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Review paper

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Inhibition of bleaching of stored red hot pepper through appropriate postharvest technologies and practices

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Key words: Capsicum *spp*., carotenoids, color fading.

Abstract: The colour qualities of hot red pepper are the major issue in pepper value chain. Due to poorly coordinated scientific evidence, information on the factors causing colour loss and the inhibition mechanism is not well known. Therefore, this review paper aimed to summarize the inhibition mechanism of stored red hot pepper bleaching through appropriate postharvest technologies and practices. The information in this paper was gathered from a variety of sources, including journal articles, books, book chapters, workshop proceedings, FAO reports, and AOAC official methods of analysis. According to these studies, carotenoids, surface colour, and extractable colour (ASTA value) are the primary colourants that define hot red pepper. The findings demonstrate that low-temperature drying methods, such as open sun drying, are best for preserving the red hot pepper powder's colour quality, while higher temperatures cause the colour to darken. Blanching, the use of desiccants ($CaCl_2$), and chemical dipping are pretreatments that preserve the best colour quality by hastening the drying time. Similarly, storage of red hot pepper powder at lower temperatures (5°C) resulted in less colour degradation. In other words, materials used for packaging that have a high barrier to light, moisture, and air, such as laminated aluminium, amber or black polyethylene, and high-density polyethylene, maintained a higher level of colour quality. Through their influence on drying and processing times, breeding technologies, varieties, and maturity level also impact colour quality. In conclusion, the colour quality of red hot pepper is highly influenced by environmental, biological, and processing methods. It is, therefore, critical to use appropriate drying and pretreatment techniques, storage time, well-managed storage temperature, appropriate processing methods and packing materials, and improved agronomic practices for the sustainable management of colour fading and adulteration that can occur throughout the value chain.

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1. Introduction

Pepper (*Capsicum*spp.) is one of the oldest and most widely used crops. Evidence from prehistoric times show that *Capsicum* species were used as a spice as early as 5500 BC. Central and South America are the origins of the *Capsicum* spp., with Peru and Mexico believed to be the second centres of origin, subsequently it spread into the New World Tropics before being introduced into Asia and Africa in 1493 (Bosland and Votava, 2000). It was introduced to Europe by Christopher Columbus in the 15th century, and it later spread to Africa and Asia via the flourishing trade routes of Spain and Portugal at the time. As it spread around the world, it was quickly adopted and used as a spice, giving rise to many regional varieties (Jarret *et al.*, 2019). Today, hot pepper (*Capsicum annuum* L.) is the world's most important vegetable cultivated after tomato, and it is used as a vegetable, spice, or condiment in fresh, dried, or processed products (Acquaah, 2009). Asia accounts for approximately 65% of global pepper production, whereas the United States, Europe, and Africa each contribute 13.3%, 11.9%, and 10.1%, respectively (FAO, 2019).

Red peppers have been used as food additives for several years. They are used fresh as green, red, and multi-colored whole fruits in sauce, paste, canning, and pickling; dried spice (whole fruits and powder); and as an ornamental (Batiha *et al.*, 2020). It is also used as a medicinal plant to treat and relieve pain due to its antioxidant, immune-modulating, antibacterial, and anticancer properties (Maji and Banerji, 2016). It also prevents gastrointestinal problems such as flatulence, loss of appetite, gastroesophageal reflux disease, and gastric ulcers (Kim *et al.*, 2014). It also reduces oxidative stress, inflammation, and body weight, and is used to treat dyspepsia, as well as antiatherosclerotic, antidiabetic, and antihypertensive medications (Baenas *et al.*, 2019).

Red pepper carotenoids are also beneficial to humans in a variety of ways, including as sources of natural food color and provitamin A (Villa-Rivera and Ochoa-Alejo, 2020). Moreover, ground pepper and oleoresins are used to improve the color and flavour of soups, stews, sausage, cheese, snacks, salad dressing, sauces, pizza, confectionaries, and beverages (Arimboor *et al.*, 2015). The oleoresin, which is used to replace synthetic food colorants extracted from red carotenoids, is now a source of income for pepper-producing countries (Melgar-Lalanne *et al.*, 2017). It also contains vitamin C, phenolic compounds, proteins, fat, carbohydrate, dietary fibre, sodium, potassium, calcium, magnesium, iron, zinc, copper, and manganese (Dobón-Suárez *et al.*, 2021).

