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Tuz Stresi Uygulanan Biber Türlerinde (*Capsicum annuum* L., *Capsicum baccatum* L. ve *Capsicum chinense* Jacq.) Meyve Olgunlaşma Dönemlerinde Meydana Gelen Fizikokimyasal ve Renk Değişimleri

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ÖZ

Bu çalışmada, tuz stresinin üç biber türünün (*Capsicum annuum* L., *Capsicum baccatum* L. ve *Capsicum chinense* Jacq.) farklı olgunlaşma aşamalarındaki fizikokimyasal ve renk özellikleri üzerindeki etkisi incelenmiştir. Biberler yeşil, alacalı ve kırmızı olgunlaşma aşamalarında 0 mM, 50 mM ve 100 mM NaCl'e maruz bırakılmıştır. Çalışma, tuzlu topraklarda biber üretiminin sürdürülebilirliği için kritik öneme sahiptir. Farklı biber türlerinin tuz stresine tepkileri yeterince araştırılmadığından, bu boşluğu doldurmayı amaçlamaktadır. Sonuçlar, tuz stresinin nem içeriği, toplam kül, pH, titre edilebilir asitlik, su aktivitesi ve renk parametrelerini önemli ölçüde etkilediğini göstermiştir. *C.chinense* en yüksek nem içeriğine ve su aktivitesine sahipken, *C.annuum* daha yüksek toplam kül içeriği ve pigment yoğunluğu (ASTA değeri) göstermiştir. Meyveler olgunlaştıkça nem içeriği azalmış ve toplam kül içeriği artmıştır. Tuz stresi su aktivitesi, pH ve titre edilebilir asitlikte azalmaya neden olurken, yüksek tuz konsantrasyonları su kaybının artmasına ve meyve kalitesinde düşüşe yol açmıştır. Ayrıca, tuz stresi renk parametrelerini ve ASTA değerlerini azaltarak karotenoid pigment sentezinin baskılandığını göstermiştir. Çalışma, tuz stresi biberin fizyolojik ve biyokimyasal kalitesini olumsuz etkilediğinden, tuza toleranslı biber çeşitlerinin geliştirilmesinin önemini vurgulamaktadır. Bu bulgular, özellikle tuzlu topraklara sahip bölgelerde sürdürülebilir biber üretimi için uygun agronomik stratejilerin ve dikkatli çevresel izlemenin gerekli olduğunu göstermektedir. Sonuçlar, tuz stresinin biber meyve kalitesini etkilediği mekanizmalar hakkında değerli bilgiler sağlamakta ve mahsulün dayanıklılığını artırmak için yollar önermektedir.

Anahtar Kelimeler: Biber, tuz stresi, olgunluk dönemi, fizikokimyasal özellikler

Physicochemical and Color Changes During Fruit Ripening in Pepper Species (*Capsicum annuum* L., *Capsicum baccatum* L. and *Capsicum chinense* Jacq.) Exposed to Salt Stress

ABSTRACT

This study examines the impact of salt stress on the physicochemical and color characteristics of three pepper species (*Capsicum annuum* L., *Capsicum baccatum* L. and *Capsicum chinense* Jacq.) at different ripening periods. Peppers were exposed to 0 mM, 50 mM and 100 mM NaCl during the green, breaking and red ripening periods. The study is critical for the sustainability of pepper production in saline soils. Since the responses of different pepper species to salt stress have not been sufficiently investigated, it aims to fill this gap. The results showed that salt stress significantly influenced moisture content, total ash, pH, titratable acidity, water activity and color parameters. *C.chinense* had the highest moisture content and water activity, while *C.annuum* demonstrated a higher total ash content and pigment density (ASTA value). As fruits ripened, moisture content decreased and total ash content increased. Salt stress caused reductions in water activity, pH and titratable acidity, with high salt concentrations leading to increased water loss and a decline in fruit quality. Furthermore, salt stress reduced color parameters and ASTA values, indicating suppressed carotenoid pigment synthesis. The study highlights the importance of developing salt-tolerant pepper varieties, as salt stress negatively impacts the physiological and biochemical quality of peppers. These findings suggest that appropriate agronomic strategies and careful environmental monitoring are essential for sustainable pepper production, particularly in areas with saline soils. The results provide valuable insights into the mechanisms through which salt stress affects pepper fruit quality and suggest avenues for improving crop resilience.

