

RESEARCH

Open Access



Insights into the chili phytochemicals, bioactive components, and antioxidant activity of instant premixes (green and red chilies) and their reconstitution products

Monisha Arya^{1,2}, Priyanka Kumari², Gyanendra Kumar², Attar Singh Chauhan³ and Parvatam Giridhar^{1,2*} 

Abstract

Chili fruits are a potential source of phytochemicals and nutrients for food and reconstituted products. Due to its high nutritional and bioactive components, the current study focused on developing chili instant food products employing hot-air drying method. The effect of the hot-air drying method on physicochemical properties, microbiological quality, retention of bioactive components, phytochemicals, antioxidant properties, and sensory quality of green and red chilies reconstitution products were investigated. HPLC quantification unveiled that fresh red chili product had retained the highest capsaicin (2703.14 µg/g) and dihydrocapsaicin (1518 µg/g) content on the 0th day. Furthermore, UPLC-MS confirmed the presence of eleven phenolic compounds such as gallic acid, chlorogenic acid, caffeic acid, syringic acid, p-coumaric acid, protocatechuic acid, trans-cinnamic acid, ferulic acid, catechin, rutin, and quercetin. Among all, ferulic acid (382.91 µg/g) was the most abundant phenolic compound in fresh green chili products, followed by trans-cinnamic acid (73.19 µg/g) in green chili reconstituted and catechin (65.66 µg/g) in green and red chili reconstituted products. The chili products retained reasonable amounts of bioactive components and antioxidants during storage without microbial growth. The correlation analysis revealed a significant correlation between capsaicinoids, phenolic compounds, and antioxidant properties, which are linearly related in green chili products. This study offers manufacturers a cost-effective technology for producing high-quality chili-reconstituted products rich in essential nutrients and health benefits.

Keywords Chili fruits, Nutritional benefits, Bioactive components, Antioxidant activities, Reconstitution products

*Correspondence:
Parvatam Giridhar
parvatamg@yahoo.com
Full list of author information is available at the end of the article



© The Author(s) 2024. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

Graphical Abstract



Introduction

Plants produce a variety of molecules called metabolites or phytochemicals, which result from their evolutionary interactions with the environment. These compounds have become a significant health source for human society (Fernández-Bedmar & Alonso-Moraga 2016; Guan et al. 2021). Plant-based foods, such as grains, nuts, seeds, vegetables, fruits, and herbs, contain diverse phytochemicals (Probst et al. 2017). Some of the common phytochemicals found in plants are isoflavones, indoles, polyphenols, anthocyanin, procyanidins, phenylpropanoids, carotenoids, catechins, and flavonoids. The consumption of these dietary phytochemicals is often linked with protecting against diseases such as cardiovascular disease, cancer, and neurological illnesses (Kumar et al. 2021; Xiao & Bai 2019). Therefore, food scientists are developing better products that retain excellent phytochemicals and nutrient profiles. In addition, there is a growing demand for quick-to-prepare functional and nutritional food products that offer possible health benefits in today's fast-paced lifestyle.

Among various vegetables available worldwide, chilies, also known as peppers (*Capsicum annuum*), have been one of the oldest and most popularly cultivated vegetable crops since 7000 BC and are consumed globally. In addition, it has a broad range of applications in food and medicine (Kraft et al. 2014; Liu & Nair 2010). Chili is a highly nutritious and flavorful food, recognized to be a good source of vitamins (A and C), minerals (potassium, iron, and magnesium), phytochemicals, and antioxidants. These phytochemicals contain vital compounds like capsaicinoids, chlorophyll, phenolic acids, and carotenoids. These compounds have therapeutic and nutritional benefits and have unique taste, aroma, color, and characteristics (Alam et al. 2018; Civan & Kumcuoglu 2019; Idrees et al. 2020). Chili is primarily known for its spicy taste and pungency due to the active compound capsaicinoids, an alkaloid unique to its family. These compounds are reported for their significant health-promoting effects, including lipid metabolism, radical scavenging activity, and anticancer properties (Civan & Kumcuoglu 2019; Fernández-Bedmar & Alonso-Moraga

2016). Capsaicinoids are plant secondary metabolites; capsaicin and dihydrocapsaicin account for 90% of the total capsaicinoids in chili (Alam et al. 2018; Naves et al. 2019). Capsaicin is a food additive that regulates pain, body temperature, and lipid metabolism. Additionally, it is asserted that they can decrease cholesterol and strengthen the immune system (Bogusz Jr et al. 2018; Chapa-Oliver & Mejía-Teniente 2016; Civan & Kumcuoglu 2019). Chilies are commonly used as condiments to make foods such as red pepper powder, hot sauce, kimchi, pickles, salted seafood, red pepper paste, water chili juice, oil chili sauce, hot pot ingredients, and quick noodles (Sharif et al. 2018).

Various fruits and vegetables in their dried powder form have more stability and high nutrient content. Hence, it is widely used to develop instant premixes and is easy to handle compared to their fresh form. Moreover, drying is a common way to preserve food quality characteristics beyond their natural shelf life. Drying prevents enzyme activity, microbial growth, and moisture-related damage. To produce the desired products in the food industry, several drying processes, such as hot air drying, vacuum drying, far infrared radiation drying, and freeze drying, are used (Chao et al. 2022). Among all the drying processes, hot-air drying is the most cost-effective and widely used for extending the shelf life of fruits and vegetables. However, drying is temperature and duration-dependent, which changes the physical and chemical aspects of fruits and vegetables, such as bioactive component contents, sensory and nutritional qualities (Chao et al. 2022).

In today's fast-paced lifestyle, people require food that is easy to prepare, minimally processed with a longer shelf life, has nutritional values, and can be taken on the go. Therefore, the researchers highly value chilies because of the capsaicin ingredients present in them, which have the potential to make diverse food products. However, no report has been found on the development of chili reconstitution products and their bioactive phytoconstituents profiling. In addition, the development of instant premixes and their reconstitution products from chili has various advantages, such

as convenience food (easily prepared before consumption), longer shelf life, accessible transportation, cost-effectiveness, and the required nutrients and health benefits. Considering all these factors, to facilitate the broad use of capsaicin in the food sector. The study aimed to develop shelf-stable chili reconstitution products employing a hot-air drying process to preserve the beneficial phytochemicals, such as capsaicinoids, phenolic compounds, antioxidants, and carotenoids. The present research also investigated various quality indicators like bioactive chemical degradation, color loss, and changes in food structure. This study offers manufacturers a cost-effective technology for producing high-quality chili-reconstituted products rich in essential nutrients and health benefits.

Materials and methods

Chemicals

Citric acid, sodium benzoate, pectin, and Fehling solutions A and B were purchased from Rankem Bangalore. Sodium hydroxide, hydrochloric acid, phenolphthalein indicator, methylene blue indicator, rose bengal chloramphenicol agar, plate count agar, violet red bile broth, Folin-Ciocalteu reagent, 2,2-diphenyl-1-picrylhydrazyl (DPPH) and various other chemicals of analytical grade were obtained from Hi Media Pvt. Ltd. (Bangalore, India) and Sisco Research Laboratory (Mumbai, India). All the high-performance liquid chromatography (HPLC) grade solvents and standards used in investigating capsaicinoids and phenolic compounds were procured from Sigma-Aldrich through Merck Life Sciences Pvt. Ltd.

Procurement of plant material and sample processing

The green and red chili fruits (*Capsicum annuum* L.) were acquired from farmer's market in the Mysore district of Karnataka. The chili fruits of similar size and color, without any mechanical damage (6 kg), were selected and thoroughly washed under running tap water to remove dust and other contaminants, afterward rinsed with reverse osmosis (RO) purified water, destalked and dried with blotting paper for removal of excess water before drying.

Preparation of chili powder and paste

A hot air-blowing dryer (48 trays capacity, 12 KW) was used to execute the drying of chili fruits. Green and red chilies (500 g) were uniformly placed in a single layer on different perforated stainless-steel trays (60 cm wide, 90 cm long, and 4 cm deep) and loaded into a hot air-blowing dryer (Jaideep Engineers, India). The hot-air dryer has a digital temperature controller, 2.5 kg maximum loading capacity, and hot air

circulation (2.7 m/s hot air velocity per square meter SS tray area). The drying temperature was maintained at 56 ± 1 °C for 24 h with 100% air circulation. The samples were dried until they acquired a moisture content of 10% (Popelka et al. 2017). The obtained end moisture content was $(7.29 \pm 0.03\%)$ for dried chili fruits. The dried chili fruits were ground into powder using a mixer grinder (Elgi Ultra Choice + RX 1000), the motor has a speed of 1000 W with 24,000 RPM) for 30 s to 1 min and sieved through a fine 150 μ m mesh size to obtain a fine powder. Subsequently, chili fruits were ground to make a fine chili paste using a mixer grinder for 40 to 60 s. The dried chili powder and fresh chili paste were used further for green and red chili product development.

Product development from green and red chilies

The hot air-dried green/red chili powder and fresh chili paste were used to prepare instant chili premix and fresh chili products. For the preliminary trials of instant chili premix, four different concentrations of chili powder were selected (0.25%, 0.5%, 0.75%, and 1%), and an experiment was conducted for all the products to choose the best and most acceptable product developed from chili. Based on the sensory evaluation and physicochemical analysis in the preliminary trials, the fresh chili pastes and powder of 1.0% were selected to develop chili instant premixes and fresh chili products. Thus, four products were developed from green and red chili fruits Viz., Product 1 (Green chili powder premix/GCPP); Product 2 (Red chili powder premix/RCPP); Product 3 (Fresh green chili paste/ FGCP); and Product 4 (Fresh red chili paste/ FRCP) respectively, displayed in Fig S1.