Natural food colourants are preferable to synthetic food colourants because they reduce the risk of synthetic food colourants to human health (Arimboor *et al.*, 2015). However, fading of the colour in red pepper is becoming a major issue due to a variety of complex reasons; as a result, fraudulent traders are adulterating the red pepper products with other artificial products such as Sudan dyes, water and oil soluble dyes, oils, and Rhodamine (Osman *et al.*, 2019). The colour fad is also caused by improper post-harvest handling and pepper production technologies (Hyderabad-Avanti *et al.*, 2019). It is also influenced by a lack of sufficient agricultural inputs, postharvest technological equipment, and knowledge, heat generated during grinding, drying techniques, red pepper powder particle size, water activity and interaction with moisture, type of packaging materials, storage periods, maturity stage, relative humidity, and light (Kasampalis *et al.*, 2022). Several novel drying technologies and postharvest handling systems were developed to preserve the nutritional and colour qualities of hot red pepper products (Getahun *et al.*, 2021). Perhaps the information on the bleaching of stored red hot pepper, the factors that cause the bleaching, and the inhibition mechanisms are not well summarized for protracted management of the problem and ensuring the nutritional importance of the red hot pepper. This paperis, therefore, aimed to review the appropriate postharvest technologies and practices that inhibit the bleaching of stored red hot pepper.

2. Materials and Methods

Literature was gathered between June 2022-September 2022. This review relied on journal articles, books, book chapters, workshop proceedings, FAO reports, AOAC official methods of analysis, bulletins, legal papers, and unpublished reports, including M.Sc. and Ph.D. dissertations. We used the NICE guidelines: the manual (NICE, 2014), Systematic Reviews: CRD's guidance for undertaking reviews in health care (CRD, 2009), The Cochrane Handbook (Lefebvre *et al.,* 2011), and The Joanna Briggs Institute Reviewers' Manual (Santos *et al*., 2018) guidelines to conduct our literature search. In total, 1406 pertinent sources of information were found after a thorough investigation of databases and websites. The databases used in this study were Food Science Technology Abstracts (FSTA), BIOSIS Citation Index, PubMed (Medline), Web of Science, CAB Abstracts, Cochrane Library, Science Direct, Wiley Online Library, Scopus, and Google Scholar. Additionally, theses and dissertations were gathered from institution websites. The related electronic literature was obtained using a Boolean search technique. Based on their direct relevance to the review's title, 107 articles from the entire corpus of downloaded literatures were used (Cooper *et al*., 2018).

3. Major red pepper colors and measurements methods

Carotenoids

Carotenoids are yellow-orange-red lipophilic pigments found in photosynthetic plants, algae, and microorganisms (Mezzomo and Ferreira, 2016). It is a fat-soluble pigment found in animals and plants that contains over 700 compounds that exhibit red, orange, and yellow colours (Jaswir *et al.*, 2011). It is a colour basal structure derived from tetraterpenephytane (C40), and any changes to this backbone result in various types of carotenoids (Mezzomo and Ferreira, 2016). Carotenoids such as β -carotene, zeaxanthin, and lutein are primary carotenoids that are directly involved in photosynthesis, whereas lycopene, α-carotene, and capsanthin are secondary carotenoids that play no role in photosynthesis (Arimboor *et al.*, 2015). Overall, it is a good natural source of colour and is commercially used as food colourants and feed additives (Jaswir *et al.*, 2011).

Carotenoids such as capsorubin, cryptoxanthin, and zeaxanthin are found in peppers as fatty acid esters. The carotenoids formed in the fruit during ripening are primarily responsible for the colour of red pepper. Red pepper carotenoids have over 50 different structures (Arimboor *et al.*, 2015). Capsanthin, capsorubin, and their isomers are the most important pigments, accounting for 30-60% and 6-18% of the total number of carotenoids in peppers, respectively (Nadeem *et al.*, 2011). It is also reported that capsanthin contributes 45.27% of total carotenoid, while antherazanthin and capsorubin contribute 8.95% and 11.45%, respectively (Ko *et al.*, 2022). The type of carotenoids depends on environmental conditions, ripening stage, cultivar and agro-climatic conditions, and so on (Kim *et al.*, 2021). Processing methods such as drying, seed removal, and grinding are also cited as major contributors to the carotenoid content of fruits (Loizzo *et al.*, 2013).

