Heliyon 10 (2024) e37406

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Varietal influence on bioactive compounds and antioxidant activity in chilies during development stages

Most Jesmin Akhter [a], Sumaia Akhter [a], Shanta Islam [a], Md. Sazzat Hossain Sarker [b], S. M. Kamrul Hasan [a,*]

[a] Department of Food Processing and Preservation, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh
[b] Department of Food Engineering and Technology, Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh

ARTICLE INFO

Keywords:
Antioxidant activity
Bioactive compound
Chili
Chlorophyll
Hotness
Maturity stages

ABSTRACT

Numerous cultivars of chili are grown in Bangladesh for their nutritional and sensory attributes, serving as both spices and food items. Among many, indigenous chili cultivars in Bangladesh include Sada Akshi, Kajini, Dhani, and Naga are the important ones. The functional qualities of chili peppers are attributed to the plentiful presence of bioactive substances. Consequently, this study aimed to determine the variations in bioactive compounds, antioxidant activities, and hotness among the pre-mature, mature, pre-ripening, and ripening stages of four distinct chili cultivars. Four different cultivars of chilis at four different maturity stages were collected and analyzed for their antioxidant and bioactive profiles. The findings of the research revealed that all chili varieties exhibited a notable range of vitamin C concentration, ranging from 1.67 to 8.45 mg/g FW during the maturity stages. The values of TPC, TFC, total carotenoids, and chlorophyll *a* and *b* ranged from 16.68 to 46.76 mg GAE/g, 2.80–8.53 mg QE/g, 4.31–85.79 μg/g DW, 2.83–15.54 and 0.74–5.66 μg/g DW on a dry weight basis, respectively. The antioxidant activity was assessed using the FRAP and the DPPH scavenging assay and the values ranged from 142.62 to 311.03 mM Fe (II) Equivalent/100g DW and 216.36–329.52 μM Trolox Equivalent/g DW, respectively. The content of vitamin C, TPC, total carotenoids, and chlorophyll *b* was increased with the stages of development. The hotness of chili also increased with the development stages. However, the antioxidant activity fluctuated during the development stages of chili. Furthermore, the study incorporated the evaluation of physical parameters, such as height, weight, and color attributes concerning chilies. The Naga variety of chili demonstrated the highest level of efficacy when compared to other varieties. The nutritional and physicochemical information of the different cultivars of chili in this study might be useful to the breeders, spice processors, and consumers for desired size, taste, and hotness with health-promoting bioactive compounds, eventually for determining the harvest time.

1. Introduction

Spices have long been recognized as a prominent category of agricultural commodities, dating back to ancient times. These natural

* Corresponding author. Department of Food Processing and Preservation, Hajee Mohammad Danesh Science and Technology University, Dinajpur, 5200, Bangladesh.
E-mail address: hasan.kamrul@hstu.ac.bd (S.M.K. Hasan).

https://doi.org/10.1016/j.heliyon.2024.e37406
Received 15 May 2024; Received in revised form 11 August 2024; Accepted 3 September 2024
Available online 3 September 2024

substances inherently possess a noteworthy quantity of antioxidants and bioactive constituents [1]. Chili (*Capsicum annum* L.) is distinguished as an extensively cultivated spice across the world when compared to other spices [2]. Belonging to the Solanaceae family, chili (*Capsicum* spp.) is an important agricultural food with nutritional, therapeutic, and economic benefits. Chili peppers are extensively cultivated in Bangladesh year-round, encompassing both the winter and summer seasons. In 2021–22, the total area under cultivation of chilies in Bangladesh was 98.34 thousand hectares, yielding around 624.83 thousand tons [3]. Chili is widely used in different food preparations as a natural food coloring and seasoning spice that has stunning color, flavor, and pungency [4]. Chili peppers are a type of fruit that can be ingested in multiple ways, including the consumption of raw or cooked vegetables, and pickles, as well as its utilization in dried form as a spice, condiment, or powder [2,5].

Chili peppers are widely recognized as a significant dietary source of essential nutrients such as vitamin E, pro-vitamin A, vitamin C, capsaicin, and carotenoid properties [6]. The fruits of red chili peppers exhibit a high content of phenolic chemicals, which are known for their antioxidant effects [7]. Moreover, the levels of antioxidants and capsaicinoids in fruits exhibit variation depending on factors such as hybrid characteristics, maturation stage, harvest conditions, agro-climatic variables, storage methods, and processing techniques [8]. For example, Ionică et al. [9] noticed the signification evolution of some bioactive compounds and antioxidant activity among the cultivars during the ripening stages of chilis. The health-beneficial compounds in chili may also vary as a function of development stages, cultivars, and growing seasons [10]. Literature also exists on the evolution of weight, color, firmness, acidity, and taste during growth and development [11]. Nevertheless, color, flavor, and taste determine the acceptability of vegetables [12]. carotenoids in vegetables can be grouped into carotenes (α-carotene and β-carotene) and xanthophylls, such as violaxanthin, neoxanthin, cryptoxanthin, zeaxanthin, lutein, etc. [13]. Chilies are categorized in those vegetables due to the presence of pigments such as chlorophyll (green), anthocyanins (violet/purple), as well as carotenoids including carotene, cryptoxanthin (yellow/orange), zeaxanthin, and lutein [14]. Chilies are also sensitive to flavonoids, which have recently gained popularity due to their antioxidant function [15]. However, vitamin levels, on the other hand, are affected by genotype (variety), maturation stage, harvesting time, postharvest handling, processing, and storage conditions [16,17].

Chili has several biochemical and pharmacological properties, including antioxidants, anti-inflammatory, antiallergenic, and anticarcinogenic properties [18,19]. Chili has considerable medical value and is used to cure a range of human ailments. Scientific studies have demonstrated the potential of capsaicin to induce cytotoxicity in several cancer cell lines, including gastric, breast, lung, prostate, and colon cancer cells [19]. The bioactive compounds of red chili have been used to treat edema, diabetes, low back pain, and acute tonsillitis as a supplementary medicine [18]. However, the levels of the antioxidant, anticancer, and anti-inflammatory properties might vary according to genotype, maturation stage, plant portion ingested, growth, and post-harvest handling circumstances [16].

In Bangladesh, a lot of varieties are grown, among them Sada Akashi (*Capsicum annum*), Kajini (*Capsicum annum*), Dhani (*Capsicum chinense*) and Naga (*Capsicum frutescens*) which are chosen for research purposes because of their availability and popularity. Moreover, they are consumed at the fully mature stage as green chili and the fully ripe stage as red chili. There is very limited research carried out in identifying and comparing the vitamin C content, phenolic compounds, and antioxidant characteristics of green chili with the stage of development. Therefore, the common people in Bangladesh, and eventually in the world are not alert of the health-promoting bioactive compounds and antioxidant activity in different varieties of chili with the stages of development. Accordingly, this study aimed to investigate the physical and proximate composition among the four chili varieties with their four maturity stages including pre-mature, mature, pre-ripening, and ripening stages. The research also assessed the bioactive compounds, antioxidant activity, and the hotness properties of chilies with their various stages of development.

2. Materials and methods

2.1. Solvent and regents

DPPH (2,2-diphenyl-1-picrylhydrazyl), Folin-Ciocalteu reagent (2.0 N), sodium bicarbonate, gallic acid, quercetin, potassium persulphate ($K_2S_2O_8$), acetone, hexane sodium nitrite ($NaNO_2$), and Aluminum chloride hexahydrate ($AlCl_3.6H_2O$) were of analytical grade (Sigma Aldrich, Germany). Methanol (99.9 %) was HPLC grade (Sigma Aldrich). Disodium phosphate, hydrochloric acid (HCl), monosodium phosphate, and sodium hydroxide (NaOH) were also of analytical laboratory grade and purchased from Merck, Germany.

2.2. Chili cultivars and growing conditions

Four varieties of chilies, namely, “Sada Akashi”, “Kajini”, “Dhani” and “Naga” were grown in the HSTU Research field during the late autumn-winter season (November to February). Five plants of each cultivar were used for each of the three replications in the growing season. During development and flowering, plants were irrigated and fertilized once weekly maintaining the same dose for each cultivar. The process of selecting chili fruits was determined by considering factors such as the variety of the chili plant and the specific number of days that had elapsed since blossoming.

2.3. Sample collection and preparation

Chilis with uniformity in shape, color, and size without any imperfection were collected simultaneously at four stages of development from the HSTU Research Field. The development stages of chili include S1 = premature, S2 = mature, S3 = pre-ripening, and S4 = ripening, which can be further defined as S1 = 14 days after flowering, S2 = 18 days after flowering, S3 = 21 days after flowering, and S4 = 23 days after flowering. The chilis were harvested from time to time according to our experimental requirement from the

same cultivating land from the same plant. These collected fruits were cleaned with distilled and tap water to get rid of any dirt or other impurities, and then they were air-dried by blowing. The chili samples were divided into two portions. A chosen portion of the specimens was utilized to ascertain the vitamin C content within 24 h timeframe. The remaining specimens were meticulously fragmented, and sliced, or diced. Subsequently, they were dried at a temperature of 55 ± 5 °C for 12–16 h in a cabinet dryer (Binder GmbH, Germany). The dried samples were grounded by a grinder (Jaipan JFM 1300) and sieved through mesh No. 80 to produce powder samples of these chilies. After being sealed in a plastic container, the acquired powder was retained at −18 °C until its subsequent application.