1 kg of instant green/red chili premix and fresh product was prepared by using dextrose (27.5%), white sugar powder (27.5%), citric acid (0.6%), sodium benzoate (0.022%), 1% green and red chili powder/paste was added. For instant chili premix, samples were mixed uniformly using a mixer and grinder for 30 s. Then, the mixed instant premix was weighed (100 ± 1 g), packed in low-density polyethylene (LDPE) bags (200-gauge size, 50.8 μ m), and stored at room temperature (25 ± 1 °C). Subsequently, fresh chili pastes and all the ingredients were added and pasteurized at 90 °C for 1 min, hot-filled into clean bottles stored at (5 ± 1 °C). The instant chili premix was drawn on the 30th day of storage and reconstituted to evaluate the quality attributes during storage. The preparation time of all the chili products was optimized, and total soluble solids (TSS) of 65–70°brix were adjusted for all formulations. The reconstituted product was cooled and stored at (5 ± 1 °C) in bottles for further studies.

Physicochemical analysis

The physicochemical analysis of instant chili premixes and fresh products, such as moisture content, was analyzed using a digital moisture analyzer (Denver Instrument Germany, Model-IR 35, Germany), and the moisture percentage was recorded at 110 ± 2 °C in an automatic mode. Total Soluble Solids (TSS) were estimated using a digital refractometer (Model RA-250HE, Kyoto Electronics Manufacturing Co. Ltd., Japan), pH (Cyberscan, Eutech Instrument, Singapore), water activity (aw) was analyzed using a water activity meter (Lab Master-aw, Novasina, Switzerland) by following previous method. Sugar was analyzed using the Lane and Eynon method, and protein content was analyzed using the Kjeldahl method (Goel et al. 2023). Particle size analysis was performed by Microtrac S3500 equipment using software from the Malvern Instrument Nano series (version 7.13) (Singh et al. 2006).

Estimation of color, chlorophyll, and carotenoid content

The color parameter was measured at 360–740 nm wavelength using a color measuring instrument (Konica Minolta CM-5, VA, USA) as described (Maciel & Teixeira 2022). The obtained results were expressed according to the Commission Internationale d'Eclairage (CIE Lab) color system. They are represented as L^* , a^* , and b^* values, where L represents lightness, a (+) = redness, a (-) = greenness, b (+) = yellowness, and b (-) = blue. The hue angle (h°) and the chroma values (c^*) were calculated by using (1) and (2) equations (Maciel & Teixeira 2022).

$$Chroma = \left[(a^{*2} + b^{*2})^{\frac{1}{2}} \right] \quad (1)$$

$$hue = \tan^{-1} \frac{b^*}{a^*} \quad (2)$$

The chlorophyll and carotenoid content of the fresh green and red chili reconstituted products was estimated by the Lichtenthaler method (Lichtenthaler & Oreld 1983). In brief, 1 g of samples were weighed and extracted with acetone (1:10 w/v) in a mortar and

645 and 450 nm. The total chlorophyll (chl t), chlorophyll (chl a), (chl b), and total carotenoids were calculated and expressed in mg/100 g by using the following Lichtenthaler Eqs. (3), (4), (5) & (6):

$$Chl.a(\mu g/ml) = 11.24 A_{661.5} - 2.04 A_{645} \quad (3)$$

$$Chl.b(\mu g/ml) = 20.13 A_{645} - 4.19 A_{661.5} \quad (4)$$

$$Chl.b(\mu g/ml) = 7.05 A_{661.5} + 18.09 A_{645} \quad (5)$$

$$\begin{aligned} \text{Total Carotenoids}(\mu g/ml) &= 1000 \times A_{450} - \\ &[1.9 \times Chl.a - 63.14 \times Chl.b]/214 \end{aligned} \quad (6)$$

Total phenolic content (TPC)

The total phenolic content of the chili product samples were estimated using the Folin-Ciocalteu method (Sadasivam & Manickam 2008). A known volume of ethanol extract was taken for the analysis; 0.5 mL of FC reagent (1:1) and 2 mL of 20% sodium carbonate were added and incubated for 1 min in a boiling water bath. Absorbance was read at 650 nm using a Genesis Thermo Fisher spectrophotometer. The total phenolic content was calculated in the samples using an equation obtained against a gallic acid standard. The phenolic content was expressed as milligram gallic acid equivalent (GAEq.) per 100 g.

In vitro antioxidant assays

Antioxidant potentials were determined using ferric-reducing antioxidant power (FRAP) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) assays. The FRAP assay was performed according to the described method by Oyaizu (Oyaizu 1986). The standard graph was plotted using ascorbic acid as a standard, and absorbance was measured at 700 nm. All the results were expressed as the mg equivalent of ascorbic acid per 100 g. The DPPH assay was assessed according to Ranganna (1986), absorbance was recorded at 517 nm, and the results were expressed as EC_{50} value obtained from the given formula (Ranganna 1986).

$$DPPH \text{ scavenging activity} = \frac{\text{Absorbance control} - \text{Absorbance Sample}}{\text{Absorbance control}} \times 100$$

pestle; then, the sample was centrifuged at 8000 rpm for 10 min. The supernatant was collected, and the absorbance was recorded with a spectrophotometer (UV 150, Genesys Thermo Scientific) at 661.5, 663,

Extraction and quantification of capsaicinoids content by HPLC

The capsaicinoids were extracted from the green/red chili fresh and reconstituted products of *C. annuum* following

the methods proposed by González-Zamora et al. (2015): Slight modification: in brief, 1 g of chili products sample was extracted in 5 mL of acetonitrile and stored at -20 °C until they were analyzed. Quantification of capsaicin and dihydrocapsaicin were performed by HPLC using a C18 column (YMC S-5 μm , 250 $\times$ 4.6 mm). Solvent (A) Milli-Q Water and (B) acetonitrile are the mobile phases in (40:60, v/v) with a flow rate of 1 mL/min in an isocratic mode. Samples were detected at 280 nm, and the injection volume was 20 μL for all samples (Sganzerla et al. 2014). Quantification was performed based on retention time and area of external standards of capsaicin, dihydrocapsaicin, and chromatogram, as shown in Fig S2. The linearity was assessed by calculating the standard area obtained from HPLC analysis, and calibration curves of phenolic standards were obtained with linearity ($r > 0.98$ –0.99), and the results were expressed in $\mu\text{g/g}$.

Identification and quantification of phenolic compounds

The molecular weight of all the compounds was identified using ultra-high-performance liquid chromatography with quadrupole time of flight mass spectrometry (UPLC-QTOF-MS/MS system, XEVO-G2-XS QTOF). The highly accurate mass measurements were carried out in negative and positive ESI modes. The mass spectrometer range was 100–2000 m/z for MS scans. Instrument control and data acquisition were done using DaMass-LynxV4.2 Software (Waters Corp., USA) (Pollini et al. 2022; Rahman 2022).

High-performance liquid chromatography (HPLC) was used to separate the phenolic compounds of chili products using a Shimadzu LC 10AS (Shimadzu Corp. Kyoto, Japan) equipped with a diode array detector and a C18 column (Sunfire 5 μm , 250 $\times$ 4.6 mm). The individual compounds were separated following Burin et al. (2011). Gallic acid, chlorogenic acid, caffeic acid, syringic acid, p-coumaric acid, protocatechuic acid, trans-cinnamic acid, ferulic acid, catechin, rutin, and quercetin were included in the list of phenolic compound standards and quantified by using the external standard method. The linearity was assessed by calculating the standard area obtained from HPLC analysis, and calibration curves of phenolic standards were obtained with linearity ($r > 0.97$ –0.99). The standards were injected in triplicates to find the linearity, and the chromatogram is given in Fig S3, S4, S5, and S6; results are expressed as $\mu\text{g/g}$.

Microbiological analysis

The microbial load of all chili product samples was analyzed using standard methods described by Khan et al. (2015). The samples were examined at regular intervals to determine the presence of the total aerobic bacterial count (Plate count agar), yeast and mold (Rose

Bengal-chloramphenicol agar), and coliforms (Violet red bile agar) to establish the microbiological safety of the product. The plates of the bacterial count were incubated at 37 °C for 24 h and 48 h, and the fungal count was recorded after five days of incubation at 28 °C, and microorganism growth was expressed as log/g of the sample.

Sensory evaluation

A panel of trained and semi-trained 20 members evaluated the sensory in two stages for green and red chili products mentioned in [Product development from green and red chilies](#) section. A scorecard was prepared using a 9-point hedonic scale (0–9) for color, spice, taste, texture, and overall acceptability for consumer acceptance. The fresh and reconstituted chili product was spread on one-fourth of the bread slice and coded with the three-digit random numbers served to the panel. Panelists were provided water to cleanse their palates in between the samples. The scores given by each panel member for each attribute were recorded, and the mean values of each sample quality parameter were calculated (Irondi et al. 2024).