The wide structural diversity, as well as possible isomeric forms and derivatives, have been used to analyse carotenoid content, but the analysis method is difficult (Yan *et al.*, 2020). Sample preparation, extraction with various solvents, purification, saponification, separation, detection, and quantification are all common analytical steps. However, the instability associated with carotenoids' characteristic conjugated double bond structure necessitates the incorporation of control measures such as minimizing the possibility of carotenoid loss during analysis (Borba *et al.*, 2019). The precautions include performing laboratory operations in dimmed, yellow, or red light and performing sample preparation, extraction, evaporation, and saponification steps in the presence of antioxidants under a protective nitrogen or argon environment at a temperature below 40°C, as well as storing the samples/extracts in an inert atmosphere at temperatures around -20°C (Arimboor *et al.*, 2015).

Surface color

Surface colour measurements are used to specify colours perceived by the human eye. Different surface colour measurement techniques have been developed to lessen the challenge of an object's colour being perceived differently by various observers. This is due to the fact that various factors, including the observer's sensitivity, the size of the object, the light source and illumination, the background colour and contrast, and the angle at which the object is viewed, affect how each observer comprehends the colour they observed (Yang *et al*., 2018). Since the late 1920s and 1930s, the relative eye's sensitivity to light was recognized as a standard observer trait (MacDougall, 2010). The CIELAB (International Commission on Illumination's Lab) colour system is used to ascertain the surface colour of red peppers (Pathare *et al*., 2013). Hunter colour parameters have also been used to determine the surface colour of red pepper (Sharangi *et al*., 2022). The Hunter Lab System has a more uniform colour space than CIE. Furthermore, the surface colour of the hot red pepper is determined by the variety, maturity stage, pretreatments made during processing and drying techniques used (Sharma *et al*., 2015).

Extractable color

Extractable colour is a spectrophotometer-measured total pigment content expressed in ASTA units. The current procedures for measuring the extractable colour in dehydrated capsicums and oleoresins were developed by the Association of Official Analytical Chemists. Higher ASTA colour units indicate a brighter red colour and product acceptability (Babu *et al.*, 2014). However, because the extraction process takes 16 hours, the ASTA method is completely objective, destructive, and time consuming (Monago-Maraña *et al.*, 2022).The extractable colour of the pepper is heavily influenced by storage condition-sand temperature (Belović *et al*., 2014), pretreatment method and maturity stage (Bhandari *et al*., 2013).

4. Kinetics of red hot pepper color fading and determinant factors

Red pepper colour degradation is caused by oxidation caused by singlet oxygen and other reactive species such as O_2, H_2O_2 and OH (Ding *et al.*, 2015). The oxidation process results in the complete loss of carotenoids. It is also caused by carotenoid isomerization from *trans* to *cis* form, which is accelerated by exposure to relatively higher heat, acids, and light (Provesi and Amante, 2015). Unlike oxidation, isomerization results in colour saturation rather than a complete loss of carotenoids (Song *et al.*, 2017). The following sections go over some of the factors that contribute to red pepper colour fading.

Light

Light has a significant impact on the colour quality of peppers both during cultivation and storage. Crop exposure to direct sunlight in the cultivation field has a negative impact on the colour and final product of the pepper. For example, a pepper grown and kept in a greenhouse for less than 200 days revealed a high extractable colour (Gómez *et al.*, 1998). Similarly, prolonged exposure to sunlight resulted in a decrease in C* values and an increase in h ab values, indicating a decrease in vividness (saturation) and an increase in yellowness in tandem with a decrease in redness, because changes in C* values are directly related to colour stability (Pathare *et al.*, 2013). The carotenoid contents in fruits grown in shaded greenhouses were also significantly higher than those grown in unshaded greenhouses and fields (Keyhaninejad *et al.*, 2012). Open sun drying with long processing times was also detrimental, resulting in losses of 79% capsaicinoids and 24.6% capsaicin (Topuz *et al.*, 2011). In comparison to frozen and hot air-dried peppers, chilli peppers dried in the open sun also preserved less bright red colour and ascorbic acid (Toontom *et al.*, 2012). Similarly, 50% ASTA colour values were reduced in Korean red pepper powders exposed to sunlight for 42 days (Kim *et al.*, 2015). In general, higher oxygen exposure and intense vaporisation from the pepper's surface cause pigment decomposition during open sun drying (Sharangi *et al.*, 2022).