2.4. Determination of weight and length of chili

A randomly selected sample of 5 chilies from each variety and each maturity stage was weighed using a digital electronic balance (Model AS 220.R2, RADWAG, Poland) with a precision of 0.001 g.

The average fruit length of different chili cultivars of 5 chili fruits at different maturity and ripening stages was determined using a digital caliper (Model 201, DITRON, Sichuan, China) with a precision of 0.02 mm [20].

2.5. Measurements of color parameters of chili

Color measurement was carried out using a colorimeter (BCM 200, Biobase, China). The outcomes are denoted as CIE L*, a*, and b* values [21]. The magnitude of color is measured in units of 'L*', 'a*', and 'b*', with the vertical axis (luminance, L) representing the degree of lightness or darkness. The chromatic portion of the solid is denoted by the values a (+) for redness, a (−) for greenness, b (+) for yellowness, and b (−) for blueness.

2.6. Determination of vitamin C of chili

The vitamin C content in the fresh chilies samples was determined using the AOAC titration method described by Hasan et al. [16], with slight modifications. Concisely, a quantity of 4 g of freshly mashed fruit pulp was combined with a volume of 10 mL of a metaphosphoric acid solution with a concentration of 20 %. Subsequently, the solution underwent filtration using a Whatman no.1 filter paper. Following this, 1 mL of the resulting filtrate was carefully transferred into a small beaker and subsequently combined with 10 mL of distilled water. Afterward, a second beaker was utilized to contain a volume of 2 mL of the diluted suspension. The contents were then agitated with the addition of 2 drops of phenolphthalein. The resulting mixture was titrated against a solution of 2,6-dichlorophenolindophenol until a discernible pink coloration persisted for a duration of approximately 15–20 s. The quantification of vitamin C was determined using the subsequent equation:

$$\text{Vitamin C}\left(\frac{\text{mg}}{\text{g}}\right) = \frac{\text{Volume made up} \times \text{Titre value} \times \text{Dye factor}}{\text{Sample weight} \times \text{Aliquot taken}}$$

2.7. Preparation of chili extracts

The samples were extracted using the methodology outlined by Islam et al. [22] with minor adjustments. A volume of 50 mL of methanol solution containing 80 % methanol was added to 2.5 g of chili powder in a 100 mL glass conical flask; the resultant solid-to-liquid ratio was 1:20 (g/mL). The mixture was subjected to extraction at room temperature in a shaking water bath operating at 100 revolutions per minute (rpm) for a duration of 60 min. Following that, the samples underwent centrifugation at a speed of 4000 revolutions per minute (Model- MF-300, Human Lab Instrument Co., Korea) for 10 min. A 10 mL plastic syringe was utilized to transfer the supernatant, which was then filtered through Whatman no. 1 filter paper before being subjected to analysis.

2.8. Determination of total phenolic content (TPC) of chili extract

The quantification of TPC on the dry basis was conducted using the Folin-Ciocalteu assay, as described in the investigation by Hasan et al. [16], with slight modifications. A 500 μL aliquot of sample extract was combined with 500 μL of Folin–Ciocalteu solution. Subsequently, 1 mL of a 7.5 % sodium bicarbonate solution was introduced to the mixture. Furthermore, the volume was filled to the mark using distilled water, resulting in a solution of 10 mL. Subsequently, the mixture underwent vortexing for a brief duration. The solutions were kept at ambient temperature in a light-restricted environment for a period of 35 min, followed by centrifugation at a rate of 4000 rpm for 10 min. Subsequently, the measurement of the absorbance was analyzed at a wavelength of 750 nm utilizing a spectrophotometer (UV-1800, Shimadzu Scientific Instruments Inc., USA). A standard curve was calibrated using gallic acid at concentrations ranging from 0 to 200 μM. The calibration curve exhibited a linear regression with an r^2 value of 0.9976. The outcomes are expressed in milligrams of gallic acid equivalent per gram of dry sample (mg GAE/g DW).

2.9. Determination of total flavonoid content (TFC) of chili extract

The colorimetric method was used to determine the TFC on the dry basis as described by Islam et al. [22]. The TFC was determined by employing a standard calibration curve for the quercetin range (0–300 μM. The TFC values were then represented as mg quercetin

equivalents per gram (mg QE/g DW) of the sample. Concisely, 1 mL of extract and 0.3 mL of 5 % $NaNO_2$ were added to 4 mL of distilled water in a centrifuge tube. The tubes were then allowed to stand for 5 min and then 0.3 mL of 10 % $AlCl_3$ was added to the reaction mixture and again allowed to stand for 1 min. Finally, 2 mL of 1 M NaOH and 2.4 mL of distilled water were added and vortexed immediately. Following a 5 min centrifugation at 4000 rpm, the containers were left at room temperature for 15 min in the dark. At 510 nm, the absorbance was measured against a negative that was likewise prepared by replacing the extract with methanol.

2.10. Determination of chlorophyll and total carotenoids content of chili extract

The determination of chlorophyll and total carotenoid levels was conducted on the dry basis with minor adjustments to the methodology described by Kamal et al. [2]. The pigments in the sample were simultaneously extracted using an acetone: hexane (4:6) mixture. A spectrophotometer was utilized to measure the optical density of each supernatant at wavelengths of 663, 645, 505, and 453 nm. The estimation of chlorophyll 'a' and chlorophyll 'b' contents (μg/g DW) was performed utilizing the subsequent equations:

Chlorophyll *a* (μg/g) = $0.999A_{663} - 0.0989A_{645}$

Chlorophyll *b* (μg/g) = $-0.328A_{663} + 1.77A_{645}$

The estimation of total carotenoid content was performed in μg/g DW utilizing the subsequent equation:

Total carotenoids (μg β – Carotene Equivalent /g DW) = $0.216A_{663} - 0.304A_{505} + 0.452A_{453}$

Where, A_{663}, A_{645}, A_{505}, and A_{453} are the absorbance at 663,645, 505, and 453 nm, respectively.

2.11. Methods of determination of antioxidant activity

2.11.1. Determination of antioxidant activity in chili extract by DPPH assay

Diphenyl-2-Picrylhydrazyl (DPPH) assay was used to determine the free radical scavenging activity according to the protocol of Islam et al. [22] with some modifications. DPPH can react directly with most of the antioxidants and be captured by them. The reduction of DPPH was measured by the decrease in absorbance at a characteristic wavelength and a determined time during the reaction (30 min). A 1.950 mL DPPH solution was pipetted into the cuvette and the absorbance was measured at 515 nm with a spectrophotometer immediately and after 30 min of adding Trolox solution (0, 5, 10, 15, 25, 30, and 50 μM) to produce a calibration curve. Similarly, the absorbance of 50 μL extracts in the DPPH solution was also measured to evaluate the scavenging capacity of the extract samples. The scavenging ability (%) was calculated as follows:

DPPH radical-scavenging activity (%) = [(A control – A sample)/ A control] × 100

Where A is the absorbance at 515 nm.

2.11.2. Determination of antioxidant activity in chili extract by FRAP assay

The FRAP assay was performed following the method outlined by Hasan et al. [16], with some adjustments. The oxidant utilized in the FRAP assay was generated by combining 2.5 mL of a 10 mM solution of TPTZ in 40 mM HCl, 25 mL of acetate buffer, and 2.5 mL of a 20 mM solution of $FeCl3*H_2O$. The combination is commonly known as the "FRAP reagent". A 50 μL extract/aliquot was transferred into an opaque test tube and subsequently combined with 2.50 mL of FRAP reagent using vortexing it. Following this, the combination was left to undergo a reaction for a duration of 30 min at room temperature. The absorbance of the combination was measured at a wavelength of 593 nm using a spectrophotometer (UV 1900i, Shimadzu, Japan). Three tubes were produced for each extract in triplicate. The FRAP results were quantified in terms of millimole of Ferrous sulphate equivalent per gram of sample (mM Fe (II)/g DW).

2.12. Determination of heat profile (hotness) of powdered chilis by sensory evaluation

A method described by Zhang et al. [23] was used to conduct an effective test to determine the hotness preferences and acceptance of four types of chilis with four distinct maturity levels. All the chili samples of four varieties with four different maturity levels were dried and ground the samples with a grinder. Each panelist was given to taste the ground powder with a slice of guava. The samples underwent numerous evaluations on various days. Supplementary flavors were provided upon request by the panelists. The testing was performed in a clean, odor-free area, and filtered water was offered between each sample to wash the palate. Ratings were presented using a well-matched 5-point hedonic scale: like, 5 = extremely like, 4 = moderately like, 3 = neutral, 2 = moderately dislike, and 1 = extremely dislike. Once the panelist determined the heat profile, it was recorded.

