweets). The study also revealed distinct color categories discernible in human visual perception, showcasing greater color intensity in flours with increasing levels of TF and TA. This comprehensive analysis provides valuable insights into the drying kinetics, quality, and visual characteristics of *S. purpurea* fruit flours across different maturation stages.

CRediT authorship contribution statement

Álvaro Gustavo Ferreira da Silva: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Franciscleudo Bezerra da Costa:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Data curation. **Ana Marinho do Nascimento:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization. **Giuliana Naiara Barros Sales:** Writing – review & editing, Visualization, Validation, Software, Methodology. **Jéssica Leite da Silva:** Writing – review & editing, Visualization, Supervision, Investigation,

Table 4
Physical parameters of *S. purpurea* fruits flours at different maturation stages.

Parameters	Maturation stages					*p*-value	Equation	R^2
	I	II	III	IV	V			
ρA (g cm^{-3})	$0.75^{b} \pm 0.0$	$0.77^{a} \pm 0.0$	$0.77^{a} \pm 0.0$	$0.73^{c} \pm 0.0$	$0.70^{d} \pm 0.0$	0.0663	$y = -0.02x + 0.80$	0.72
ρC (g cm^{-3})	$0.93^{ab} \pm 0.0$	$0.93^{ab} \pm 0.0$	$0.96^{a} \pm 0.0$	$0.89^{b} \pm 0.0$	$0.83^{c} \pm 0.0$	0.1547	$y = -0.02x + 0.98$	0.56
CIn (%)	$17.0^{a} \pm 1.4$	$18.5^{a} \pm 0.7$	$19.5^{a} \pm 0.7$	$18.0^{a} \pm 0.0$	$16.0^{a} \pm 1.4$	0.1185	$y = -0.68x^2 + 3.82x + 13.80$	0.97
HR (dimensionless)	$0.83^{a} \pm 0.0$	$0.82^{a} \pm 0.0$	$0.81^{a} \pm 0.0$	$0.82^{a} \pm 0.0$	$0.84^{a} \pm 0.0$	0.1058	$y = 0.01x^2 - 0.03x + 0.86$	0.96

Results expressed as mean ± standard deviation. Means followed by equal letters on the line do not differ by Tukey's test ($p < 0.05$). Coefficient of determination (R^2), apparent density (ρA), compacted density (ρC), Carr index (CIn), and Hausner ratio (HR).

Table 5
Pearson correlation matrix for bioactive and colorimetric parameters of *S. purpurea* fruits flours at different maturation stages.

	BI	YI	CI	TCh	TCa	AsA	CPh	TF	TA
BI	1.000								
YI	0.9860**	1.000							
CI	0.9132*	0.8385ns	1.000						
TCh	-0.1731ns	-0.0099ns	-0.5236ns	1.000					
TCa	0.8358ns	0.7759ns	0.7957ns	-0.4268ns	1.000				
AsA	-0.8935*	-0.8190ns	-0.9149*	0.4915ns	-0.9565*	1.000			
CPh	0.1696ns	0.3207ns	-0.1379ns	0.8825*	-0.2806ns	0.2514ns	1.000		
TF	0.8958*	0.8117ns	0.9619**	-0.5573ns	0.9132*	-0.9881**	-0.2656ns	1.000	
TA	0.9657**	0.9092*	0.9764**	-0.4200ns	0.8890*	-0.9605**	-0.0810ns	0.9766**	1.000

Statistical significance of ANOVA: ** $p < 0.01$; * $p < 0.05$; ns, not significant. Browning index (BI), yellowing index (YI), color index (CI), total chlorophylls (TCh), total carotenoids (TCa), ascorbic acid (AsA), phenolic compounds (CPh), total flavonoids (TF), and total anthocyanins (TA).

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Data availability statement

Data available on request from the authors.

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Declaration of competing interest

We wish to confirm that there are no known conflicts of interest associated with this publication and that there is no significant financial support for this work that may have influenced its outcome.

We confirm that the manuscript has been read and approved by all the named authors and that there are no other people who have met the criteria for authorship, but are not listed. We also confirm that the order of the authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the only contact for the Editorial process (including the Editorial Manager and direct communications with the office). He is responsible for communicating with other authors about progress, submission of reviews and final approval of evidence. We confirm that we have provided a correct and current email address, accessible by the Corresponding Author and which has been configured to accept the email: brunofonsecafeitosa@live.com; fonsecabruno869@gmail.com.

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