Water activity

"Water activity" is a thermodynamic measure of water in material that is calculated by dividing the vapour pressure of the water in a sample by the vapour pressure of pure water at a given temperature, which ranges from 0.1-1 (Lewicki *et al.,* 2004).It gauges how effectively the water in the reaction can participate in a chemical or physical process. Moreover, it has a negative impact on the colour and safety of red pepper (Rhim and Hong, 2011). It has been reported that 0.4-0.6 water activity values result in less colour loss (Lee, 2012), but higher water activity develops brown and tarnish-black colour, indicating that the degradation of carotenoid pigments, non-enzymatic browning index, ASTA values, and surface colour (Rhim and Hong, 2011). In other words, water activity between 0.4 and 0.6 reduces red pepper surface colour deterioration (Lee, 2012). Moreover, high water activity at high storage temperatures exacerbates the level of colour fading. Therefore, storing red pepper powder below 25°C, below medium ranges of water activity, and between 10-14% moisture content to maintain red pepper colour quality (Rhim and Hong, 2011). For instance, storing red peppers powder at water activity below 0.3, in a nitrogen atmosphere and/or reducing the package free space volume and lowering storage temperature improves the carotenoid content (Lee *et al.*, 1992). An increasing trend of colour stability was also observed with increasing water activity values during pepper powder storage, with the greatest stability observed at a water activity of 0.64 (relative moisture, 14%), but increasing the moisture level above this value caused a significant reduction in colour intensity (Kanner *et al.*, 1977).

Drying and storage temperature

Temperature is an important factor that contributes to the degradation of red pepper colour quality by causing oxidation of carotenoid pigments due to heat destruction and lipid oxidation at high temperatures (Maurya *et al.*, 2018). It also results in the loss of volatile compounds and nutrients like vitamins C, capsaicinoids, phenolic compounds, antioxidant capacities, and other physicochemical properties. For example, colour reduction of pepper powder is observed to be rapid at high temperatures even when moisture content is low during storage (Kim *et al.*, 2004). Temperature and relative humidity above ambient storage conditions also degrade the colour of pepper, but pepper powder stored in refrigeration and freeze showed a minimal extractable and surface colour loss (Addala *et al.*, 2015).

In other words, the drying kinetics of red and yellow chilli peppers showed a decreasing trend of red colour decomposition at lower drying air temperatures (less than 55°C) (Andrade *et al.*, 2019).For instance, yellow sweet peppers dried in a microwave convective dryer showed a 3.5-fold increase in red colour decomposition with increasing microwave power and temperature due to isomerization of carotenoids at high temperatures (Swain *et al.*, 2014). However, carotenoids are more stable at high temperatures in pungent cultivars because capsaicinoids in pungent varieties affect the chemical interactions of carotenoids in red pepper tissues, providing significant protection against thermal destruction. Thermal destruction and lipid oxidation, on the other hand, can be inhibited by endogenous antioxidants such as phenols, vitamin C, and E. For example, heat has reduced the carotenoid degradation of dried pepper prior to milling to greater than 2 mg/g, but pungency cannot be guaranteed for more than 3 storage months (Daood *et al.*, 2006).

Processing methods

The red pigment of red pepper is also affected by processing methods and conditions. Furthermore, the kinetics of colour degradation during processing and storage are temperature and water-activity dependent. For example, the colour of ground pepper deteriorated faster than that of non-ground pepper during storage, indicating that powdering reduces carotenoid concentration (Carnevale *et al.*, 1980). Exoquin and irradiation-treated samples also retained more red colour of the pepper powder after six months of storage (Addala *et al.*, 2015). Similarly, after 12 months of storage, red pepper with 10% seed had higher colour stability than controls (Van Blaricom and Allen, 1953). Dry-heat cooking methods such as stir-frying and roasting are also preferred over moist heat cooking methods such as boiling and steaming to retain the nutrient compositions and antioxidant properties of red pepper (Wang *et al*., 2017).