The chili pepper heat profile was established by Ref. [24] with slight modification. This analysis focused on four distinct features: 1) Development, 2) Duration, 3) Location, and 4) Sensation. These attributes were examined to provide descriptive and discriminative information on the heat profile of chili peppers. Development and Duration attributes can be categorized based on their relationship to time. The description is given below-

2.12.1. Chili pepper heat profile components and descriptions

The development of the perception of heat might occur either immediately or after a delay of 5, 15, 30 s, or even longer. The heat sensation duration remained for just a moment, disappearing rapidly, or may last for several minutes and even a few hours. However, the location of heat sensation felt in the lips, the entrance of the mouth, the tip of the tongue, the mid-palate, or the throat was evaluated. Also, the feeling of heat was perceived as either a sharp, pinprick-like sensation or a flat, smearing or painting-like experience. The heat profile component was described in Table 1.

2.13. Statistical analysis

The data underwent examination by a two-way analysis of variance (ANOVA) using the statistical software (SPSS version 26). The data analysis was conducted on three separate replications, and the individual data were presented as means with the corresponding standard deviation. The means were compared using the Duncan test, with a significance level set at $p < 0.05$.

3. Results and discussion

3.1. Physical characteristics of chili

The results of the analysis of the physicochemical properties of four cultivars of chili fruit- Sada Akashi (*Capsicum annum*), Kajini (*Capsicum annum*), Dhani (*Capsicum chinense*) and Naga (*Capsicum frutescens*) cultivated in Bangladesh were shown in Table 2.

3.1.1. Weight and height analysis of chili cultivars

The weight of different stages of individual chili cultivars and an individual stage of different varieties was significantly different ($p < 0.05$). The highest weight was found in the pre-ripening stage of the Naga chili cultivar (2.70 g) and the lowest weight value was found in the pre-mature stage of the Kajini chili cultivar (0.38 g) (Table 2).

The length of an individual variety of chill increased gradually from pre-mature to ripening stages ($p < 0.05$) (Table 2). Kajini variety was the largest chili variety and Naga was the smallest chili variety among the four cultivars of chili. The results vary due to the genomic differences of the chilies [25]. Nonetheless, these outcomes could potentially be attributed to additional factors such as chili cultivars, geographical positioning, soil fertility, and environmental circumstances [16].

3.1.2. Color measurement of chili

A discernible variation in color was noted across the stages of chili pepper development, ranging from premature to ripening, as depicted in Fig. 1. The L*, a*, and b* values of the samples obtained from the analysis conducted on the physical attributes were presented in Table 2. Considering distinct varieties of Sada Akashi, Kajini, Dhani, and Naga cultivars, the L* ($p < 0.05$) values among the various stages of maturity followed the order: S2 > S1 > S3 > S4, S3 > S4 > S1 > S2, S1 > S3 > S4 > S2 and S4 > S3 > S2 > S1, respectively. During ripening, the L values of all chili cultivars decreased, except the Naga cultivar, which was a paler red chili variety than the other three cultivars [26].

The green hue of chili peppers was assessed by the negative values of a*($p < 0.05$) in both premature and mature stages across all kinds. The Kajini had the lowest negative values, indicating a lower level of a certain characteristic. This observation might be attributed to the blackish-green color of the chili variety, as depicted in Fig. 1 and Table 2. During the pre-ripening and ripening stages, the progressive augmentation of the a*-value serves as evidence for the enhanced intensity of red coloration, which is indicative of the fruit's ripeness [20]. The gradual increase of b* value ($p < 0.05$) from immature to maturing stages revealed the yellowness of the chili cultivars as the ripened chili changed color from yellow to red [26].

3.2. Vitamin C content analysis of chili

The amount of vitamin C contents in four types of fresh chili at four different maturity stages are presented in Table 3. The content of vitamin C among the different stages of each variety of chili was significantly ($p < 0.05$) different and showed the rank S4 > S3 > S2 > S1. Considering the variety of chili, Naga (8.45 mg/g FW) and Kajini (8.11 mg/g FW) showed significantly ($p < 0.05$) higher amounts of vitamin C followed by Dhani (6.73 mg/g FW) and Sada Akashi (4.23 mg/g FW). According to Howard et al. [17], the process of ripening has the potential to enhance the ascorbic acid concentration in red peppers by around 30 % when compared to

Table 1
Hotness test of chili.

Rating scale	Development	Duration	Location	Feeling
5. Extremely Like	Immediately	Incredibly Sharp	Middle of Tongue	Dissipates Fairly Rapidly
4. Moderately Like	Very Rapid	Very Sharp	Tip of Tongue	Gradual Loss of Heat
3. Neither Like or Dislike	Moderately Rapid	Moderately Sharp	Middle of Mouth	Dissipates on Tongue
2. Moderately Dislike	Rapid	Sharp	Front of Mouth	Lingers
1. Extremely Dislike	Delayed	Flat	Lips	Dissipates Quickly

Note: significantly different ($p < 0.05$).

Table 2
Physical characteristics of fresh raw chili.

Variety	Stages	Weight (g)	Length (cm)	Color parameter		
				L*	a*	b*
Sada Akashi	S1	$^{B}0.39 \pm 0.08^{c}$	$^{AB}2.14 \pm 0.12^{b}$	^{B} 37.43 ± .45^{b}	^{B}-1.18 ± .35^{c}	^{C}1.10 ± .23^{d}
	S2	$^{C}1.01 \pm 0.04^{a}$	$^{C}3.64 \pm 0.23^{a}$	^{A}39.81 ± .12^{a}	^{B}-1.64 ± .14^{d}	^{C}2.99 ± .08^{c}
	S3	$^{C}0.84 \pm 0.06^{ab}$	$^{B}3.49 \pm 0.21^{a}$	^{D}30.70 ± .53^{c}	^{D}4.18 ± .09^{b}	^{B}6.14 ± 12^{b}
	S4	$^{C}0.79 \pm 0.17^{b}$	$^{B}3.37 \pm 0.08^{a}$	^{D}27.34 ± .13^{d}	^{A}12.14 ± .22^{a}	^{B}6.87 ± .52^{a}
Kajini	S1	$^{A}1.61 \pm 0.10^{a}$	$^{AB}2.11 \pm 0.07^{b}$	^{D}24.79 ± .43^{c}	^{A}-0.83 ± .05^{d}	^{D}-0.78 ± .13^{c}
	S2	$^{B}2.06 \pm 0.28^{a}$	$^{A}6.90 \pm 0.23^{a}$	^{D}23.74 ± .10^{d}	^{A}-0.45 ± .01^{c}	^{D}-1.55 ± .43^{d}
	S3	$^{B}1.94 \pm 0.45^{a}$	$^{A}6.65 \pm 0.41^{a}$	^{C}35.19 ± .66^{a}	^{C}6.58 ± .46^{b}	^{D}2.11 ± .00^{b}
	S4	$^{B}1.80 \pm 0.13^{a}$	$^{A}6.31 \pm 1.18^{a}$	^{C}31.64 ± .10^{b}	^{C}8.88 ± .09^{a}	^{C}3.09 ± .23^{a}
Dhani	S1	$^{B}0.38 \pm 0.01^{b}$	$^{B}1.93 \pm 0.15^{b}$	^{A}43.57 ± 1.78^{a}	^{D}-3.92 ± .45^{c}	^{B}2.81 ± .34^{d}
	S2	$^{C}1.01 \pm 0.33^{a}$	$^{B}4.12 \pm 0.07^{a}$	^{B}38.68 ± .42^{d}	^{C}-6.27 ± .42^{d}	^{B}3.09 ± .09^{c}
	S3	$^{C}0.99 \pm 0.31^{a}$	$^{B}4.01 \pm 0.68^{a}$	^{B}40.35 ± .34^{b}	^{A}8.73 ± .14^{b}	^{C}6.09 ± .03^{b}
	S4	$^{C}0.78 \pm 0.23^{ab}$	$^{B}3.73 \pm 0.44^{a}$	^{B}39.54 ± .10^{c}	^{B}9.54 ± .23^{a}	^{A}9.76 ± .12^{a}
Naga	S1	$^{A}1.39 \pm 0.29^{b}$	$^{A}2.21 \pm 0.19^{b}$	^{C}30.05 ± .17^{d}	^{C}-2.94 ± .02^{c}	^{A}3.85 ± .22^{d}
	S2	$^{A}2.69 \pm 0.17^{a}$	$^{D}2.80 \pm 0.23^{b}$	^{C} 37.87 ± .07^{c}	^{D}-6.68 ± .07^{d}	^{A} 5.09 ± .11^{c}
	S3	$^{A}2.70 \pm 0.28^{a}$	C2.24 ± 0.35^{b}	^{A}40.56 ± .39^{b}	^{B}6.61 ± .09^{b}	^{A}7.42 ± .09^{b}
	S4	$^{A}2.65 \pm 0.18^{a}$	$^{B}3.49 \pm 0.56^{a}$	^{A}42.14 ± .22^{a}	^{D}8.76 ± .22^{a}	^{A}9.76 ± .08^{a}

Note: S1 = pre-mature, S2 = Mature, S3 = Pre-ripening, and S4 = Ripening, Capital alphabets (A, B, C, and D) followed by each column are significantly different ($p < 0.05$) among varieties. Small alphabets (a, b, c & d) followed by each column are significantly different ($p < 0.05$) among different stages.