Keywords: Pepper, salt stress, ripening period, physicochemical properties

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INTRODUCTION

Solanaceae is a large family of plants that play a crucial role in agricultural and health affairs, made up of important genus that include potato, tomato, eggplant, pepper, tobacco and petunia. It has been estimated that this large family contains about 100 genus and 2,500 species, all varying in the biological and economic importance of the species within it [1]. Some bioactive compounds in Solanaceae plants include phenolic compounds, alkaloids, saponins, terpenes and lipids, among others [2]. These are known to have protective effects due to the richness of antioxidant properties and vitamin content against several diseases including cancer [3]. Capsicum genus is one of the economically and nutritionally valuable families, native to Central and South America. The wide usage of peppers in culinary, medicinal and industrial applications spread across the world [4]. Among the 43 species in the Capsicum genus, there are only five: *C.chinense*, *C.baccatum*, *C.frutescens*, *C.pubescens* and *C.annuum* that are of commercial and nutritional importance. Peppers contain lots of vitamins A, C and E, carotenoids, phenolic compounds as well as capsaicinoids, which are very beneficial to human health [5].

The process of fruit ripening is a complex phenomenon that results from the biochemical changes in the plant and directly affects the flavor, color, aroma, texture and nutritional value of the fruit [6]. In this regard, there are remarkable changes in the levels of phenolic compounds and antioxidant activities during ripening [7]. The maturity of pepper fruit at ripening significantly influences the nutritive quality of ascorbic acid, total phenolic content, chlorophyll and carotenoids [8].

Environmental stress factors, especially salt stress, have a high influence on the quality of fruits. The mechanisms affecting plant growth and development under salt stress are mainly due to osmotic and ionic effects on water uptake and nutrient balance [9]. In salt-sensitive plants such as peppers, the stress evokes physiological and biochemical changes in the plant, leading to variations in phenolic compounds, antioxidant capacity and other key biochemical properties. The literature includes enough reports on modifications that occur in biochemical features of pepper fruits under saline stress [10, 11]. This study aims to investigate the effects of salt stress on the physicochemical and color characteristics of *C.annuum*, *C.baccatum* and *C.chinense* fruits at different ripening periods. Pepper fruits were subjected to 0 mM (control), 50 mM and 100 mM NaCl concentrations during their green, breaking and red ripening periods. The objective is to evaluate how salt stress influences the physiological, biochemical and color properties of pepper fruits at various growth periods and to assess changes in fruit quality under stress conditions.

MATERIALS AND METHODS

Cultivation of Plant Materials and Salt Stress Conditions

The plant materials used in this study were cultivated in greenhouses at the Agricultural Practice and Research Center of Kilis 7 Aralık University between March and September. To achieve a broad range of biological diversity, pepper plants of different genetic backgrounds and geographical origins were selected. Three different pepper species were chosen for this purpose: *Capsicum baccatum* L. (PI439381), *Capsicum chinense* Jacq. (PI152225) and *Capsicum annuum* L. (PI636147).

For seedling cultivation, a sufficient quantity of seeds from the three pepper species (*C.baccatum*, *C.annuum* and *C.chinense*) were sown in March 2022. The sowing was carried out in greenhouses equipped with an automatic irrigation system and heating apparatus and the seeds were left to germinate. The seeds were planted in 384-cell trays filled with a 3:1 mixture of peat and perlite (EC: 0.26 dS/m, pH: 6.2). After the plants developed their fourth true leaves, they were transplanted into 10-liter pots in May 2022. The transplanting was done in acclimation greenhouses, with only one plant per pot.