Pepper seed addition

The initial carotenoid concentration of extractable colour is also strongly influenced by the extent of powdering and seed inclusion. The inclusion of seeds reduces the carotenoid content because seeds have little carotenoid content and are highly affected by water activity, packaging atmosphere, storage temperature, and pepper treatment (Lee *et al.*, 1992). In other words, adding seed to the flesh slows the rate of colour loss, but because the seed dilutes the initial colour, it reduces the overall shelf life (Klieber and Bagnato, 1999). The addition of 10% seed to sesame-treated samples also improved red pepper colour stability even after a 12-month storage period (Van Blaricom and Allen, 1953).

Variety

The studies revealed that cultivar and growing conditions all have an effect on the degree of pepper coloration. For example, a significant difference in total carotenoid content was observed among different pepper varieties grown in Nigeria, with genotypes UNS3 and Nskyre exhibiting the highest total carotenoids content and genotype Tatase containing high-carotene content (17.30±0.35 mg/100 g) (Abu *et al.*, 2020). Color value difference was also observed among three red hot pepper varieties grown in Ethiopia, with Marakofana having the highest ICU value (648331±31673)(Kinfe, 2009). The colour of hot red pepper pods also varied significantly among Dilla-grown varieties, with Melkazala having a darker-red pod colour than Marekofana (Teferi *et al.*, 2015). Similarly, ASTA values ranging from 2-296 were reported for local and exotic hot pepper genotypes grown in the same conditions in Ethiopia, indicating that variety influences hot red pepper colour (Aklilu *et al.*, 2018).

Fruit ripening at harvest

Pepper colour varies greatly depending on maturity stage due to its carotenoids content; unripe fruit can be green, yellow, or white, turning to red, dark red, brown, and sometimes black when mature (Mohd-Hassan *et al.*, 2019). Capsanthin, capsorubin, and cryptocapsin are keto carotenoids that produce a brilliant red colour, whereas -carotene, zeaxanthin, violaxanthin, and -cryptoxanthin produce a yellow-orange colour (Arimboor *et al.*, 2015). In other words, red peppers contain β-cryptoxanthin, capsanthin, capsorubin, β-carotene, antheraxanthin, violaxanthin lutein and α-carotene, while yellow colored peppers contains β-carotene, zeaxanthin, antheraxanthin, violaxanthin lutein and α-carotene, but brown colored peppers have green color (chlorophll *b*) and lutein (Mohd-Hassan *et al.*, 2019).

Ripe pepper fruits of various varietiesexhibit a wide range of colours ranging from white to deep red (Mohd-Hassan *et al.*, 2019). For example, total carotenoids content increased with maturity stage, with red sweet pepper having the highest total carotenoids compared to orange, yellow, green, and white cultivars (Gnayfeed *et al.*, 2001). Total carotenoids also increased up to 24 fold with increasing ripening, with deep red pepper containing the most total carotenoids, followed by faint red and colour breaks (Markus *et al.*, 1999).

The apparent colour values of Marekofana varieties grown in Ethiopia also varied according to maturity stage, with green pepper having the highest L* (38) and b (23.3) values (Getahun *et al.*, 2020). Similarly, the after-ripened spice paprika had the highest ASTA colour value when compared to the early and late harvest stages (Sipos *et al.*, 2010). The pepper powder produced from fruits left to dry on the plant (40-25% moisture content) had also the highest ASTA colour value (270 ASTA unit), but decreased to 160 ASTA unit in succulent fruits immediately after red-ripening (Kanner *et al.*, 1977). However, the green matured stage of hot red pepper (Bhandari *et al.*, 2013) cultivars had higher b-carotene content than the ripe red stage.