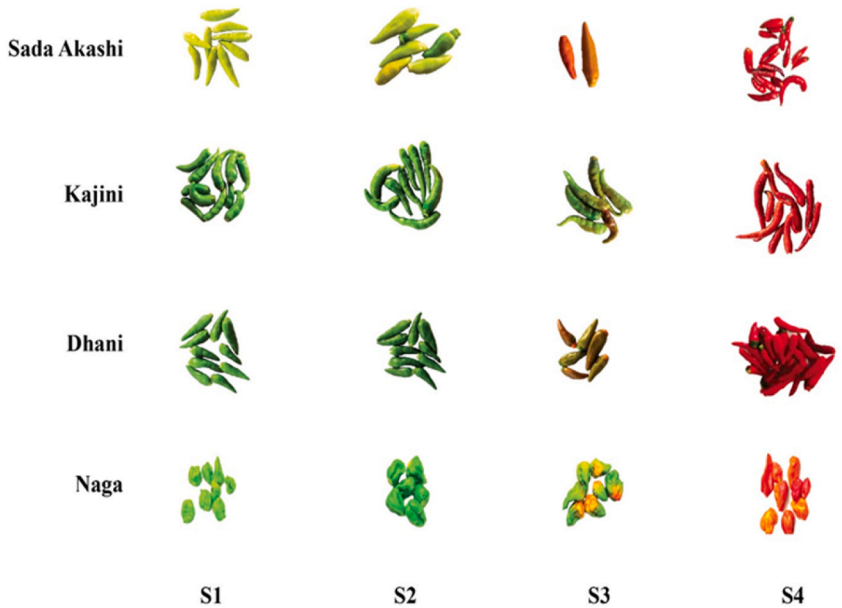

Fig. 1. Four varieties of chilis at premature (S1), mature (S2), pre-ripening (S3), and ripening (S4) stages.

green peppers. The results of this study exhibited equivalence with the data reported in the existing literature by Ionică et al. [9] documenting a similar upward trend with the development stages. The concentration of ascorbic acid demonstrates an upward trend as the fruit undergoes maturation, with this heightened concentration being particularly evident in the red-stage fruit [27]. However, the levels of ascorbic acid in chili may vary due to several factors such as the specific cultivar, genetic factors, phases of ripening, and agro-climatic circumstances [26]. Moreover, the mature stage has elevated amounts as a result of increased light intensities and glucose concentrations, which serve as precursors for ascorbic acid [27]. Nevertheless, the vitamin C content of these chili cultivars is sufficient to satisfy the daily value recommendation of 60 mg/100 g of raw chilies while consumers eat fresh chili as vegetables [20]. Therefore, the addition of pre-ripe and ripe chili to the diet could be of great interest to human health rather than pre-mature and mature chilis.

3.3. Total phenolic contents (TPC) of chili extract

Phenols are widely found in vegetables and grouped into simple phenols [28], numerous phenolic acids, such as hydroxybenzoic

Table 3
Vitamin C, Total Phenolic and Total Flavonoid Content of four verities chili at various maturity stages.

Vitamin C (mg/g)					Total Phenolic Content (mg GAE/g)				Total Flavonoid Content (mg QE/g)			
Variety	Stage				Stage				Stage			
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4
Sada	$^{D}1.67 \pm 0.09^{d}$	$^{D}2.36 \pm .009^{c}$	$^{D}3.16 \pm .002^{b}$	$^{D}4.23 \pm .017^{a}$	$^{C}24.82 \pm .01^{c}$	$^{B}23.40 \pm .12^{d}$	$^{D}25.50 \pm .53^{b}$	$^{C}27.18 \pm .03^{a}$	$^{C}2.81 \pm .02^{c}$	$^{D}2.80 \pm .02^{d}$	$^{C}3.22 \pm .09^{a}$	$^{C}3.08 \pm .08^{b}$
Akashi												
Kajini	$^{C}2.09 \pm 0.01^{d}$	$^{A}3.73 \pm .10^{c}$	$^{A}7.09 \pm .019^{b}$	$^{B}8.13 \pm .011^{a}$	$^{D}18.70 \pm .53^{d}$	$^{C}20.74 \pm .10^{c}$	$^{C}26.25 \pm .56^{b}$	$^{B}27.66 \pm .10^{a}$	$^{D}2.95 \pm .09^{b}$	$^{C}3.14 \pm .03^{a}$	$^{D}2.04 \pm .02^{d}$	$^{D}2.67 \pm .15^{c}$
Dhani	$^{B}2.22 \pm 0.09^{d}$	$^{C}2.89 \pm .016^{c}$	$^{C}5.52 \pm .011^{b}$	$^{C}6.73 \pm .022^{a}$	$^{B}25.38 \pm 1.48^{c}$	$^{D}16.68 \pm .52^{d}$	$^{B}27.76 \pm .17^{a}$	$^{D}26.54 \pm .10^{b}$	$^{B}6.72 \pm .02^{b}$	$^{B}6.89 \pm .01^{a}$	$^{B}6.52 \pm .01^{c}$	$^{B}6.23 \pm .02^{d}$
Naga	$^{A}2.53 \pm 0.07^{d}$	$^{B}3.28 \pm .90^{c}$	$^{B}6.43 \pm .030^{b}$	$^{A}8.45 \pm .011^{a}$	$^{A}40.00 \pm .18^{d}$	$^{A}41.80 \pm .07^{c}$	$^{A}46.76 \pm .49^{a}$	$^{A}43.43 \pm .24^{b}$	$^{A}8.53 \pm .07^{a}$	$^{A}8.28 \pm .09^{d}$	$^{A}8.43 \pm .03^{c}$	$^{A}8.45 \pm .01^{b}$

All values are mean ± SD of three replicates.

Note: S1 = pre-mature, S2 = Mature, S3 = Pre-ripening and S4 = Ripening. $^{a\text{-}d}$ Means followed by different superscript alphabets in each row are significantly different ($P \leq 0.05$) among different stages. $^{A-D}$ means followed by different superscript alphabets in each column are significantly different ($P \leq 0.05$) among different varieties.

acids [29], and hydroxycinnamic acids [30] which are responsible for antioxidant activity [31]. Table 3 displays the phenolic contents of four distinct varieties of chili fruits at different maturity points. Among the varieties of chili, Naga found a significantly ($p < 0.05$) higher value of the TPC than other varieties and a lower value was in Kajini < Dhani < Sada Akashi < Naga. The contents of total phenolic were increased with the development stage of chili in all cultivars, Naga showed a slight decline ($p > 0.05$) in the TPC (43.43 mg GAE/g) at the ripening stage, however, at the pre-ripening stage, Naga had the highest content of TPC (46.76 mg GAE/g), and lowest in Dhani at mature stages (16.68 mg GAE/g). The main factors of variation of phenolic content were plant maturity and the color of the plant [32]. An increasing trend in the total phenolic contents among most cultivars and higher in the red fruit than in the green fruits [7]. However, the levels of TPC contents reported in this study and the stages of development of different varieties of chili species were consistent. Moreover, some of the discrepancies in the content of total phenolics may be attributed to various parameters, including genetic constitution [33], genotypic makeup [34], environmental conditions [35], and analytical methodologies for the extraction of phenolics [9,16].

3.4. Total flavonoid content (TFC) of chili extract

Flavonoids of vegetables can be grouped into flavones [36], flavanones [37], flavonols [38], flavanols [39] anthocyanins, etc., and promote health [40]. The present investigation found that the TFC in the Naga variety was much higher compared to the other kinds, with Dhani exhibiting the second highest concentration, followed by Kalini and Sada Akashi (Table 3). On the other hand, it was observed that the flavonoid concentration in Sada Akashi exhibited a notable lower in comparison to the remaining samples. The overall flavonoid concentration exhibited varying patterns across the development stages of all cultivars, with a notable drop observed as the maturity stages progressed in Naga, the same in the case of the Dhani and Kajini kinds. The concentration of flavonoids in *Capsicum Chinense Jacq*. (Habanero) decreases as the fruit ripens, as reported by Ref. [41]. Similar types of findings were also observed by Chávez-Mendoza et al. [42]. However, there exists a disparity in the behavioral pattern observed in chili that undergoes ripening in various colors. The principal flavonoids detected in chili fruits encompass catechin, epicatechins, luteolin, rutin, kaempferol, quercetin, and myricetin [43]. The variations in flavonoid content, specifically quercetin, and catechin, were influenced by the different chili pepper cultivars as well as development stages [44]. Moreover, the variation in the total flavonoid content among different chili types can be influenced by the solvent utilized, and the extraction method employed along with the inherent characteristics of the plant including its genotype, and cultural practices [16].