Statistical analysis

The statistical variations between chili products concerning bioactive profiling, phytochemical, and quality assessment were performed. Each analysis was performed minimum in triplicates, and the results were expressed as mean $\pm$ SD of three replicates. The statistical differences ($p < 0.05$) between the results were measured by one-way (ANOVA), and Tukey's test was applied for comparisons. All the figures were made using OriginPro 2023 (Origin-Lab Corporation, Northampton, USA) 8.5 software. Statistical correlation based on Pearson's coefficient (r) among them was performed by the corrplot package (Wei et al. 2021) in R-Studio (Allaire 2012).

Results and discussion

Physicochemical properties of reconstituted and fresh chili products

The moisture content was between 20.13% and 25.29%, TSS content was 68.23 to 70.63°brix, water activity ranged from 0.81 to 0.68, and pH values for red and green chili products were 3.14 to 3.31, respectively. The sugar content was 8.37 to 11.35%, and the protein content was 0.44% and 0.26%, respectively. However, significant changes were observed in the products, with increased TSS, pH, sugar, and protein content. The change in pH and TSS could be due to the inherent acids and hydrolysis of polysaccharides and other constituents in the product. Similar results were reported in *Basella rubra* fruit pulp-based gooseberry

Table 1 Physicochemical analysis of 1% fresh green, red and reconstituted chili food products during storage

Parameters	0 Days				90 Days			
	FGCP	GCPP	FRCP	RCPP	FGCP	GCPP	FRCP	RCPP
Colour measurement								
L*	2.69±0.03 ^c	2.01±0.07 ^c	18.44±1.35 ^c	11.61±0.61 ^c	12.3±0.06 ^b	8.44±0.3 ^b	24.06±0.08 ^a	26.79±0.1 ^a
a*	12.35±0.1 ^b	7.94±0.18 ^b	27.05±0.06 ^d	19.41±0.74 ^{ab}	14.9±0.1 ^c	7.34±0.06 ^c	13.92±0.03 ^c	10.62±0.03 ^b
b*	12.64±0.09 ^a	8.19±0.16 ^a	25.94±0.51 ^c	14.72±0.74 ^c	19.32±0.10 ^a	11.19±0.22 ^a	8.05±0.06 ^b	7.62±0.11 ^c
Chroma	1.35±0.01 ^b	1.32±0.1 ^b	37.50±0.51 ^b	24.37±0.15 ^b	0.88±0.0 ^b	0.72±0.0 ^b	16.08±0.51 ^a	13.07±0.14 ^a
Hue angle	70.63±0.18 ^b	68.23±0.58 ^c	0.76±0.0 ^c	0.65±0.01 ^b	72.93±0.80 ^a	67.9±3.59 ^c	0.52±0.0 ^b	0.62±0.0 ^b
Total chlorophyll content (mg/100 g)	0.55±0.38 ^c	1.90±0.08 ^d	na	na	1.71±0.6 ^c	1.27±0.55 ^b	na	na
Carotenoid content (g/100 g)	na	na	0.05±0.01 ^c	1.9±0.03 ^a	na	na	0.65±0.01 ^c	1.35±0.02 ^c

CIE parameters: L* Lightness, a* Redness, b* Yellowness, na Not analyzed, chroma and hue angle were calculated from L, a, and b values and FGCP Fresh green chili product and GCPP Green chili powder product, FRCP Fresh red chili product and RCPP Red chili powder product, respectively. Data are represented as the mean ± standard deviation of three replicates and different letters above denote statistical differences in the samples whereas similar letters shows no significant difference ($p < 0.05$)

RTS product (Hemalatha et al. 2018; Kumar et al. 2020). The low pH, pasteurization, and preservatives added to the product generally inhibit microbial growth, maintain stability, and enhance the product's shelf-life (Besbes et al. 2009).

Effect on color and photosynthetic pigments

Color is one of the essential sensory aspects that indicates the freshness, flavor, and quality of food products. The color attributes impact the perception of food products for consumers and the food industries. The chili products were subjected to measure color parameters like L* represents Lightness, a*(redness or greenness), and b* (yellowness or blueness) values presented in Table 1. The results exhibited significant changes in L* values of fresh and reconstituted green/red chili samples during storage (Table 1). There was a substantial increase in L* values and a decrease in a* and b* values during storage in fresh and reconstituted products. The L*, a*, and b* values of color change might be due to pigments and enzymatic and oxidative degradation during storage (Hemalatha et al. 2018).

The total chlorophyll content in GCPP was 1.9 mg/100 g and FCPP (0.55 mg/100 g) on the 0th day (Table 1). There was an initial increase in total chlorophyll content for 60 days (2.6 mg/100 g for GCPP and

2.4 mg/100 g for FCPP). Later, it was observed that total chlorophyll content started decreasing slowly, possibly due to the stored temperature. Similarly, the carotenoid content was measured in red chili products, and maximum carotenoid content was recorded in red chili reconstituted product on the 60th day (2.6 g/100 g), shown in Table 1. Our results showed that carotenoid content increased during storage for 60 days; gradually, carotenoid stability declined after 90 days to 1.35 g/100 g. Consequently, the stability of carotenoids is affected by the chemical interactions between capsaicinoids and carotenoids in chili tissues, thereby protecting against thermal degradation (Henderson & Henderson 1992). The loss in color after 60 days may be due to the Maillard reaction, which condenses and destroys pigments, or by creating melanoidins, which are significantly related to temperature and water content (da Costa et al. 2017).

Effect on total phenolic content (TPC) and antioxidant capacities

The TPC was ascertained in fresh green/red chili, and its reconstituted product is illustrated in Fig. 1a. The TPC of the green/red reconstituted product was highest on the 0th day (83.42 mg/100 g GAEq.) compared to fresh green (68.96 mg/100 g GAEq.), and a similar trend was observed

(See figure on next page.)

Fig. 1 a Total phenolic content b FRAP antioxidant activity c DPPH radical scavenging activity of chili product during storage. Here, FRAP = ferric reducing antioxidant power; DPPH = 2,2-Diphenyl-1-picrylhydrazyl; EC50 = effective concentration; GAEq. and AAeq. are gallic acid and ascorbic acid equivalents; GCPP = Green chili powder product; FGCP = Fresh green chili product; RCPP = Red chili powder product and FRCP = Fresh red chili product respectively. Data represented in triplicates as mean ± SD of three replicates and different letters above the bar indicate statistical differences in the samples, whereas similar letters show no significant difference ($p < 0.05$)

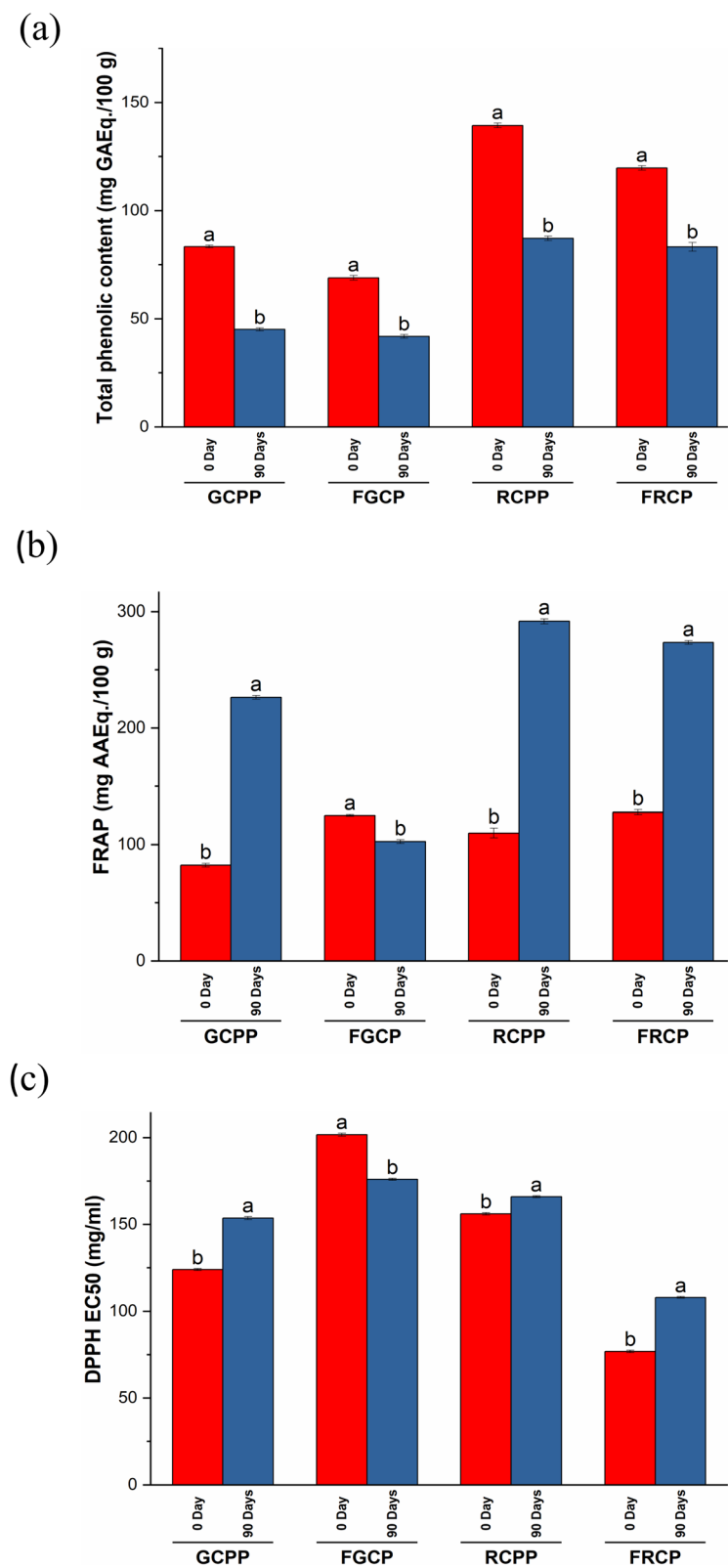


Fig. 1 (See legend on previous page.)