The water-holding capacity (field capacity) of the growth medium used in the pots was determined by gravimetric method. Field capacity was computed as the saturation weight minus the dry weight after which the growth medium is completely saturated with water. From the measures derived, field capacity for the 10-liter pots was approximately 2 liters of water. Irrigation was maintained at 1.5 liters to ensure it stayed at 75% of its field capacity and it was applied as per the plant's demand in regular intervals during the growing season. The experiment was laid out in a Randomized Complete Block Design (RCBD) with three replications. Eight plants were included in each replication. This design was therefore necessary to ascertain the impacts of the salt treatments and avoid the risk of coming up with invalid results due to statistics. Salt treatments were made using irrigation with solutions of NaCl at different molarities. The control was irrigated with water without salt (0 mM NaCl). The other molarities was irrigated with 50 mM and 100 mM NaCl, respectively. During all the fruiting period until all plants bore completely red fruits, the samples were taken at all ripening periods-green, breaking and riped red. The concentrations of 50 mM and 100 mM NaCl were selected based on previous studies that examined the effects of salt stress on pepper plants [12, 13, 14]. These levels represent moderate to high salinity conditions commonly found in agricultural soils affected by salinization. Moreover, these concentrations were chosen to ensure comparability with existing research and to observe clear physiological and biochemical responses in the plants.

Physicochemical Analyses

Moisture content, total ash, pH, titratable acidity and water activity were some of the physicochemical properties determined in the pepper species. All these analyses were done in triplicates on the pepper species to compare the physicochemical profile at different ripening periods.

Moisture Content

Moisture content was determined by the loss in weight of each pepper sample after drying at a predetermined temperature. Pepper samples of the three different species taken were at various degrees of ripening. One-gram portions were then oven dried to constant weight at a temperature of 105°C. The process lasted for 2 to 3 hours and the weights before and after drying were recorded. The moisture content was calculated as the percentage from the weight loss ($g.g^{-1}$). All analyses were carried out in triplicate for each sample [15].

Total Ash Content

For total ash content determination, 2 g of the pepper samples was taken in porcelain crucibles and incinerated in a muffle furnace within a temperature range of 500-550°C. The samples were incinerated until they turned into ash; this took between 2-3 hours. The samples were allowed to cool inside a desiccator until constant weight was obtained. The total ash content was calculated as a percentage in relation to the weight difference prior and post incineration ($g.g^{-1}$). All measurements were taken in triplicate for better precision [16].

pH and Titratable Acidity

Fresh pepper samples were mechanically homogenized to extract the juice, which was separated from the solid components. The pH of the pepper juice was measured using an ST20 model pH meter. Each sample was measured three times and the average values were recorded [16]. For titratable acidity analysis, 10 mL of pepper juice was titrated with 0.1 N NaOH solution until a pH of 8.1 was reached, with phenolphthalein as an indicator. The titratable acidity was calculated as a percentage of citric acid and all measurements were repeated three times.

Water Activity (aw)

The water activity (aw) of the pepper samples was measured using an Amtast brand portable water activity meter. Three measurements were taken for each sample and the average water activity values were recorded for each sample [17].

Color Analysis of Fruits

The color analysis of the pepper samples was conducted at different ripening periods using both colorimetric and spectrophotometric methods. Colorimetric measurements were performed with a Techkon colorimeter in the L*, a* and b* color space. Spectrophotometric analysis followed the protocol [18]. In this method, 0.1 g of pepper sample was extracted in 100 mL of acetone for 16 hours at room temperature. After the extraction period, absorbance was measured at 460 nm against acetone using a Libra S70 spectrophotometer. The color intensity (ASTA) was calculated using the following formula:

ASTA = Absorbance × 16.4 × If / weight

(Where If represents the instrument factor, calculated by dividing the theoretical absorbance of the standard color solution (0.001 M $K_2Cr_2O_7$ and 0.09 M $(NH_4)_2Co(SO_4)_2.6H_2O$ in 1.8M H_2SO_4) at 460 nm by the actual absorbance measured. All analyses were performed in triplicate for each sample).