3.5. Total carotenoid content of chili

The results shown in Fig. 2 were significantly ($P < 0.05$) varied in the total carotenoid concentration among four distinct chili types and various phases of maturation. The values of total carotenoid content increased gradually in different cultivars of chilis from the pre-mature to the ripening stage. However, the variety Dhani had the highest concentration of total carotenoids during the pre-ripening stage (S3), whereas the variety Sada Akashi displayed the lowest concentration during the pre-mature (S1) and mature stage (S2), as it was more white-yellowish in color (Fig. 1). The carotenoid contents in the pre-ripening and ripening stages exhibited a statistically significant ($p < 0.05$) increase compared to the pre-mature and mature stages. The results of the current study revealed a significant reduction in values in comparison to the previously conducted research by Ref. [45] on bell peppers [46], on green and red peppers, and [5] on fresh green chili. The study conducted by Deepa et al. [6] revealed an apparent rise in the carotenoid

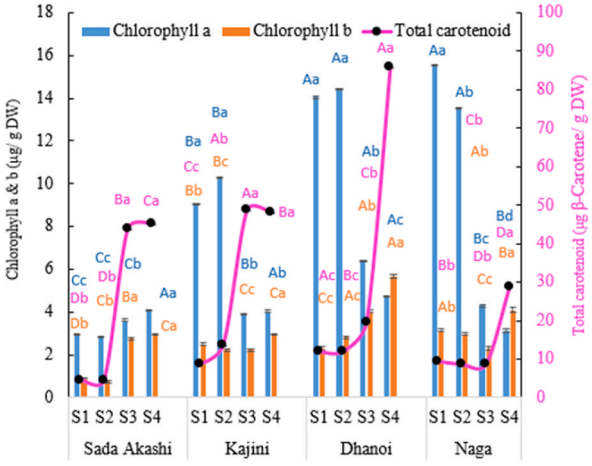

Fig. 2. Total carotenoid content, Chlorophyll 'a' and Chlorophyll 'b' of four verities chili at different maturity stages.
Note: S1 = pre-mature, S2 = Mature, S3= Pre-ripening, and S4 = Ripening. All values are mean ± SD of three replicates. $^{a\text{-}d}$ Means followed by different superscript alphabets in each row are significantly different ($P \leq 0.05$) among different stages. $^{A-D}$ Means followed by different superscript alphabets in each column are significantly different ($P \leq 0.05$) among different varieties.

concentrations of peppers as they progressed toward the red stage of maturation. The vibrant and unique red hue of mature chili peppers was attributed to their abundant carotenoid pigment content, which not only imparts color to food but also offers significant health advantages as total carotenoid has antioxidant, anti-inflammatory, and anticancer functions [47].

3.6. Chlorophyll 'a' and chlorophyll 'b' content of chili

The amounts of chlorophyll 'a' and chlorophyll 'b' were found to range from 2.83 to 15.54 μg/g and from 0.73 to 5.68 μg/g, respectively (Fig. 2). The values of chlorophyll 'a' increased only in Sada Akashi but the chlorophyll 'b' increased in all cultivars of chili during the development stages (from the pre-mature to ripening stages). The study noticed a decreasing trend of chlorophyll 'a' in Kajini, Dhani, and Naga cultivars with stages of development. Furthermore, the decreased values of chlorophyll 'a' and increased values of chlorophyll 'b' indicated the green color of chili changed to a red color (Fig. 1) and increased the content of total carotenoids (Fig. 2). The chlorophyll 'a' levels observed in the current study were slightly greater compared to the levels reported by Kamal et al. [2] in their investigation of green and red chili powder. Nevertheless, minor variations were also seen in the levels of chlorophyll 'b' when compared to the findings presented by Kamal et al. [2]. These changes are likely associated with varietal, environmental growing conditions, such as light exposure, temperature, and soil characteristics along with methodological variations.

3.7. Antioxidant activities of chili extract

Antioxidant compounds in foods contribute to inhibiting the oxidative damage caused by reactive oxygen species, thus preserving nutritional quality [48]. The assessment of antioxidant capacity holds significant importance in determining the potential health benefits associated with a certain dietary product. The antioxidant activity of chili at various stages of development was assessed by two in-vitro assays: namely DPPH and FRAP.

3.7.1. DPPH scavenging activity of chili extract

Fig. 3 displays the scavenging activity percentages (μM Trolox Equivalent/g DW)) of chilies at various stages of maturation. The present investigation revealed that the variety Naga had the significantly highest DPPH scavenging activity, whereas the remaining three varieties showed comparatively lower levels of activity. The DPPH scavenging activity throughout the maturation stages is progressively increasing in the Sada Akashi variety, however, a slight decreased and increased trend was observed in other varieties. Due to the metabolic activity of chili during the maturation process, antioxidant compounds such as phenolic, carotenoid, and vitamin C were broken down, thus resulting in decreased and increased trends in antioxidant activity [16]. In a study conducted by Alam et al. [7], it was observed that the DPPH scavenging activity of several peppers, namely Cili Padi Rangup, Cili Padi Centil, and Cili Padi Putih, exhibited a significant rise. According to the findings of Wangcharoen & Motasuk [49], the DPPH radical scavenging capabilities of fresh green and red bird chili were measured to be 3.06 and 2.39 mg vitamin C Equivalent/g, respectively. The inclusion of the challenges associated with comparing outcomes reported in the literature for DPPH testing is crucial. These challenges arise from variations in methodologies employed and the diverse approaches utilized to present the data. Furthermore, the variation in the antioxidant activity observed can be attributed to the composition and concentration of antioxidant chemicals present in the peppers [50].

3.7.2. FRAP of chili extract

The FRAP assay examined four potential chili varieties for their antioxidant activity (Fig. 3). The technique known as FRAP is

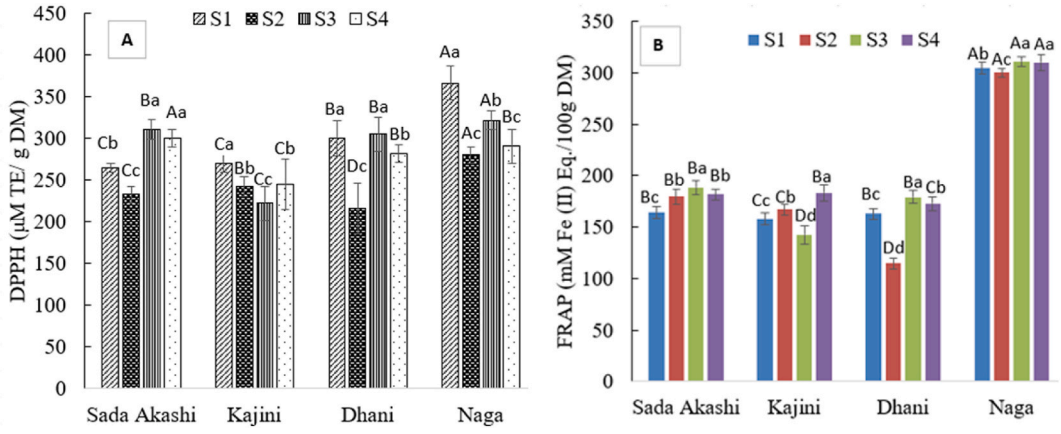

Fig. 3. DPPH (A) and FRAP (B) scavenging activity of four varieties of chili at different maturity stages.
Note: S1 = pre-mature, S2 = Mature, S3 = Pre-ripening, and S4 = Ripening, Capital alphabets (A, B, C, and D) followed by each bar are significantly different ($p < 0.05$) among different varieties. Small alphabets (a, b, c & d) followed by each bar are significantly different ($p < 0.05$) among different stages.

commonly employed to assess the capacity of the food matrix to chelate metal ions [51]. The FRAP activity (mM Fe (II)/100g) in chili ranged from 164.23 to 188.51 in variety Sada Akashi, 142.71 to 183.50 in variety Kajini, 114.53 to179.42 in variety Dhani, and 300.13 to 317.73 in variety Naga. The variations in antioxidant activity seen among different chili cultivar extracts can be attributed to the distinct chemical compositions present in each sample [7]. Nevertheless, the majority of the inquiries have indicated that the antioxidant activity exhibits a rising pattern as the fruit reaches maturation [52]. Evidently, the FRAP value increased from the immature to the ripening stage. The utilization of FRAP analysis during the ripening stage of peppers serves to highlight the significant nutritional value associated with the consumption of these peppers in a ripe, red, or yellow state. In a study conducted by Grozeva et al. [53], it was observed that red hot peppers had a higher level of antioxidant activity compared to green hot peppers. In addition, the authors discovered that chili peppers with a greater degree of ripeness possessed a greater level of antioxidant activity [8]. The potential reason for this phenomenon can be attributed to the enhanced level of capsaicin found in the chili. However, Huei et al. [54] agreed that the TPC has a substantial correlation with FRAP antioxidant activity. The relationship between TPC and antioxidant levels in various chili cultivars was also demonstrated in Tables 3 and 4. The variability of results obtained from the FRAP approach can be attributed to the solubility characteristics of the chemicals employed in the analysis. Furthermore, the efficacy of the extraction process was determined by a multitude of extraction parameters, encompassing solvent type, concentration, temperature, duration of extraction, solvent-to-solid ratio, and additional determinants [51].