in red chili reconstituted product (139.42 mg/100 g GAEq.) compared to fresh product (119.72 mg/100 g). Consequently, evidence illustrates that the TPC of hot-air dried chili reconstituted products was higher than that of fresh chili products. Several chemical processes occur concurrently during drying that can either increase or decrease the TPC. Correspondingly, the heat treatments cleave phenolic acid's ester and glycoside bond, reducing TPC in fresh products. According to the results, the TPC of the fresh and chili reconstituted product gradually decreases during storage. This gradual decrease in TPC was also reported in ready-to-serve beverages, including jamun squash, cape gooseberry, and kainth products, probably due to polymeric oxidation, which leads to the development of brown pigment (Hemalatha et al. 2018; Kumar et al. 2020; Prakash et al. 2022; Sharma et al. 2012). Eventually, phenolic compounds contribute significantly to the flavor and taste of processed food products and nutritional properties (Sharma et al. 2012).

The chilies are consumed because they are rich in capsaicinoids and polyphenol content and also due to the presence of antioxidants. Therefore, FRAP and DPPH assays were performed to know the antioxidant potential of chili products, and the results are shown in Fig. 1b & c. The green and red chili reconstituted product showed the highest antioxidant activity (EC_{50}) against DPPH (125 and 157.5 $\mu\text{g/mL}$), and the FRAP activity also showed a similar trend. Likewise, it was found that there was retention in FRAP activity in chili products after 90 days of storage, supported by other reports of increased antioxidant activity in GuCa enriched with nanoliposomes (Amjadi et al. 2018). According to the obtained results, it is remarkable that every antioxidant assay has distinct thermodynamic and kinetic properties, and every reagent has a naturally varying oxidizing power against a particular antioxidant at a given period (Maciel & Teixeira 2022).

Quantification of capsaicinoids content by HPLC

Capsaicin and dihydrocapsaicin are two capsaicinoids most prevalent in chili fruits and contribute most to the pungency and spiciness of hot chilies. Therefore, only capsaicin and dihydrocapsaicin were measured in the samples shown in Fig. 2a and b. The highest capsaicin and dihydrocapsaicin content were recorded in the fresh red products (2703.14 and 1518.0 $\mu\text{g/g}$) compared to green (1633.52 and 993.8 $\mu\text{g/g}$) on the 0th day, respectively. In red chili reconstituted products, capsaicin and dihydrocapsaicin content were comparatively less (2363.98 and 1027.0 $\mu\text{g/g}$) than the fresh red products. The results showed that fresh chili products have a higher amount of capsaicinoids content compared to reconstituted chili products. Our findings are similar to

earlier research; they have reported that duration, temperature, and heat treatment provided for chili fruits during drying and processing significantly affect capsaicinoids content, showing low content compared to fresh (Alvarez-Parrilla et al. 2011; Yap et al. 2022). Furthermore, the release of capsaicinoids and thermal deterioration may happen simultaneously (Martín-Cabrejas et al. 2009), which was due to the cleavage of amide and vanillin bond, arrangement of methylnonenamide, or hydrogenation and deamination of 8-methyl-6-nonemide (Henderson & Henderson 1992). This result was contradicted by Zhou et al., who stated that the capsaicinoids content decreased by up to 18% during the drying process (depending on the chili variety) (Zhou et al. 2016). Furthermore, an oxidation reaction occurs between capsaicin and dihydrocapsaicin that results in the degradation of peroxidase enzymes when the cell ruptures to remove the water content during drying.

Profiling of phenolic compounds in fresh green and red chili reconstituted products

Phenolic compounds are the central plant secondary metabolites associated with sensory acceptability, color, and antioxidant capacity of vegetables, fruits, and grains, with a high potential to neutralize and protect against free radicals (Castrejón et al. 2008). Consumption of these phytochemicals reduces the risk of developing degenerative and chronic diseases due to their high antioxidant activity (Alvarez-Parrilla et al. 2011). Therefore, we have identified and quantified critical phenolic compounds in chili processed food products by UPLC-MS and HPLC, respectively. The following eleven phenolics and flavonoids identified in fresh and chili reconstituted products: gallic acid, chlorogenic acid, caffeic acid, syringic acid, catechin, rutin, protocatechuic acid, p-coumaric acid, ferulic acid, quercetin, trans-cinnamic acid shown in Figs. 3a & b and 4a & b. Ferulic acid was predominant and stable amongst all the compounds in the fresh green product (382.91 $\mu\text{g/g}$) and fresh red product (370.21 $\mu\text{g/g}$), followed by trans-cinnamic acid (73.19 $\mu\text{g/g}$), p-coumaric acid (38.50 $\mu\text{g/g}$) and protocatechuic acid (27.50 $\mu\text{g/g}$). Interestingly, the trans-cinnamic acid (68.43 $\mu\text{g/g}$) and catechin (65.66 $\mu\text{g/g}$) were found more in chili reconstituted products. However, catechin content was the highest in red chili reconstituted product on the 0th day. Subsequently, phenolic compound stability was significantly affected in chili reconstituted products compared to fresh products; these changes may be because of degradation and transformation during the drying of chili fruits and the pasteurization process. However, it was earlier reported in kainth products that during pasteurization, chlorogenic acid pathway degradation occurs and transforms into quinic acid and caffeic

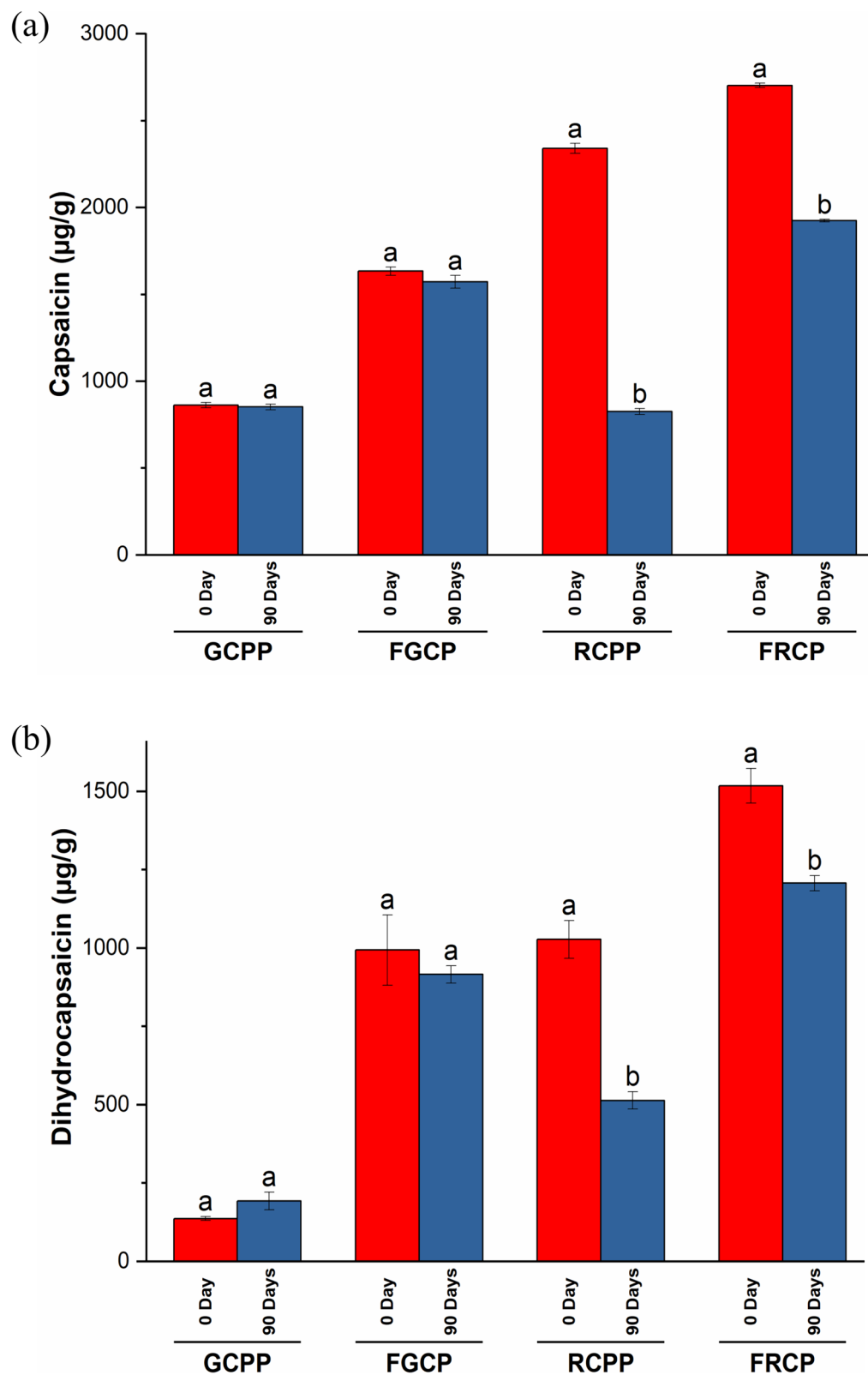


Fig. 2 **a** Capsaicin content **b** Dihydrocapsaicin content of chili product during storage. Here, GCPP=Green chili powder product; FGCP=Fresh green chili product; RCPP=Red chili powder product and FRCP=Fresh red chili product, respectively. Data represented in triplicates as mean $\pm$ SD of three replicates and different letters above the bar indicate statistical differences in the samples whereas similar letters show no significant difference ($p < 0.05$)