Statistical Analyses

All data obtained from the experiment were subjected to variance analysis using JMP 14 software. Multiple comparison tests were conducted using Student's t-test. A significance level of 0.05 was set for all parameters and results with $p \leq 0.05$ were considered statistically significant.

RESULTS AND DISCUSSION

Physicochemical Analyses

Moisture Content

The results indicated significant differences in moisture content among the pepper species (Table 1). *C.chinense* had the highest average moisture content (94.99%), followed by *C.baccatum* (91.71%) and *C.annuum* (89.95%). These findings suggest that the genetic makeup and water-holding capacities of these species vary. The tropical origin of *C.chinense* may contribute to its higher water retention capacity. When examined by ripening period, the green period had the highest moisture content (95.79%), which decreased to 93.18% during the breaking period and further dropped to 91.44% at the red period. This suggests that as pepper fruits mature, they lose water and the cell walls become denser. Green fruits, having less mature cell structures, tend to retain more water, while water loss naturally increases as the fruit ripens.

In the salt stress treatments, the control group exhibited the highest average moisture content (94.87%), which decreased to 91.31% with 50 mM NaCl treatment and further decreased to 90.74% with 100 mM NaCl treatment. These results depict the influence of salt stress on the moisture content. High salt concentrations change the osmotic balance within plants, which results in cell water loss. This leads to a decrease in the plant's water holding ability and hence leads to low moisture content [19].

Table 1. Comparison of the effects of salt stress treatments on physicochemical properties according to pepper species and plant ripening periods

	Moisture (%, g.g^{-1})	Total ash (%, g.g^{-1})	pH	Titration acidity (citric acid, %)	Water activity (aw)
Species (S)	**	***	**	***	*
C.annuum	89.95 C	5.91 C	5.81 C	0.65 A	0.94 B
C.baccatum	91.71 B	6.82 B	5.94 B	0.53 B	0.97 A
C.chinense	94.99 A	7.59 A	6.18 A	0.27 C	0.98 A
Fruit Ripening Period (RP)	***	**	**	***	**
Green	95.79 x	6.31 z	5.79 y	0.54 x	0.99 x
Breaking	93.18 y	6.72 y	5.95 x	0.47 y	0.97 x
Red	91.44 z	7.83 x	6.01 x	0.12 z	0.93 y
Salt Treatments (ST)	***	***	***	***	*
0 mM NaCl (Control)	94.87 a	5.85 c	5.82 c	0.48 a	0.98 a
50 mM NaCl	91.31 b	6.18 b	5.94 b	0.32 b	0.96 b
100 mM NaCl	90.74 c	7.47 a	6.06 a	0.15 c	0.94 c
Mean	92.66	6.74	5.94	0.39	0.96
S × RP	**	**	**	***	**
S × ST	**	***	**	***	*
RP × ST	***	**	**	***	**
S × RP × ST	ns	ns	*	*	*

Letters show the mean values of different groups in each column. ns non-significant, *$p \leq 0.05$, **$p \leq 0.01$, ***$p \leq 0.001$, as indicated by the Tukey's HSD test.

The findings were consistent with other studies from the literature. For example, Kacjan Maršić et al. (2021) argued that salt-induced high-water deficit in low moisture content plants is caused by reduced retention of water [20]. Similarly, Yadav et al. (2011) demonstrated that when plants are subjected to salt stress, this would lead to increased water losses because of its high osmotic pressure, eventually leading to low moisture content [21]. Meanwhile, fruits lose water as a result of the normal ripening process; hence, mature fruits have low moisture content. According to Kim et al. (2004), maturation in pepper fruits was also found to be associated with loss of water and that the cell wall became denser [22].

Total Ash Content

Significant differences in total ash content were observed among the pepper species (Table 1). *C.chinense* had the highest average ash content (7.59%), followed by *C.baccatum* (6.82%) and *C.annuum* (5.91%). Ash content in a plant is a measure of the mineral content and the buildup of inorganic substances in the plant tissue. Therefore, these values may imply that *C.chinense* tends to accumulate more minerals, which might be inherent in the plant's genetic constitution and in the environmental conditions under which it is grown. When evaluated by ripening period, the total ash content was highest during the red period (7.83%) and lowest during the green period (6.31%). These findings suggest that mineral accumulation increases as the fruit matures. Ripening fruits tend to accumulate more minerals in their cellular structures, which increases ash content. Besides that, the concentration of inorganic substances becomes higher with the ripeness of a fruit due to the loss of water during ripening.