The findings in this study revealed that the stage of development and variety of chili greatly affected the antioxidant activities along with vitamin C, TPC, TFC (Table 3), and total carotenoid content (Fig. 2) which might be due to the genetic factor [55]. However, the selected chili varieties were excellent sources of the mentioned bioactive compounds with antioxidant properties. Among the varieties, Naga represented the highest amount of bioactive compounds and antioxidant activity. The pre-ripening and ripening stages exhibited the highest vitamin C, TPC, TFC (Table 3), and total carotenoid content (Fig. 2). Therefore, the study suggests that the chili should be harvested either at pre-ripening or ripening stage for better retention of bioactive compounds for the consumption with optimal nutritional benefits and medicinal uses.

3.8. Sensory evaluation for hotness of powdered chili

Sensory evaluation was performed by organoleptic heat test using skilled panelists in four varieties of chili at different maturity stages are presented in Fig. 4. The four factors are (i) development, ii) duration, iii) location, and iv) feeling) of heat profile have the potential to delineate the primary sensory attributes of chili peppers, hence enabling discrimination among different chili cultivars. The sensory panel has ascertained the hotness or heat qualities associated with each chili variety that has been enumerated. By employing the heat profile descriptors (development, duration, location, and feeling), certain individuals demonstrated a greater capacity to precisely articulate the sensory characteristics associated with the spiciness of chili. The hotness or heat profile in all varieties of chili in the pre-ripening and ripening stages is extremely higher than in other maturation stages. Accordingly, the heat profile in the pre-mature stage was: i) moderately rapid, ii) moderately sharp, iii) middle of the mouth, and iv) dissipated on the tongue; whereas, in the pre-ripening and ripening stages were i) immediately, ii) incredible sharp, iii) middle of tongue and iv) dissipated fairly rapid except in Sada Akashi and Dhani. The mature stage represented a mixed behavior heat pattern among the varieties. In Bangladesh, the hotness or heat profile of chili with a character of the immediately, incredibly sharp, middle of the tongue and dissipated fairly rapidly is the required quality. Notably, the highest amount of hotness is found in the Naga variety followed by Dhani, Kajini, and Sada Akashi. In the Naga variety, the hotness is developed immediately on the middle and tip of the tongue with incredible sharp duration and fairly rapid feelings during the maturation stages. This could be due to the presence of a high amount of bioactive compounds in the Naga variety (Table 3 and Fig. 3) compared with other varieties. Ku et al. [56] reported that the levels of capsaicin and dihydrocapsaicin are subject to the pungency in the rep peppers, and Korean red peppers with high amounts of capsaicin rated high heat profile. Moreover, Guzmán, & Bosland [24] also reported that capsaicinoids provide the feeling of heat or hotness when consumed by consumers. Nevertheless, the genetics, cultivar, cultivation practices, maturity of the fruit, and environmental factors (differentiation of the total heat level of chili peppers is attributed to a combination of chili peppers [24].

3.9. Correlation of chili's hotness, vitamin C, TPC, TFC, antioxidant activity, and stages of development

A Pearson correlation analysis ($p < 0.05$) was conducted to examine the relationship between the hotness of chili peppers and bioactive molecules, antioxidant activities, and the stages of development. (Table 4). The hotness profile of chilis had a strong positive correlation with the content of vitamin C, TPC, TFC, antioxidant activity, and stages of development with a correlation coefficient (r) of

Table 4
Pearson's correlation coefficient analysis among chili hotness, vitamin C, TPC, TFC, antioxidant activity, and stages of development.

Variables	Hotness	Vitamin C	TPC	TFC	Antioxidant activity	Development stages
Hotness	1					
Vitamin C	0.906	1				
TPC	0.584	0.801	1			
TFC	0.860	0.732	0.675	1		
Antioxidant actiivty	0.936	0.711	0.742	0.779	1	
Development stages	0.943	0.994	0.754	0.766	0.778	1

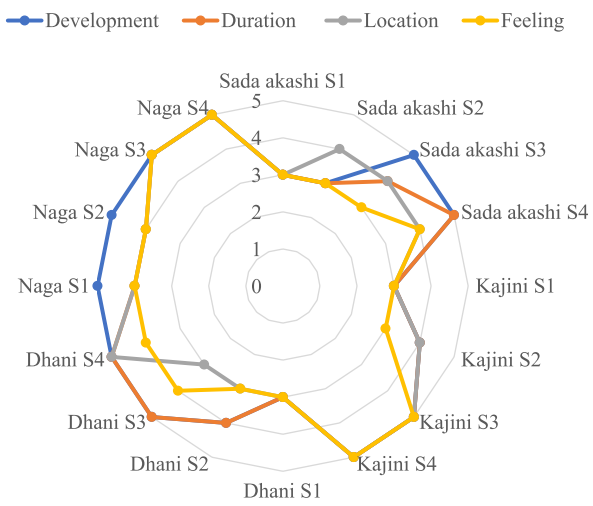

Fig. 4. Sensory evaluation of four varieties of chilis at different maturity stages. Note: S1 = pre-mature, S2 = Mature, S3= Pre-ripening and S4= Ripening.

0.90, 0.58, 0.86, 0.93, and 0.94 respectively. The correlation data indicated a robust positive association among TPC, TFC, and antioxidant properties (with data from FRAP). These results are consistent with the work that found significant positive associations between capsaicinoids, TPC, and TFC molecules and antioxidant properties [10]. Another study also found a significant association (r = 0.90) between the DPPH scavenging activities and the levels of TPC, capsaicin, and ascorbic acid in Capsicum [57]. The stages of development showed the strongest correlation with hotness, vitamin C, TPC, TFC, and antioxidant activity of chili with a correlation coefficient (r) of 0.94, 0.99, 0.75, 0.76, and 0.77 respectively. This indicated that the ripe chili is suitable for use and consumption with the possibility of high bioactive compounds and their functional properties.

4. Conclusion

In conclusion, this comprehensive study investigated the bioactive compound profiles and antioxidant capacities of four distinct chili varieties at varying stages of maturity. This finding revealed that vitamin C levels were predominantly influenced by the specific cultivars and ripening stages, with Naga chili exhibiting the highest total carotenoids and total phenolic content. Notably, the Naga variety also displayed elevated flavonoid content, antioxidant activities, and vitamin C content, underscoring its remarkable potential as a rich source of antioxidants. All the varieties of chilis revealed maximum bioactive compounds and antioxidant activities in their pre-ripening stages. So, the optimal benefits for nutritional and medicinal purposes will be fulfilled if the chilis can be harvested and consumed in the pre-ripening stages. Also, this research underlines the significance of selecting antioxidant-rich foods in combating chronic diseases like diabetes and cancer. Further research should focus on isolating and identifying the specific compounds responsible for the potent antioxidant properties observed in chili pepper samples with analytical techniques like HPLC or GC-MS. Moreover, a DNA sequencing study can be conducted to identify any genetic markers that can be explained the reason for high concentrations of specific bioactive compounds among the cultivars.

Data share statement

Data will be made available on request.

Ethics statement

All relevant rules, guidelines, and regulations were followed, and consent was sought and obtained from all panelists/participants for sensory analysis in this study.

CRediT authorship contribution statement

Most Jesmin Akhter: Writing – original draft, Supervision, Data curation, Conceptualization. **Sumaia Akhter:** Writing – original draft, Formal analysis, Data curation. **Shanta Islam:** Writing – original draft, Methodology, Investigation, Formal analysis, Conceptualization. **Md. Sazzat Hossain Sarker:** Writing – review & editing, Supervision, Conceptualization. **S. M. Kamrul Hasan:** Writing – review & editing, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:S M Kamrul Hasan reports financial support was provided by Bangladesh Academy of Sciences. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was supported by the Bangladesh Academy of Sciences (BAS), Bangladesh under the BAS-USDA Endowment Program (Grant # 4th Phase BAS-USDA HMDSTU CR - 11). The authors also acknowledge Hajee Mohammad Danesh Science and Technology University, Dinajpur- 5200, Bangladesh, for partially supporting this work (HSTU/IRT/3358, Year: 2021–2022, Serial number: 91).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e37406.