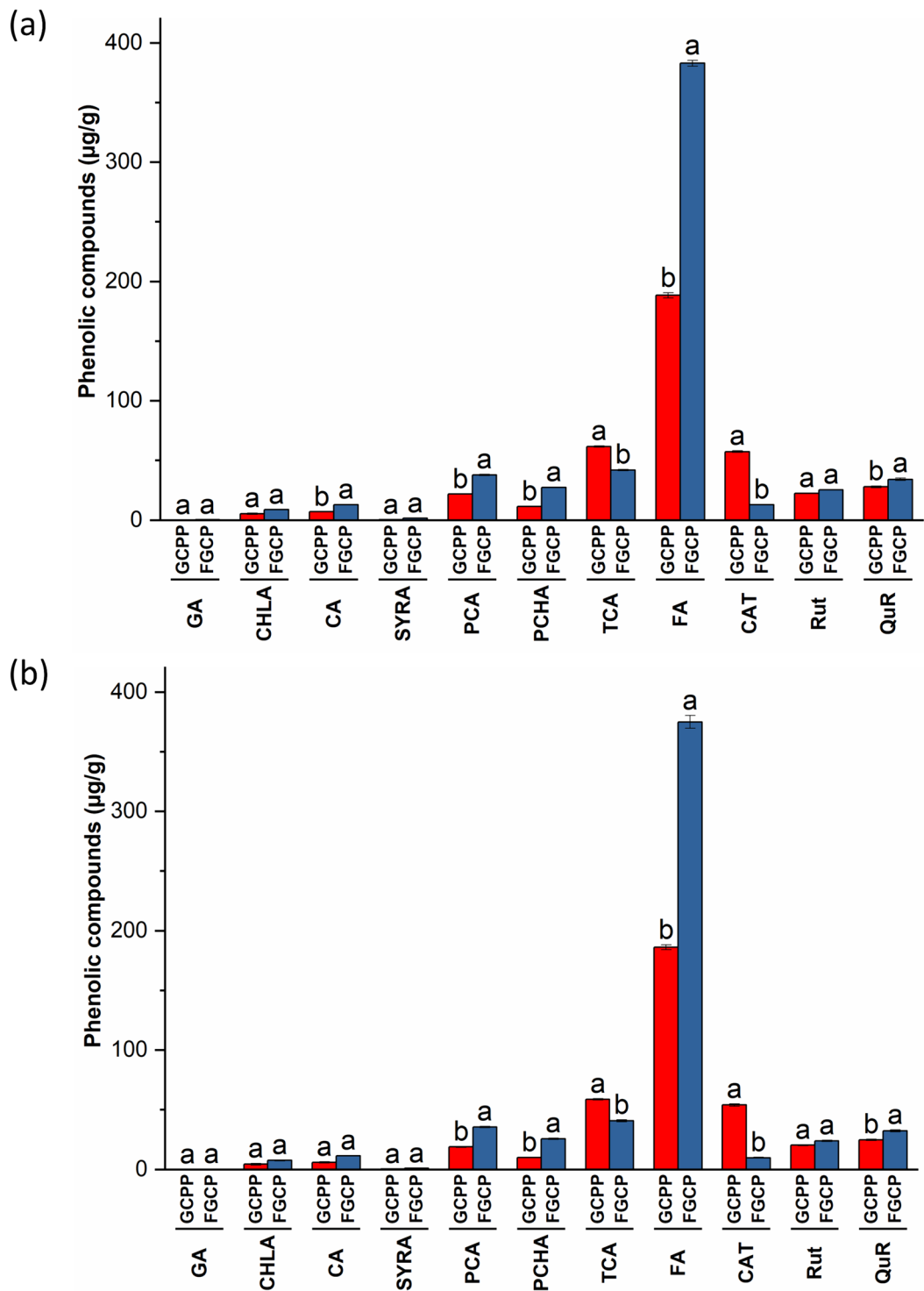


Fig. 3 Phenolic and flavonoid content **a** GCPP and FGCP at 0th day **b** GCPP and FGCP at 90 days during storage. Here, GA=Gallic acid; CHLA=chlorogenic acid; CA=caffeic acid; SYRA=syringic acid; PCA=p-coumaric acid; PCHA=protocatechuic acid; TCA=trans-cinnamic acid; FA=ferulic acid; CAT=catechin; Rut=rutin; QuR=quercetin; GCPP=Green chili powder product and FGCP=Fresh green chili product, respectively. Data represented in triplicates as mean ± SD of three replicates and different letters above the bar indicate statistical differences in the samples, whereas similar letters show no significant difference ($p < 0.05$)

acid as a degradation product of the chlorogenic acid pathway proposed by Moon et al., consistent with the results (Moon & Shibamoto 2010). The trans-cinnamic acid and catechin were the most stable compounds in green and red reconstituted products, even after drying and pasteurization.

In flavonoids, quercetin was observed to be more thermostable compared to rutin. The maximum quercetin content (52.56 $\mu\text{g/g}$) was found in fresh red chili products (Fig. 4). The significant reduction in the content of quercetin and rutin observed during storage was due to glycosylation, hydroxylation, and the transfer of hydrogen atoms from flavonols (Buchner et al. 2006). Currently, it is observed that phenolic compound degradation occurs in chili fruits during the drying process; the integrity of the cell structure will be weakened, causing the compounds to migrate, break down, or degrade as a result of various chemical reactions caused by degradative enzymes, light, and oxygen (Torki-Harchegani et al. 2016).

Yap et al., in their studies, stated that physiochemical reactions such as epimerization, dimerization, oxidation, hydrolysis, and polymerization break down the phenolic compounds during food processing (Yap et al. 2022). The various changes during processing and storage are linked to chemical functionalities like destructions, transformation and modifications, sensitivity to oxidation, and hydrolysis. Furthermore, polyphenolics are heat-labile and acidic; the phenolic rings and nucleophilic properties can also be reduced by combining with other compounds during food processing and storage, leading to oxidation and irreversible structural changes in food products (R  blov   2012).

Correlation between bioactive compounds of green and red chili products

The correlation between the bioactive compounds of red and green chili products will help us to understand the significant positive and negative relations among the bioactive compounds. Therefore, Pearson's correlation test was performed between green and red chili concerning the experimental parameters (capsaicin, dihydrocapsaicin, rutin, protocatechuic acid, chlorogenic acid, syringic acid, trans-cinnamic acid, trans-ferulic acid, quercetin, gallic acid, caffeic acid, catechin, total phenolic and flavonoids, chlorophyll and carotenoids, protein, DPPH,

FRAP, reducing sugars, water activity, pH, moisture, color, particle size, and total soluble solids). A significant positive and negative correlation was observed between the metabolites across green and red chili-prepared products. The correlation plot was constructed using Pearson's correlation matrix in R for green and red chili and is shown in Fig. 5a and b (Allaire 2012; Wei et al. 2021). The color scale for positive and negative correlations is given on the right side of the figures; strong positive correlations are given in dark blue, and strong negative correlations are given in red. The p -value (green & red product Tables S1 and S2) and the correlation values of all the metabolites used in the studies are given in the Additional file (green & red product Tables S3 and S4). The variables with an r^2 value $\leq \pm 0.80$ and a p -value of 0.01 are considered significant for the present analyses.

In the green chili, a significant positive and negative correlation was observed among all the bioactive compounds; protein, acidity, sugars, and p-coumaric acid did not seem to be affected by any of the screened variables. Bioactive compounds like capsaicin, dihydrocapsaicin, pH, rutin, protocatechuic acid, color, chlorogenic acid, syringic acid, trans-cinnamic acid, particle size, ferulic acid, quercetin, gallic acid, lightness, water activity, and FRAP have shown significant positive correlations. Meanwhile, caffeic acid, chlorophyll, catechin, DPPH, phenolic, reducing sugars, moisture, and TSS showed a significant negative correlation. The experimental data of the bioactive compounds' p -value, r^2 , and positive and negative correlation are in Table (S1, S2, S3, and S4).

In red chili products, we also observed various positive and negative correlations among the variables; however, the results of the red chili were completely different from the green chili correlation data. Majorly, capsaicin showed a positive correlation among the various variables in green chili. However, the capsaicin showed no significant correlations with most of the quantified bioactive compounds in red chili. In addition, total inverted sugar, acidity, capsaicin, TSS, and syringic acid also showed no significant correlations among various bioactive compounds. Whereas catechin, chlorogenic acid, rutin, p-coumaric acid, ferulic acid, quercetin, trans-cinnamic acid, and protocatechuic acids showed significant positive and negative correlations.

(See figure on next page.)