The salt stress significantly affected the average total ash content. The ash content was 5.85% in the control group, but after 50 mM NaCl, the ash content shot up to 6.18%, further increasing to 7.47% with the treatment of 100 mM NaCl. These results indicated that salt stress could lead to the increase of Na and Cl and ashes in the organs of treated plants. Several studies have also reported that the salt stress can enhance the accumulation of minerals, which in turn increases the total ash level. For example, Sarker et al. (2018) indicated that salt stress enhances ion accumulation in plants and therefore leads to a significant increase in ash content [23]. Similarly, Smith et al. (2016) elaborated that at high salt concentrations, plant materials accumulate more inorganic matter, therefore increasing its ash content [24]. These salts are absorbed by plants from soil in saline conditions and increase the number of minerals in tissues. Mineral imbalance in plant species and increased ash content in all the parts of the plant species are a common report in literature for salt stress.

All these will help identify the essential agricultural practices for pepper cultivation in saline soils. More minerals accumulated in the plants under salinity will affect the performance of the plant, not only in growth but also the nutritional value in the fruit. An increase in ash content may be taken as an adaptive response to salt stress and calls for strictly controlling the environmental conditions during pepper cultivation.

pH and Titratable Acidity

The pH and titratable acidity of pepper fruits showed significant changes due to both ripening and salt stress (Table 1). On average, *C.chinense* had the highest pH value (6.18) and *C.annuum* had the lowest pH (5.81). Concerning titratable acidity, *C.annuum* was the acidulous fruit (0.65%), while *C.chinense* showed the least acidity (0.27%). During the ripening periods, pH increased from 5.79 at green maturity to 6.01 at red maturity and titratable acidity decreased from 0.54% to 0.12%. This inverse relationship is related to the fact that its content of acidic compounds decreases while the accumulation of sugar increases as it matures and, respectively, it tastes sweeter. These results are within the range of those already reported [25, 26].

Salt stress created an effect similar to that produced by drought. The average pH changed from 5.82 in the control up to 6.06 under the highest salt treatment, 100 mM NaCl. In contrast, titratable acidity decreased from 0.48% in the control down to 0.15% under the highest salt treatment. Suppressed organic acid production minimizes acidity and increases pH in salt-stressed plants [27]. In relation with the available literature, this result could be associated with the fact that the presence of salt stress disrupts the balance between acids and sugars in plant metabolism by decreasing the generation of acid because of osmotic pressure [28]. Panchal et al. (2021) also emphasized that salt stress results in a reduced production of organic acids and, thereby, lowers pH, associated with a reduction of the availability of acidic compounds in plant tissues [29].

The pH and titratable acidity statistically showed significant differences in the parameters among species, ripening periods and salt stress. In the analysis of variance of pH, the result was extremely remarkable at the level $p \leq 0.01$. The results of titratable acidity similarly also demonstrated statistically significant differences among ripening periods and salt stress ($p \leq 0.001$). Titration acidity significantly reduced during the course of maturity, with an increase in salt stress [30]. These results imply that both ripening and salt stress induce a significant impact on the chemical composition of pepper fruits with an inverse relationship between pH and titratable acidity. This assay's results demonstrate a change in maturity in the different ripening periods of pepper fruits and under different environmental conditions, both pH and titratable acidity; such changes have a significant effect on flavor profiles and fruit quality traits. For peppers grown under saline environments, product quality can only be maintained if these two parameters are monitored.