5. Inhibiting red hot pepper bleaching via postharvest technologies and practices

Drying method

Drying red pepper before processing is a common practice around the world to maintain colour quality (Yang *et al.*, 2018). Open sun drying is the most widely used drying technique in developing countries and produces the best red pepper colour when compared to hot air and infrared drying, but infrared drying significantly improved drying time at the same drying temperature (Cao *et al.*, 2016). For example, sun-dried paparika contained more carotenoids than paparika dried in a hot air oven, refractive window, or freeze drier (Topuz *et al.*, 2011). The convectional drying method, on the other hand, resulted in colour darkening and a decrease in vitamins and bioactive compounds (Guiné, 2018). In other words, as compared to other unconventional dryers, solar drying is generally more cost-effective, and consistent, and does not rely on weather conditions (Tiwari, 2016). In contrast to sun drying, reflection window drying is less expensive, takes less time to dry, and improves product quality (El-Hamzy and Ashour, 2016).

Hot air drying is also preferred over sun drying due to its rapid, massive, uniform, and sanitary drying; however, due to its higher temperature requirement, nutrient degradation and a lower rehydration ratio have been reported (Guo *et al.*, 2021). Similarly, the highest colour retention was found in red pepper dried at 65°C in oven-dried red pepper at the shortest drying time (480 min), but prolonged sun-dried products had the hardest texture (Sharangi *et al.*, 2022). Dry heat processing is also believed to preserve the colour of red pepper better than wet processing (Rybak *et al.*, 2020).

Drying pretreatments

Pretreatments are used to reduce drying time, increase energy efficiency, and improve product quality (Srimagal *et al.*, 2017). Several pretreatment methods were used to reduce drying time while retaining the red colour and other nutritional properties of red pepper. The most commonly used pretreatment techniques in drying red pepper are ethyl oleate and microwave blanching (Srimagal *et al.*, 2017), hot water blanching, the use of desiccants ($CaCl_2$) (Romauli *et al.*, 2021), and chemical dip (Guiné, 2018). Of these, steam blanching produced more colour and other bioactive compounds than hot water blanching (Rybak *et al.*, 2020). Similarly, ohmic heat treated pepper and bell pepper blanching in boiling solution containing 1% sodium hydroxide and 0.25% magnesium carbonate for 3 minutes and drying at 50°C air temperature (Singh *et al.*, 2000) produced better colour quality than the other methods. The highest red pigment and drying kinetics were also observed in OH-pretreated pepper powder as compared to hot Water Blanching because OH pretreatment and drying at 70°C reduce drying time while retaining red pepper quality (Incedayi, 2020).

The use of 2% ethyl oleate and 5% K_2CO_3 solution dip pretreatments at 50°C during hot air dying of red pepper dried also exhibited the highest Hunter L (lightness), *a (redness), and *b (yellowness) values than untreated peppers (Máximo *et al.*, 2017). Similarly, microwave blanching followed by brine solution dipping improved the drying rate and retained more beta carotene content in the samples (Delfiya *et al.*, 2018). The ASTA and surface colour values of the rehydrated peppers were also greatly improved by pretreatment with a solution containing calcium, salts (10%), and sodium metabisulfite prior to hot-air, oven (50-80°C), or microwave drying at 60-180 W (Vega-Gálvez *et al.*, 2008). The surface colour of the pepper powder made from sliced chilli pods without the pedicle and pretreated with 0.01% KMS (Sarker *et al.*, 2012) and bell pepper shreds dried in a solar polytunnel drier after pretreatment with a KMS 0.20%+CA 0.50% solution (Sharma *et al.*, 2015) was also better than the control. Ethoxyquin-treated and irradiated samples also retained a better extractable colour after six months of storage (Addala *et al.*, 2015). Similarly, red pepper powder blanching in the microwave, infrared, and high-humidity hot air impingement had the highest red pigments when compared to hot water treatment (Wang *et al.*, 2017) (Table 1).