Fig. 4 Phenolic and flavonoid content **a** RCPP and FRCP at 0th day **b** RCPP and FRCP at 90 days during storage. Here, GA = Gallic acid; CHLA = chlorogenic acid; CA = caffeic acid; SYRA = syringic acid; PCA = p-coumaric acid; PCHA = protocatechuic acid; TCA = trans-cinnamic acid; FA = ferulic acid; CAT = catechin; Rut = rutin; QuR = quercetin; RCPP = Red chili powder product and FRCP = Fresh red chili product, respectively. Data represented in triplicates as mean $\pm$ SD of three replicates and different letters above the bar indicate statistical differences in the samples, whereas similar letters show no significant difference ($p < 0.05$)

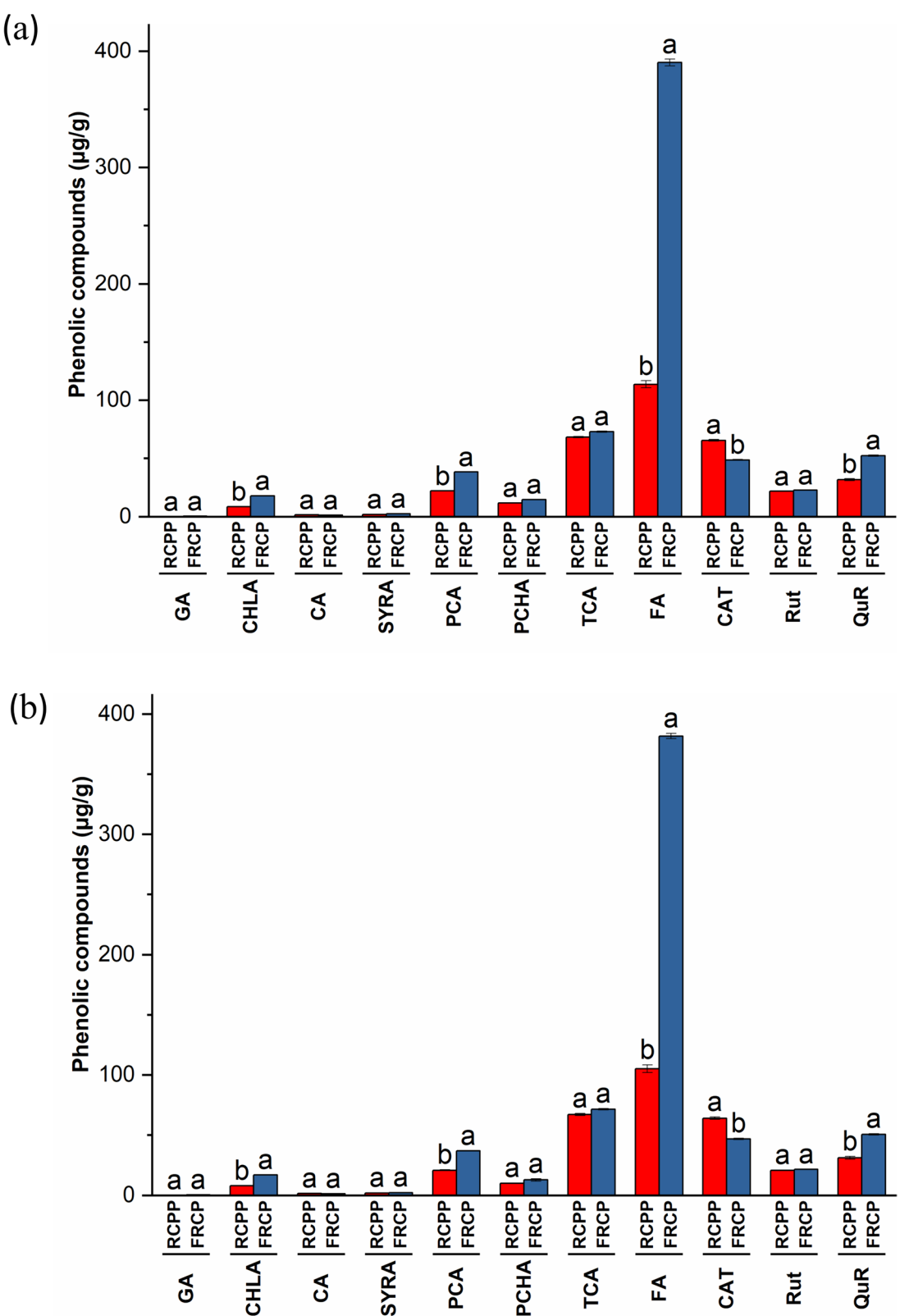


Fig. 4 (See legend on previous page.)

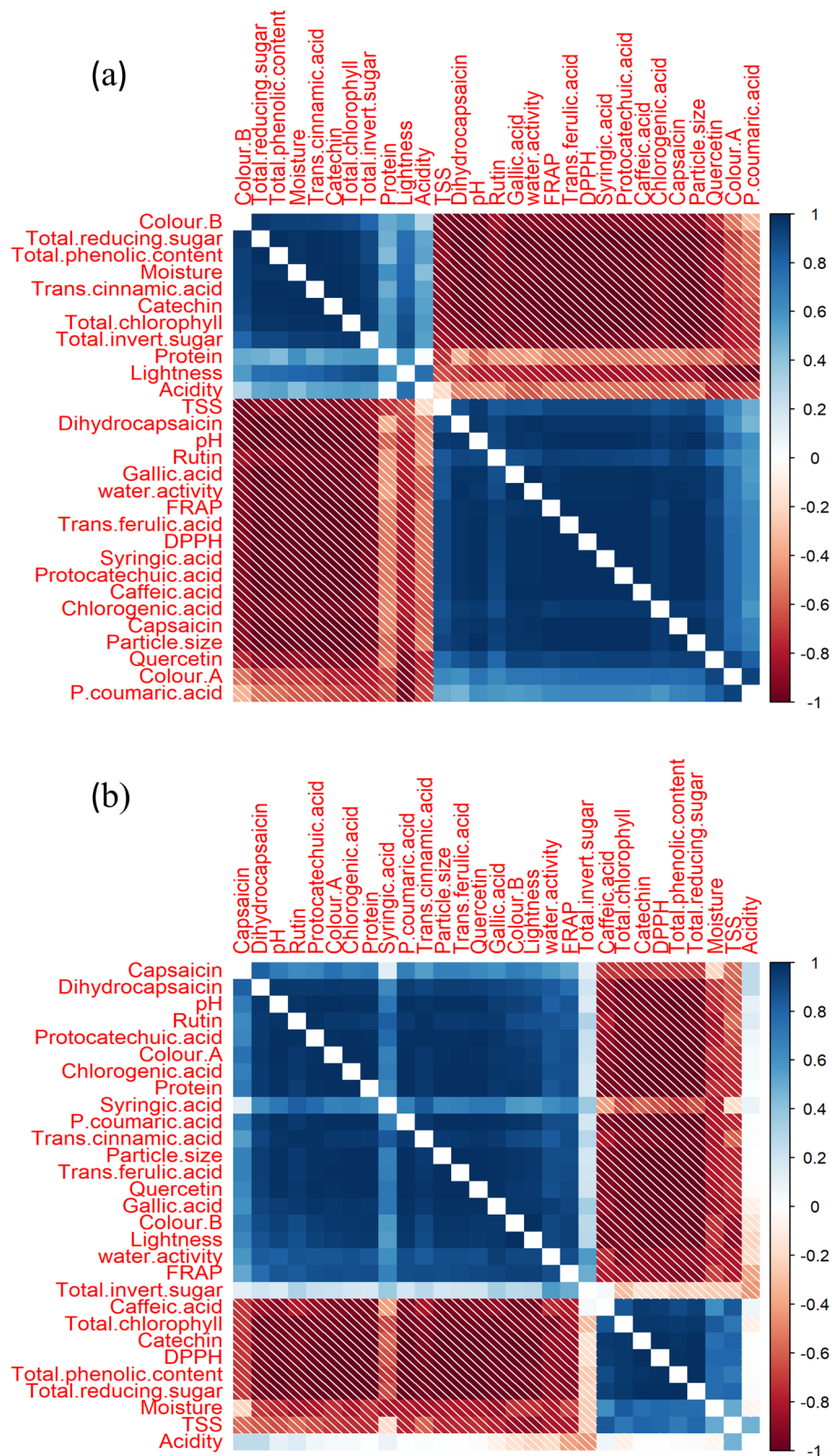


Fig. 5 a & b Correlation matrix of total phenolic, antioxidant activity, total soluble solids, sugar, chlorophyll and carotenoids, capsaicinoids, and phenolic compounds in green and red chili reconstituted products. The color intensity of the matrix shows the strength of the Pearson correlation; positive correlations are in dark blue, and negative correlations are in dark red. The *p*-values and correlation values of both red and green chilies are given in the Additional file 1 (Table S1, S2, S3 and S4)

Microbiological and sensory analysis of quality product

The microbiological analysis was performed in fresh green and red chili reconstituted products for 90 days of storage. No microbial growth, yeast, mold, or bacterial count was detected, and the product is microbiologically safe for consumption during storage.

The sensory evaluation was measured by six appropriate characteristics: appearance, texture, color, spice, mouthfeel, and overall acceptability, as shown in Fig S7. The panel members enjoyed more green and red chili reconstituted products than fresh products due to their texture and taste; overall acceptability was 7.50 ± 0.83 and 8.22 ± 0.92 throughout the storage period. Subsequently, consumers suggested that the chili reconstituted products were suitable for commercial applications.