Water Activity (aw)

The averaged values of water activity were variable among treatments, species and ripening periods of salt treatment (Table 1). According to averaged aw, *C.chinense* has a higher water activity (0.98), with *C.annuum* having the lowest (0.94). These results reflect differences in the water retention capacity of the pepper species. Water activity, which deals with the amount of free water in the fruit, is a most important parameter that directly affects shelf life and susceptibility to spoilage by microorganisms. According to reports, species of tropical origin tend to have higher water activity, this being in line with our result for *C.chinense* [31]. Meanwhile, if the data were analyzed according to ripening period, the water activity was highest during the green period (0.99) and dropped to 0.93 during the red period. This may be due to an increase in terms of water loss and cell density due to fruit maturation. Similarly, Gallardo-Guerrero et al. (2010) reported that water activity is reduced due to the decrease in water content in ripening pepper fruits [32]. In addition, the reduction in water activity associated with fruit maturation would increase the risk of spoilage by other microbes, as mentioned by [33].

Water activity was also significantly affected by salt stress. The control group revealed an average water activity of 0.98 and declined to 0.96 with 50 mM NaCl, then to 0.94 with 100 mM NaCl. There are several reports that salinity reduces water activity due to the imposition of salt stress. Salt application increases osmotic pressure in plants by increasing solute concentration, which gives rise to the inability of plants to retain cellular water. In line with this, Pirasteh-Anosheh et al. (2016) noted that because of salt stress, functionalities of proteins and carbohydrates holding water in the plant cell decline whereby free water is released from the cell and water activity decreases [34]. Lowering the water activity means decreased levels of intercellular water and direct osmotic stress by salt.

Results were evaluated as to be a significant difference. As indicated in the ANOVA results, differences of water activities were found significant between the species, period of ripening and the salt stress ($p \leq 0.05$). Results were compared in each of the treatments based on comparison to untreated controls. There was a statistically significant decrease in water activity with increasing salt stress, with the largest difference seen at the 100 mM NaCl treatment. This was confirmed with Muns (2002), stating that high concentrations of salts in the cells led to increased osmotic pressure, hence water loss and low water activity [35]. Many reports have noted that salt stress decreases the ability of the cells to hold water and thus affects the general structure and resilience of the fruit [36, 37]. Overall, it is known that both ripening and salt stress significantly affect the activity of water in the fruits of pepper. Therefore, these results stress that water activity should be taken into account to control pepper fruit quality and shelf life.

Color Analysis

Observations of the color parameters and ASTA values showed significant differences among pepper species (Table 2). *C.annuum* had the lowest average L* (89.95) and a* (5.91) values, while *C.chinense* had the highest L* (94.99) and a* (7.59) values. These results are consistent with findings from Wahyuni (2014) and Erol (2024-a), which reported that *C.annuum* is rich in carotenoids, while *C.chinense* exhibits brighter color tones [38, 39]. When measured according to the period of ripening, the L* value in the green period was 61.74 with -7.41 as the average a* value and the average b* value was 19.48. In the breaking period, these values increased to 49.08, 9.43 and 40.15, respectively. In the red period, the L* value decreased to 31.42, while the a* value increased to 34.07 and the b* value rose to 54.01. These findings support the observations by Kevrešan et al. (2013) and Erol (2024-b), which noted that red pigments increase during the ripening process in red peppers [40, 41].

Table 2. Comparison of the effects of salt stress treatments on colorimetric and extractable colors according to pepper species and plant ripening periods

	Colorimetric Color			Extractable Color
	L*	a*	b*	ASTA
Species (S)	*	***	*	***
C.annuum	89.95 B	5.91 C	5.81 B	97.45 A
C.baccatum	91.71 B	6.82 B	5.94 B	81.17 B
C.chinense	94.99 A	7.59 A	6.18 A	70.59 C
Fruit Ripening Period (RP)	***	**	**	***
Green	61.74 x	-7.41 z	19.48 z	27.06 z
Breaking	49.08 y	9.43 y	40.15 y	72.99 y
Red	31.42 z	34.07 x	54.01 x	141.08 x
Salt Treatments (ST)	***	**	**	***
0 mM NaCl (Control)	57.91 a	27.05 a	50.99 a	111.02 a
50 mM NaCl	40.15 b	16.73 b	53.40 a	100.95 b
100 mM NaCl	25.44 c	15.92 b	39.76 x	91.14 c
Mean	60.26	12.90	30.63	88.16
S × RP	**	**	**	***
S × ST	**	***	**	***
RP × ST	***	**	**	***
S × RP × ST	ns	ns	*	**

Letters show the mean values of different groups in each column. ns non-significant, * $p \leq 0.5$, ** $p \leq 0.01$, ***$p \leq 0.001$, as indicated by the Tukey's HSD test.