References

[1] T. Hudáková, M. Šuleková, J. Tauchen, M. Šemeláková, M. Várady, P. Popelka, Bioactive compounds and antioxidant activities of selected types of chilli peppers, Czech J. Food Sci. 41 (3) (2023), https://doi.org/10.17221/45/2023-CJFS.
[2] M.M. Kamal, M.R. Ali, M.M. Rahman, M.R.I. Shishir, S. Yasmin, M.S.H. Sarker, Effects of processing techniques on drying characteristics, physicochemical properties and functional compounds of green and red chilli (C apsicum annum L.) powder, Journal of food science and technology 56 (2019) 3185–3194, https://doi.org/10.1007/s13197-019-03733-6.
[3] BBS, Statistical Yearbook of Bangladesh, Bangladesh Bureau of Statistics, Dhaka: Ministry of Planning, 1980 to 2022.
[4] O. Ayob, P.R. Hussain, P. Suradkar, F. Naqash, S.A. Rather, S. Joshi, Z.R.A. Ahmad Azad, Evaluation of chemical composition and antioxidant activity of Himalayan Red chilli varieties, LWT 146 (2021), https://doi.org/10.1016/j.lwt.2021.111413.
[5] M.S.H. Sarker, S.M.K. Hasan, M.G. Aziz, M.T. Islam, S.M.R. Azam, S. Roy, M.N. Ibrahim, The effect of processing treatments on the shelf life and nutritional quality of green chilli (capsicum annuum l.) powder, Pertanika J. Trop. Agric. Sci. 35 (4) (2012).
[6] N. Deepa, C. Kaur, B. George, B. Singh, H.C. Kapoor, Antioxidant constituents in some sweet pepper (Capsicum annuum L.) genotypes during maturity, LWT 40 (1) (2007), https://doi.org/10.1016/j.lwt.2005.09.016.
[7] M.A. Alam, N.F. Syazwanie, N.H. Mahmod, N.A. Badaluddin, K. Mustafa, N. Ain, Alias, F. Aslani, M.A. Prodhan, Evaluation of antioxidant compounds, antioxidant activities and capsaicinoid compounds of Chili (Capsicum sp.) germplasms available in Malaysia, Journal of Applied Research on Medicinal and Aromatic Plants 9 (2018), https://doi.org/10.1016/j.jarmap.2018.02.001.
[8] R. Alonso-Villegas, R.M. González-Amaro, C.Y. Figueroa-Hernández, I.M. Rodríguez-Buenfil, The genus capsicum: a review of bioactive properties of its polyphenolic and capsaicinoid composition, Molecules 28 (10) (2023), https://doi.org/10.3390/molecules28104239.
[9] M.E. Ionică, V. Nour, I. Trandafr, Bioactive compounds and antioxidant activity of hot pepper fruits at different stages of growth and ripening, J. Appl. Bot. Food Qual. 90 (2017), https://doi.org/10.5073/JABFQ.2017.090.029.
[10] H. Bae, G.K. Jayaprakasha, K. Crosby, K.S. Yoo, D.I. Leskovar, J. Jifon, B.S. Patil, Ascorbic acid, capsaicinoid, and flavonoid aglycone concentrations as a function of fruit maturity stage in greenhouse-grown peppers, J. Food Compos. Anal. 33 (2) (2014), https://doi.org/10.1016/j.jfca.2013.11.009.
[11] S. Martínez, A. Curros, J. Bermúdez, J. Carballo, I. Franco, The composition of Arnoia peppers (Capsicum annuum L.) at different stages of maturity, Int. J. Food Sci. Nutr. 58 (2) (2007) 150–161, https://doi.org/10.1080/09637480601154095.
[12] U. Sarker, S. Oba, Color attributes, betacyanin, and carotenoid profiles, bioactive components, and radical quenching capacity in selected Amaranthus gangeticus leafy vegetables, Sci. Rep. 11 (1) (2021) 11559, https://doi.org/10.1038/s41598-021-91157-8.
[13] U. Sarker, S. Oba, Leaf pigmentation, its profiles and radical scavenging activity in selected Amaranthus tricolor leafy vegetables, Sci. Rep. 10 (1) (2020.) 18617, https://doi.org/10.1038/s41598-020-66376-0.
[14] T. Hernández-Pérez, M. del R. Gómez-García, M.E. Valverde, O. Paredes-López, Capsicum annuum (hot pepper): an ancient Latin-American crop with outstanding bioactive compounds and nutraceutical potential. A review, Compr. Rev. Food Sci. Food Saf. 19 (6) (2020), https://doi.org/10.1111/1541-4337.12634.
[15] S.M.K. Hasan, M. Scampicchio, G. Ferrentino, M.O. Kongi, L.D. Hansen, Thermodynamics and kinetics of the Fenton reaction in foods, Thermochim. Acta 682 (2019), https://doi.org/10.1016/j.tca.2019.178420.
[16] S.M.K. Hasan, M.R. Kabir, M.R. Kabir, M.R. Islam, M.J. Akhter, J.Y. Moury, Proximate composition, minerals, phytochemicals, and functional activities of jujube fruits grown in Bangladesh, Journal of Agriculture and Food Research 8 (a) (2022), https://doi.org/10.1016/j.jafr.2022.100302.
[17] L.R. Howard, R.T. Smith, A.B. Wagner, B. Villalon, E.E. Burns, Provitamin A and ascorbic acid content of fresh pepper cultivars (Capsicum annuum) and processed jalapeños, J. Food Sci. 59 (2) (1994), https://doi.org/10.1111/j.1365-2621.1994.tb06967.x.
[18] N. Gurnani, M. Gupta, D. Mehta, B.K. Mehta, Chemical composition, total phenolic and flavonoid contents, and in vitro antimicrobial and antioxidant activities of crude extracts from red chilli seeds (Capsicum frutescens L.), J. Taibah Univ. Sci. 10 (4) (2016), https://doi.org/10.1016/j.jtusci.2015.06.011.
[19] A. Szallasi, Capsaicin and cancer: guilty as charged or innocent until proven guilty? Temperature 10 (1) (2023) https://doi.org/10.1080/23328940.2021.2017735.
[20] O.R.A. Don, P.A. Ahi, S.N. Gnanguy, L.P. Kouame, Physical, nutritional characteristics and bioavailability of a chili pepper cultivar (Capsicum annuum) grown in eastern Côte d'Ivoire, Int. J. Food Sci. Nutr. Eng. 9 (3) (2019) 49–56, 1010.5923/j.food.20190903.01.
[21] K. Hasan, R. Islam, M. Hasan, S. Hossain, S. Mehedi, H. Biswas, Effect of alginate edible coatings enriched with black cumin extract for improving postharvest quality characteristics of guava (Psidium guajava L) fruit, Food Bioprocess Technol. 15 (9) (2022) 2050–2064, https://doi.org/10.1007/s11947-022-02869-2.
[22] M.R. Islam, A.R. Haque, M.R. Kabir, M.M. Hasan, K.J. Khushe, S.M.K. Hasan, Fruit by-products: the potential natural sources of antioxidants and α-glucosidase inhibitors, J. Food Sci. Technol. 58 (5) (2021) 1715–1726.
[23] J. Zhang, C. Wang, J. Wang, Y. Yang, K. Han, E.P. Bakpa, J. Li, J. Lyu, J. Yu, J. Xie, Comprehensive fruit quality assessment and identification of aroma-active compounds in green pepper (Capsicum annuum L.), Front. Nutr. 9 (2023), https://doi.org/10.3389/fnut.2022.1027605.
[24] I. Guzmán, P.W. Bosland, Sensory properties of Chile pepper heat – and its importance to food quality and cultural preference, Appetite 117 (2017), https://doi.org/10.1016/j.appet.2017.06.026.
[25] Q. Qanytah, D.S. Anggono, W. Broto, Characterization of two new varieties of curly chili (Capsicum annuum L.) for quality standard, in: Proceedings of the International Symposium Southeast Asia Vegetable 2021 (SEAVEG 2021), 2023, https://doi.org/10.2991/978-94-6463-028-2_12.