Conclusion

In this study, chili reconstituted products were developed using the hot-air drying method and compared with the fresh products. Both green and red chili products showed good retention of capsaicinoids, phenolics, color, and antioxidant potential for up to 90 days of storage. Trans-cinnamic acid and catechin were observed to be most stable after drying and food processing in green and red reconstituted products. Protocatechuic acid, trans-cinnamic acid, capsaicin, dihydrocapsaicin, and antioxidant activity positively correlated with the green chili reconstituted products compared to red chili products. In addition, it was also observed that the samples from quality parameters and sensory point of view did not show significant changes during storage. Hence, these research findings offer products that demonstrate health benefits as they contain antioxidants, such as phenolic acids, flavonoids, capsaicinoids, and carotenoids, which help combat oxidative stress and reduce the risk of chronic diseases. The food industry can benefit from this cost-effective technology to manufacture food products. The potential of chili-based food products will be examined for biofunctional properties to treat a range of lifestyle problems under in vivo conditions.

Abbreviations

a*	Red-green
b*	Yellow blue
L*	Lightness
TSS	Total soluble solids
EC50	Effective concentration
Rut	Rutin
CA	Caffeic acid
FA	Ferulic acid
GA	Gallic acid
CAT	Catechin
QuR	Quercetin
SYRA	Syringic acid
CHLA	Chlorogenic acid
PCA	p-coumaric acid
PCHA	Protocatechuic acid

TCA	Trans-cinnamic acid
AAEq	Ascorbic acid equivalent
GAEq	Gallic acid equivalent
GCPP	Green chili powder product
FGCP	Fresh green chili product
RCPP	Red chili powder product
FRCP	Fresh red chili product
FRAP	Ferric reducing antioxidant power
DPPH	2,2-Diphenyl-1-picrylhydrazyl
HPLC	High performance liquid chromatography
UPLC-MS	Ultra-performance liquid chromatography mass spectrometry

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s43014-024-00248-2>.

Additional file 1: Fig S1. Pictorial representation of different concentration of green and red chili premix pack of 100 g (a) & (b). After preparation of fresh and premix reconstituted 1% green and red chili product in 100 g jar (c) & (d) Here, GCPP = Green chilli powder product, FGCP = Fresh green chilli product, RCPP = Red chilli powder product and FRCP = Fresh red chilli product, respectively. **Fig S2.** (a) Standard chromatogram of the mixture of capsaicinoids (1) Capsaicin (2) Dihydrocapsaicin (b) The chromatogram of fresh red chili reconstituted product at 280 nm by HPLC method. **Fig S3.** LC-MS spectrum indicated the presence (a) Quercetin (b) protocatechuic acid and (c) p-coumaric acid. **Fig S4.** LC-MS spectrum indicated the presence (a) Syringic acid (b) trans-cinnamic acid and caffeic acid, and (c) rutin. **Fig S5.** LC-MS spectrum indicated the presence (a) Ferulic acid and catechin (b) chlorogenic acid and (c) gallic acid. **Fig S6.** (a) Standard chromatogram of the phenolic and flavonoids mixture (1) Gallic acid (2) protocatechuic acid (3) Catechin (4) Caffeic acid (5) Chlorogenic acid (6) Syringic acid (7) Rutin (8) p-coumaric acid (9) Ferulic acid (10) Quercetin (11) and t-cinnamic acid (B) The chromatogram of Red chili reconstituted product at 280 nm by HPLC method. **Fig S7.** Sensory profile of fresh green and red chilli reconstituted product. Here, GCPP = Green chilli powder product, FGCP = Fresh green chilli product, RCPP = Red chilli powder product and FRCP = Fresh red chilli product and data represented in triplicates as mean $\pm$ SD of three replicates, respectively.

Acknowledgements

The authors thank the Director, CSIR-CFTRI, Mysore, for providing the research facilities. Authors are thankful to IOE, University of Mysore, Manasagangotri, Mysore 570006 India, for providing LC-MS instrument support.

Authors' contributions

Monisha Arya: Conceptualization, Methodology, Formal Analysis, Investigation, Writing-original draft. Priyanka Kumari: Formal Analysis, Visualization, Data curation. Gyanendra kumar: Formal analysis, Interpretation, Software, Writing - review & editing. Attar Singh Chauhan: Conceptualization, Investigation, Supervision, Interpretation, Writing-review & editing. Parvatam Giridhar: Conceptualization, Resources, Supervision, Writing-review & editing.

Funding

Department of Biotechnology (DBT), Government of India, New Delhi, funded this study under the Institution-based Research Grant (Grant/ Award Number: BT/PR25758/NER/95/1300/2017).

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publications

Not applicable.

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

¹Academy of Scientific and Innovative Research (AcSIR), Ghaziabad 201002, India. ²Plant Cell Biotechnology Department, CSIR–Central Food Technological Research Institute, Mysore 570020, India. ³Traditional Foods and Applied Nutrition Department, CSIR–Central Food Technological Research Institute, Mysore 570020, India.