Storage time and temperature management

Lower temperatures are recommended to prevent red pepper colour loss during storage (Rhim and Hong, 2011). For example, red pepper powders had the same ASTA colour value, capsanthin content, and redness (a*) when stored at -5 and -20°C than 20°C, 2°C, and -1°C storage temperatures (Choi

Table 1 - Effect of pretreatment on the colour quality of red hot pepper

Pretreatments	Drying method	Recommendation	References
Sample without pedicle, cut longitudinally and treated with 0.01% KMS; sample without pedicle and sliced; sample without pedicle as a whole; sample with pedicle as a whole	Sundrying	The powder without pedicle, sliced into two parts along the length and treated with 0.01% KMS maintained better sensory quality	Sarker *et al.* (2012)
Blanching at 93°C in plain or in 2% NaCl solution for 4 min	Solar dryingand in the open sun	Blanching followed by drying in natural convection solar dryer scored better color acceptability	Owusu-Kwarteng *et al*. (2017)
Submerging for 10 min at 25°C in an aqueous solution of 15% (w/w) NaCl, 1.0% (w/w) CaCl2 and 0.3% (w/w) Na2S2O5; blanching in hot water at 85 °C	Refractancewindow™ drying; oven drying; sun drying	Blanching prior to refractance window drying enhanced stability of pepper colorfor 12 months storage period	El-Hamzy and Ashour (2016)
Dipping in chemical solutions (w/v):2% ethyl oleate;2% ethyl oleate+2% NaOH; 2% ethyl oleate+2% NaOH+4% potassium carbonate. Dipping temperature; 23°C; 60°C	Greenhouse drying; open sun drying	Dipping red peppers in 2% ethyleoleate + 2% NaOH + 4%K_2CO_3 solution at 60°C resulted in best color retention	Ergüneş and Tarhan (2006)
Blanching with hot water; blanching with steam at 98°C for 3 minutes; Ultrasonic Treatment (US); Pulsed Electric Field Treatment (PEF); combined methods	Vacuum drying (10 mPa, 70°C for 24 h)	Better retention of vitamin C and carotenoids content was observed for the treatment combination based on sonication with a pulsed electric field	Rybak *et al.* (2020)
Control (without any pre-treatment); blanching in boiling water for 3 min; blanching + soaking for 5 min in the following chemical solutions: KMS (potassium meta bisulphite) 0.25%; KMS 0.35%; CA (citric acid) 0.3%; CA 0.6%; KMS 0.2% + CA 0.5%; KMS 0.3% + CA 0.25%	Dehydrator a 58±2°C till constant weight obtained	Blanching of bell pepper shreds in boiled water followed by pretreatments with KMS 0.20%+CA 0.50% at 55-60°C resulted higher colour stability	Sharma *et al*. (2015)

et al., 2018). Furthermore, as the storage period increased up to 12 months at high temperature, the overall freshness, redness, hot flavour, moisture release, and edibility decreased (Wang *et al.*, 2017).

Chilli powders stored at 5°C retained vitamin C and colour for up to 6 months without the use of any synthetic preservatives. Additionally, chilli pepper powders packed in flexible foil and stored at 5°C retained more vitamin C and colour without the addition of preservatives for up to 6 months as compared to high-density polypropylene storage (Al-Sebaeai, 2017). In other words, red pepper lightness (CIE L*) and yellow colour intensity (CIE b* value) increased, but red colour (CIE a* value) decreased, and the hue angle shifted from red orange to orange-yellow after three years of storage at 21.5°C (Belović *et al.*, 2014). For samples stored at 35°C for 42 days, the L*, a*, b*, delta E, visual colour acceptability, and total carotenoids also revealed a decreasing trend in Candida red, Candida orange, and Candida yellow (Kim *et al.*, 2015).

Similarly, minimum (5%) extractable colour and Hunter L, a, b values change observed for red pepper stored under refrigeration and freeze conditions for both pretreated and non-treated samples at 6 months storage time compared to the room (22°C) and elevated temperatures (35°C and 80%) (Addala *et al.*, 2015). Total carotenoid content loss is also facilitated by storing the microencapsulated NAEC at temperatures above 35°C (Guadarrama-Lezama *et al.*, 2014). In general, the longer the storage period, the lower the storage temperature required, and vice versa (Choi *et al.*, 2018).Red pepper can also be stored at low temperatures (0-5°C) for up to 6 months and frozen (-5°C) for longer than 6 months (Wang *et al.*, 2017).