Salt stress also had a significant effect on color parameters; in the control group, the average L* value was 57.91, average a* value was 27.05 and average b* value was 50.99, while under 100 mM NaCl treatment, these values decreased to 25.44, 15.92 and 39.76, respectively. Salt stress has been frequently reported to inhibit the synthesis of photosynthetic pigments, leading to a reduction in red and yellow tones. Ziaf et al. (2019) noted that salt stress suppresses the production of chlorophyll and carotenoid pigments in pepper fruits, resulting in lower color parameter values [42].

When examining average ASTA values, *C.annuum* showed the highest average value at 97.45, while *C.chinense* had the lowest at 70.59. This may be related to the higher carotenoid content and pigment density in *C.annuum*. The statement that *C.annuum* is the most productive in carotenoid biosynthesis, which is also evident from the study of Hugueney et al. (1998). These study compares *C.annuum* with other species that produce carotenoids [43]. By ripening period, the data of ASTA effects color can be illustrated as they are the following: 27.06 when green -72.99 when breaking - 141.08 when red. This rising is linked to the formation of carotenoid pigments during the ripening process, as confirmed by [44].

The study observed that as salt stress aggravated, the average ASTA values was observed, with the control group showing an average value of 111.02, which decreased to 91.14 under 100 mM NaCl treatment. The carotenoid pigment biosynthetic pathway of peppers was observed to be under-generated by the deleterious effects of the stress on the plants and the resulting astaxanthin concentration of the plants, as detailed in the investigation made by [45]. The follow-up statistical analysis regulated that the difference between the salt stress treatments, ripening periods and species was found to be highly significant in color and ASTA values ($p \leq 0.01$ and $p \leq 0.001$). Therefore, the data imply that salt stress brings about changes in the properties of astaxanthin pigments and in pigment density of the plants.

The negative effect of salt stress on the color characteristics and the pigment synthesis is clear. It is reported that *C.annuum* has more red pigment, but the pigmentation is rather dense, whereas *C.chinense* is rarer but more intense. What's more, the suppressive role of salt stress on pigment synthesis and color characteristics at the same time is evident. Color is one of the most crucial factors when it comes to consumer perception and the market value of food and spice industries, therefore, maintaining the color quality of the peppers can be crucial. Meanwhile, the fall in ASTA values suggests that pigments have been lost leading to a possible nutritional feebleness of the fruit. So, these findings suggest the cruciality of salt-tolerant pepper varieties development and the usage of sustainable agriculture for the continuation of product quality during salt stress conditions.

CONCLUSION

This study provides a comprehensive investigation into the effects of varying salt stress levels on the physicochemical and color characteristics of *Capsicum* spp. fruits. The findings indicated that both genetic structures and environmental stress factors exert a significant influence on the quality parameters of pepper fruits. *C.chinense* exhibited a high moisture content and water activity, whereas *C.annuum* demonstrated a higher total ash content and pigment density (ASTA value). As the ripening process advanced, a loss of moisture and an increase in total ash content were observed in all pepper species. In fruits exposed to salt stress, significant reductions in water activity, pH and titratable acidity were observed, with high salt concentrations leading to increased water loss and physiological degradation of the fruit. In addition, salt stress was found to reduce color parameters and ASTA values, probably due to the suppression of carotenoid pigment synthesis. These results emphasize the critical importance of managing salt stress and developing salt-tolerant varieties in pepper cultivation, as both yield and product quality are affected. In areas where peppers are cultivated under saline conditions, careful monitoring of environmental factors and the application of appropriate agronomic strategies are essential for sustainable pepper production.

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