[26] Z. Ye, Z. Shang, M. Li, X. Zhang, H. Ren, X. Hu, J. Yi, Effect of ripening and variety on the physiochemical quality and flavor of fermented Chinese chili pepper (Paojiao), Food Chem. 368 (2022), https://doi.org/10.1016/j.foodchem.2021.130797.
[27] T.L. Olatunji, A.J. Afolayan, The suitability of chili pepper (Capsicum annuum L.) for alleviating human micronutrient dietary deficiencies: a review, Food Sci. Nutr. 6 (8) (2018), https://doi.org/10.1002/fsn3.790.
[28] N. Jahan, U. Sarker, M.M.H. Saikat, M.M. Hossain, M.G. Azam, D. Ali, K.S. Golokhvast, Evaluation of yield attributes and bioactive phytochemicals of twenty amaranth genotypes of Bengal floodplain, Heliyon 9 (9) (2023) e19644, https://doi.org/10.1016/j.heliyon.2023.e19644.
[29] U. Sarker, S. Ercisli, Salt eustress induction in red amaranth (Amaranthus gangeticus) augments nutritional, phenolic acids and antiradical potential of leaves, Antioxidants 11 (12) (2022) 2434, https://doi.org/10.3390/antiox11122434.
[30] U. Sarker, S. Oba, Phenolic profiles and antioxidant activities in selected drought-tolerant leafy vegetable amaranth, Sci. Rep. 10 (1) (2020) 18287, https://doi.org/10.1038/s41598-020-71727-y.
[31] U. Sarker, S. Oba, R. Ullah, A. Bari, S. Ercisli, S. Skrovankova, J. Mlcek, Nutritional and bioactive properties and antioxidant potential of Amaranthus tricolor, A. lividus, A viridis, and A. spinosus leafy vegetables, Heliyon 10 (9) (2024) e30453, https://doi.org/10.1016/j.heliyon.2024.e30453.
[32] E. Martínez-Ispizua, M.R. Martínez-Cuenca, J.I. Marsal, M.J. Díez, S. Soler, J.V. Valcárcel, Á. Calatayud, Bioactive compounds and antioxidant capacity of Valencian pepper landraces, Molecules 26 (4) (2021), https://doi.org/10.3390/molecules26041031.
[33] U. Sarker, M.A. Iqbal, M.N. Hossain, S. Oba, S. Ercisli, C.C. Muresan, R.A. Marc, Colorant pigments, nutrients, bioactive components, and antiradical potential of danta leaves (Amaranthus lividus), Antioxidants 11 (6) (2022.) 1206, https://doi.org/10.3390/antiox11061206.
[34] U. Sarker, S. Oba, W.F. Alsanie, A. Gaber, Characterization of phytochemicals, nutrients, and antiradical potential in slim amaranth, Antioxidants 11 (6) (2022) 1089, https://doi.org/10.3390/antiox11061089.
[35] M.N. Hossain, U. Sarker, M.S. Raihan, A.A. Al-Huqail, M.H. Siddiqui, S. Oba, Influence of salinity stress on color parameters, leaf pigmentation, polyphenol and flavonoid contents, and antioxidant activity of Amaranthus lividus leafy vegetables, Molecules 27 (6) (2022) 1821, https://doi.org/10.3390/molecules27061821.
[36] U. Sarker, M.N. Hossain, S. Oba, S. Ercisli, R.A. Marc, K.S. Golokhvast, Salinity stress ameliorates pigments, minerals, polyphenolic profiles, and antiradical capacity in lalshak, Antioxidants 12 (1) (2023) 173, https://doi.org/10.3390/antiox12010173.
[37] U. Sarker, M.N. Hossain, M.A. Iqbal, S. Oba, Bioactive components and radical scavenging activity in selected advance lines of salt-tolerant vegetable amaranth, Front. Nutr. 7 (2020) 587257, https://doi.org/10.3389/fnut.2020.587257.
[38] U. Sarker, S. Oba, Polyphenol and flavonoid profiles and radical scavenging activity in leafy vegetable Amaranthus gangeticus, BMC Plant Biol. 20 (2020) 1–12, https://doi.org/10.1186/s12870-020-02700-0.
[39] U. Sarker, S. Oba, Nutraceuticals, phytochemicals, and radical quenching ability of selected drought-tolerant advance lines of vegetable amaranth, BMC Plant Biol. 20 (2020) 1–16, https://doi.org/10.1186/s12870-020-02780-y.
[40] U. Sarker, Y.P. Lin, S. Oba, Y. Yoshioka, K. Hoshikawa, Prospects and potentials of underutilized leafy Amaranths as vegetable use for health-promotion, Plant Physiol. Biochem. 182 (2022) 104–123, https://doi.org/10.1016/j.plaphy.2022.04.011.
[41] A.M. Vera-Guzmán, J.L. Chávez-Servia, J.C. Carrillo-Rodríguez, M.G. López, Phytochemical evaluation of wild and cultivated pepper (Capsicum annuum L. And C. Pubescens ruiz & pav.) from oaxaca, Mexico, Chil. J. Agric. Res. 71 (4) (2011), https://doi.org/10.4067/s0718-58392011000400013.
[42] C. Chávez-Mendoza, E. Sanchez, E. Muñoz-Marquez, J.P. Sida-Arreola, M.A. Flores-Cordova, Bioactive compounds and antioxidant activity in different grafted varieties of bell pepper, Antioxidants 4 (2) (2015), https://doi.org/10.3390/antiox4020427.
[43] M. Ghasemnezhad, M. Sherafati, G.A. Payvast, Variation in phenolic compounds, ascorbic acid and antioxidant activity of five coloured bell pepper (Capsicum annum) fruits at two different harvest times, J. Funct.Foods 3 (1) (2011), https://doi.org/10.1016/j.jff.2011.02.002.
[44] S. Bal, A.B. Sharangi, T.K. Upadhyay, F. Khan, P. Pandey, S. Siddiqui, M. Saeed, H.J. Lee, D.K. Yadav, Biomedical and antioxidant potentialities in chilli: perspectives and way forward, Molecules 27 (19) (2022), https://doi.org/10.3390/molecules27196380.
[45] R. Sharma, V.K. Joshi, M. Kausha, Effect of pre-treatments and drying methods on quality attributes of sweet bell-pepper (Capsicum annum) powder, J. Food Sci. Technol. 52 (6) (2015), https://doi.org/10.1007/s13197-014-1374-y.
[46] G.E. Igbokwe, C.O. Anagonye, Determination of β–carotene & vitamin C content of fresh green pepper (capsicum annnum), fresh red pepper (Capsicum annum) and fresh tomatoes (Solanumly copersicum) fruits, The Bioscientist Journal 1 (1) (2013).
[47] A. Ponder, K. Kulik, E. Hallmann, Occurrence and determination of carotenoids and polyphenols in different paprika powders from organic and conventional production, Molecules 26 (10) (2021), https://doi.org/10.3390/molecules26102980.
[48] H.S.M. Kamrul, A. Schiraldi, M.S. Cosio, M. Scampicchio, Food and ascorbic scavengers of hydrogen peroxide, Journal of Thermal Analysis and Calorimetry 125 (2) (2016) 729–737.
[49] W. Wangcharoen, W. Motasuk, Antioxidant capacity changes of bird Chili (Capsicum frutescens Linn.) during hot air drying, Kasetsart Journal - Natural Science 43 (1) (2009).
[50] I.G. Hwang, Y.J. Shin, S. Lee, J. Lee, S.M. Yoo, Effects of different cooking methods on the antioxidant properties of red pepper (Capsicum annuum L.), Preventive Nutrition and Food Science 17 (4) (2012), https://doi.org/10.3746/pnf.2012.17.4.286.
[51] Z. Leng, B. Zhong, H. Wu, Z. Liu, A. Rauf, S. Bawazeer, H.A.R. Suleria, Identification of phenolic compounds in Australian-grown bell peppers by liquid chromatography coupled with electrospray ionization-quadrupole-time-of-flight-mass spectrometry and estimation of their antioxidant potential, ACS Omega 7 (5) (2022), https://doi.org/10.1021/acsomega.1c06532.
[52] M. Hamed, D. Kalita, M.E. Bartolo, S.S. Jayanty, Capsaicinoids, polyphenols and antioxidant activities of Capsicum annuum: comparative study of the effect of ripening stage and cooking methods, Antioxidants 8 (9) (2019), https://doi.org/10.3390/antiox8090364.
[53] S. Grozeva, I. Tringovska, A.N. Nankar, V. Todorova, D. Kostova, Assessment of fruit quality and fruit morphology in androgenic pepper lines (Capsicum annuum L.), Crop Breeding, Genetics and Genomics 2 (1) (2020), https://doi.org/10.20900/cbgg20200005.
[54] C.S. Huei, A. Azlan, A. Ismail, N.H. Shafie, S. Sultana, Antioxidant and anti-obesity properties of local chilies varieties in Malaysia, J. Food Sci. Technol. 57 (10) (2020), https://doi.org/10.1007/s13197-020-04400-x.
[55] S.K. Hasan, M.R. Islam, M.M. Rahman, M.R. Islum, M.M. Esha, Exploring the nutraceutical potential: evaluating the nutritional and bioactive functions of five pomelo fruit varieties in Bangladesh, Heliyon 10 (11) (2024) e31786, https://doi.org/10.1016/j.heliyon.2024.e31786.
[56] K.H. Ku, K.A. Lee, J.B. Park, Physicochemical properties and sensory evaluation for the heat level (hot taste) of Korean red pepper powder, Preventive Nutrition and Food Science 17 (1) (2012), https://doi.org/10.3746/pnf.2012.17.1.029.
[57] F. Menichini, R. Tundis, M. Bonesi, M.R. Loizzo, F. Conforti, G. Statti, B. De Cindio, P.J. Houghton, F. Menichini, The influence of fruit ripening on the phytochemical content and biological activity of Capsicum chinense Jacq. cv Habanero, Food Chem. 114 (2) (2009), https://doi.org/10.1016/j.foodchem.2008.09.086.