Received: 21 January 2024 Accepted: 13 March 2024

Published online: 01 November 2024

References

- Alam, M. A., Syazwanie, N. F., Mahmood, N. H., Badaluddin, N. A., Mustafa, K., Alias, N., Aslani, F., & Prodhan, M. A. (2018). Evaluation of antioxidant compounds, antioxidant activities and capsaicinoid compounds of Chili (*Capsicum* sp.) germplasm available in Malaysia. *Journal of Applied Research on Medicinal and Aromatic Plants*, 9, 46–54.
- Allaire, J. (2012). RStudio: Integrated development environment for R. *Boston, MA*, 770(394), 165–171.
- Alvarez-Parrilla, E., De La Rosa, L. A., Amarowicz, R., & Shahidi, F. (2011). Antioxidant activity of fresh and processed Jalapeño and Serrano peppers. *Journal of Agricultural and Food Chemistry*, 59(1), 163–173. <https://doi.org/10.1021/jf103434u>
- Amjadi, S., Ghorbani, M., Hamishehkar, H., & Roufegarinejad, L. (2018). Improvement in the stability of betanin by liposomal nanocarriers: Its application in gummy candy as a food model. *Food Chemistry*, 256, 156–162.
- Besbes, S., Drira, L., Blecker, C., Deroanne, C., & Attia, H. (2009). Adding value to hard date (*Phoenix dactylifera* L.): Compositional, functional and sensory characteristics of date jam. *Food Chemistry*, 112(2), 406–411.
- Bogusz, S., Jr., Libardi, S. H., Dias, F. F., Coutinho, J. P., Bochi, V. C., Rodrigues, D., Melo, A. M., & Godoy, H. T. (2018). Brazilian Capsicum peppers: Capsaicinoid content and antioxidant activity. *Journal of the Science of Food and Agriculture*, 98(1), 217–224.
- Buchner, N., Krumbein, A., Rohn, S., & Kroh, L. W. (2006). Effect of thermal processing on the flavonols rutin and quercetin. *Rapid Communications in Mass Spectrometry: An International Journal Devoted to the Rapid Dissemination of Up-to-the-Minute Research in Mass Spectrometry*, 20(21), 3229–3235.
- Burin, V. M., Arcari, S. G., Bordignon-Luiz, T. M., & Costa, L. L. F. (2011). Determination of some phenolic compounds in red wine by RP-HPLC: Method development and validation. *Journal of Chromatographic Science*, 49(8), 647–651.
- Castrejón, A. D. R., Eichholz, I., Rohn, S., Kroh, L. W., & Huyskens-Keil, S. (2008). Phenolic profile and antioxidant activity of highbush blueberry (*Vaccinium corymbosum* L.) during fruit maturation and ripening. *Food Chemistry*, 109(3), 564–572.
- Chao, E., Tian, J., Fan, L., & Zhang, T. (2022). Drying methods influence the physicochemical and functional properties of seed-used pumpkin. *Food Chemistry*, 369, 130937. <https://doi.org/10.1016/j.foodchem.2021.130937>
- Chapa-Oliver, A. M., & Mejía-Teniente, L. (2016). Capsaicin: From plants to a cancer-suppressing agent. *Molecules*, 21(8), 8. <https://doi.org/10.3390/molecules21080931>
- Civan, M., & Kumcuoglu, S. (2019). Green ultrasound-assisted extraction of carotenoid and capsaicinoid from the pulp of hot pepper paste based on the bio-refinery concept. *LWT*, 113, 108320.
- da Costa, G. M., de Carvalho Silva, J. V., Mingotti, J. D., Barão, C. E., Klososki, S. J., & Pimentel, T. C. (2017). Effect of ascorbic acid or oligofructose supplementation on *L. paracasei* viability, physicochemical characteristics and acceptance of probiotic orange juice. *LWT*, 75, 195–201.
- Fernández-Bedmar, Z., & Alonso-Moraga, A. (2016). In vivo and in vitro evaluation for nutraceutical purposes of capsaicin, capsanthin, lutein and four pepper varieties. *Food and Chemical Toxicology*, 98, 89–99.
- Goel, A., Chauhan, A. S., & Halami, P. M. (2023). Lactiplantibacillus plantarum MCC5231 enriched carrot (*Daucus carota*) nectar: A value-added beverage with enhanced vitamin A. *Journal of Food Measurement and Characterization*, 17(6), 6425–6439. <https://doi.org/10.1007/s11694-023-02104-2>
- González-Zamora, A., Sierra-Campos, E., Pérez-Morales, R., Vázquez-Vázquez, C., Gallegos-Robles, M. A., López-Martínez, J. D., & García-Hernández, J. L. (2015). Measurement of capsaicinoids in chiltepin hot pepper: A comparison study between spectrophotometric method and high-performance liquid chromatography analysis. *Journal of Chemistry*, 2015, 709150. <https://doi.org/10.1155/2015/709150>
- Guan, R., Van Le, Q., Yang, H., Zhang, D., Gu, H., Yang, Y., Sonne, C., Lam, S. S., Zhong, J., Jianguang, Z., Liu, R., & Peng, W. (2021). A review of dietary phytochemicals and their relation to oxidative stress and human diseases. *Chemosphere*, 271, 129499. <https://doi.org/10.1016/j.chemosphere.2020.129499>
- Hemalatha, R., Kumar, A., Prakash, O., Supriya, A., Chauhan, A. S., & Kudachikar, V. B. (2018). Development and quality evaluation of ready to serve (RTS) beverage from cape gooseberry (*Physalis peruviana* L.). *Beverages*, 4(2), 42.
- Henderson, D. E., & Henderson, S. K. (1992). Thermal decomposition of capsaicin. 1. Interactions with oleic acid at high temperatures. *Journal of Agricultural and Food Chemistry*, 40(11), 2263–2268.
- Idrees, S., Hanif, M. A., Ayub, M. A., Hanif, A., & Ansari, T. M. (2020). Chili pepper. In *Medicinal plants of South Asia* (pp. 113–124). Elsevier.
- Irondi, E. A., Olatoye, K. K., Abdulameed, H. T., Aliyu, O. M., Ajani, E. O., & Ogbor, O. F. (2024). Physicochemical, in vitro starch digestibility and sensory characteristics of biofortified yellow maize-cowpea composite flours and biscuits. *Food Production, Processing and Nutrition*, 6(1), 15. <https://doi.org/10.1186/s43014-023-00201-9>
- Khan, M. I., Harsha, P. S., Chauhan, A. S., Vijayendra, S. V. N., Asha, M. R., & Giridhar, P. (2015). Betalains rich *Rivina humilis* L. berry extract as natural colorant in product (fruit spread and RTS beverage) development. *Journal of Food Science and Technology*, 52, 1808–1813.
- Kraft, K. H., Brown, C. H., Nabhan, G. P., Luedeling, E., Luna Ruiz, J. D. J., Coppens d'Eeckenbrugge, G., Hijmans, R. J., & Gepts, P. (2014). Multiple lines of evidence for the origin of domesticated chili pepper, *Capsicum annum*, in Mexico. *Proceedings of the National Academy of Sciences*, 111(17), 6165–6170. <https://doi.org/10.1073/pnas.1308933111>
- Kumar, S. S., Arya, M., Chauhan, A. S., & Giridhar, P. (2020). Basella rubra fruit juice betalains as a colorant in food model systems and shelf-life studies to determine their realistic usability. *Journal of Food Processing and Preservation*, 44(8), e14595.
- Kumar, G., Saad, K. R., Puthusseri, B., Arya, M., Shetty, N. P., & Giridhar, P. (2021). Exogenous serotonin and melatonin regulate dietary isoflavones profoundly through ethylene biosynthesis in soybean (*Glycine max* (L.) Merr.). *Journal of Agricultural and Food Chemistry*, 69(6), 1888–1899. <https://doi.org/10.1021/acs.jafc.0c07457>
- Lichtenthaler, R. G., & Oreld, F. (1983). Rapid high-performance liquid chromatographic method for hydrocarbon class separation in environmental samples. *Journal of Chromatography A*, 282, 501–507.
- Liu, Y., & Nair, M. G. (2010). Capsaicinoids in the hottest pepper Bhut Jolokia and its antioxidant and antiinflammatory activities. *Natural Product Communications*, 5(1), 91–94.
- Maciel, L. G., & Teixeira, G. L. (2022). Plant-based pecan nut cake beverage enrichment of phytochemicals and antioxidant properties using multi-stage block freeze concentration. *Food Production, Processing and Nutrition*, 4(1), 35. <https://doi.org/10.1186/s43014-022-00116-x>
- Martín-Cabrejas, M. A., Aguilera, Y., Pedrosa, M. M., Cuadrado, C., Hernández, T., Díaz, S., & Esteban, R. M. (2009). The impact of dehydration process on antinutrients and protein digestibility of some legume flours. *Food Chemistry*, 114(3), 1063–1068. <https://doi.org/10.1016/j.foodchem.2008.10.070>
- Moon, J.-K., & Shibamoto, T. (2010). Formation of volatile chemicals from thermal degradation of less volatile coffee components: Quinic acid, caffeic acid, and chlorogenic acid. *Journal of Agricultural and Food Chemistry*, 58(9), 5465–5470.
- Naves, E. R., de Ávila Silva, L., Sulpice, R., Araújo, W. L., Nunes-Nesi, A., Peres, L. E., & Zsögön, A. (2019). Capsaicinoids: Pungency beyond Capsicum. *Trends in Plant Science*, 24(2), 109–120.
- Oyaizu, M. (1986). Antioxidative activities of browning reaction prepared from glucosamine. *Japanese Journal of Nutrition*, 44, 307–315.
- Pollini, L., Juan-García, A., Blasi, F., Mañes, J., Cossignani, L., & Juan, C. (2022). Assessing bioaccessibility and bioavailability in vitro of phenolic compounds from freeze-dried apple pomace by LC-Q-TOF-MS. *Food Bioscience*, 48, 101799. <https://doi.org/10.1016/j.fbio.2022.101799>

- Popelka, P., Jevinová, P., Šmejkal, K., & Roba, P. (2017). Determination of capsaicin content and pungency level of different fresh and dried chilli peppers. *Folia Veterinaria*, 61(2), 11–16. <https://doi.org/10.1515/fv-2017-0012>
- Prakash, O., Baskaran, R., Chauhan, A. S., & Kudachikar, V. B. (2022). Effect of heat processing on phenolics and their possible transformation in low-sugar high-moisture (LSHM) fruit products from Kainth (*Pyrus pashia* Buch.-ham ex D. Don) fruit. *Food Chemistry*, 370, 130988.
- Probst, Y. C., Guan, V. X., & Kent, K. (2017). Dietary phytochemical intake from foods and health outcomes: A systematic review protocol and preliminary scoping. *British Medical Journal Open*, 7(2), e013337. <https://doi.org/10.1136/bmjopen-2016-013337>
- Rahman, M. A. (2022). Development of UPLC-MS/MS method and its pharmacokinetic application for estimation of sertraline in rat plasma. *MethodsX*, 9, 101750.
- Ranganna, S. (1986). *Handbook of analysis and quality control for fruit and vegetable products*. Tata McGraw-Hill Education.
- Réblová, Z. (2012). Effect of temperature on the antioxidant activity of phenolic acids. *Czech Journal of Food Sciences*, 30(2), 171–175.
- Sadasivam, S., & Manickam, A. (2008). *Biochemical methods* (3rd ed., pp. 116–117). New Age International (P) Ltd. Publishers.
- Sganzerla, M., Coutinho, J. P., de Melo, A. M. T., & Godoy, H. T. (2014). Fast method for capsaicinoids analysis from *Capsicum chinense* fruits. *Food Research International*, 64, 718–725.
- Sharif, M. K., Ejaz, R., & Pasha, I. (2018). Nutritional and therapeutic potential of spices. In *Therapeutic, probiotic, and unconventional foods* (pp. 181–199).
- Sharma, M., Gehlot, R., Singh, R., & Siddiqui, S. (2012). Changes in chemical constituents and overall acceptability of guava jamun blend RTS drink and squash during storage. *Beverage Food World*, 39(4), 39–42.
- Singh, R., Mangaraj, S., & Kulkarni, S. D. (2006). Particle-size analysis of tomato powder. *Journal of Food Processing and Preservation*, 30(1), 87–98. <https://doi.org/10.1111/j.1745-4549.2005.00050.x>
- Torki-Harchegani, M., Ghanbarian, D., Pirbalouti, A. G., & Sadeghi, M. (2016). Dehydration behaviour, mathematical modelling, energy efficiency and essential oil yield of peppermint leaves undergoing microwave and hot air treatments. *Renewable and Sustainable Energy Reviews*, 58, 407–418.
- Wei, T., Simko, V. R., Levy, M., Xie, Y., Jin, Y., & Zemla, J. R. (2021). package "corrplot": Visualization of a Correlation Matrix. 2017. Version 0.84.
- Xiao, J., & Bai, W. (2019). Bioactive phytochemicals. *Critical Reviews in Food Science and Nutrition*, 59(6), 827–829. <https://doi.org/10.1080/10408398.2019.1601848>
- Yap, E. S. P., Uthairatanakij, A., Laohakunjit, N., & Jitareerat, P. (2022). Influence of hot air drying on capsaicinoids, phenolics, flavonoids and antioxidant activities of 'Super-Hot' chillies. *PeerJ*, 10, e13423.
- Zhou, L., Cao, Z., Bi, J., Yi, J., Chen, Q., Wu, X., & Zhou, M. (2016). Degradation kinetics of total phenolic compounds, capsaicinoids and antioxidant activity in red pepper during hot air and infrared drying process. *International Journal of Food Science & Technology*, 51(4), 842–853.

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.