Packaging materials

Packaging is a method of providing proper environmental conditions for food during storage, and the materials used in packaging are determined by the nature of the product, storage, and handling conditions (temperature, humidity, risk of physical deterioration) (Marsh and Bugusu, 2007). The air composition inside the package is determined by the nature of the packaging materials, which affects the rate and extent of nutrient loss and microbial activity (Amit *et al.*, 2017). Natural jute sacks, for example, were the most widely used bags to pack pepper pods in the world, with significant retention of product quality, but red peppers stored in jute bags were vulnerable to aflatox in contamination as compared to pods packed in polyethylene bags (Iqbal *et al.*, 2015). Hot peppers stored in LDPE film also spoiled faster than unpacked control fruits at 18-20°C and 28-30°C storage temperatures due to excess water vapour accumulated inside the package (Mahajan *et al.*, 2016). Similarly, 77.4% of the initial amounts of health and nutrition-promoting compounds in pepper pods stored in natural jute at room temperature for five months were preserved, but capsaicinoids and antioxidant levels gradually decreased in dry pepper pods over the long storage period (Iqbal *et al.*, 2015).

Purdue Improved Crop Storage (PICS) bags have recently been introduced to store agricultural products because they provide a better barrier to light, air, and moisture. Other storage materials used to pack dried peppers include High-density Polyethylene (HDPE) bags, which have a high moisture barrier and thus cause less deterioration to dried products than natural jute sacks (Sachidananda *et al.*, 2013). Five months of storage in synthetic HDPE plastic bags at room temperature preserved 87.3% of the initial amounts of total carotenoids and ascorbic acid (Iqbal *et al.*, 2015).

Similarly, due to the high rate of migration of water vapour from the storage environment into these packaging materials, aluminium foil, and High-Density Poly Ethylene bag had no effect on water activity for the entire storage period for both red and yellow capsicum pod up to 60 days as compared to polypropylene and Poly Ethylene bags (Sachidananda *et al.*, 2013). The studies also revealed that red pepper pods stored in laminated aluminium for more than 120 days showed the least difference in total carotenoid content and browning index, followed by high-density polyethylene (HDPE) and polypropylene (Weil *et al.*, 2017). This is due to the low light transitivity through the laminated aluminium foil, which results in less reduction of the photo-degradable carotenoid pigments. In general, aluminium foil laminate was generally recommended for storing chilli pepper powder because it is a barrier to light, moisture, and air. As alternatives, amber or black polyethylene, high-density polyethylene, and Saran/Cello/Saran poly laminate pouches are recommended (Sachidananda *et al.*, 2013). Table 2 also illustrates some packaging-related effects on the colour quality of red hot peppers.

Table 2 - Effect of packaging materials on the colour quality of red hot pepper

Packaging materials	Type	Conservation method	Recommendation	References
Polypropylene; aluminum laminated pouch; woven polypropylene bags	Red chilli powder	With and without vacuum pumping storage at 5±0.5°C and 26±1°C for 12 months	Less color loss was recorded at 5±0.5°C and in laminated bags under vacuum at both storage temperature	Prerna *et al*. (2019)
Aluminum; LDPE; HDPE; paper bags; polythene line gunny bags; gunny bags	Dried red pepperpod	Storage for two months under ambient conditions	Laminated aluminium film retained highest color, ascorbic acid and oleoresin	Anjaneyulu and Sharangi (2022)
Polypropylene packages with thickness of 3, 4, 5, 12.5, 20 and 30 micron	Ground chilli pepper	Storage at room temperature (28±2°C) for two months	Polypropylene films with thicknesses of 30 and 20 microns exhibited enhanced preservation of carotenoid content	Akusu and Emelike (2019)
Low density polythene pouch; PET jar; laminated film pouch	Green chilli pepper slice	Storage for 28 days after 7% $K_2S_2O_5$ pretreatment + blanching for 1.5 min + dehydration in a hot oven at 53°C	PET jar and laminated film poach preserved better visual colour of the slices	Ansari *et al.* (2020)
Sealed polyethylene bags; sealed polypropylene bags	Sweet peppers pod	Storage for 28 days at 8°C after dipping in hot water at 50°C for 3 min and 55°C for 1 min	Polypropylene bags exhibited superior preservation of appearance, carotenoids, and ascorbic acid regardless of the temperature used for dipping	Said *et al*. (2013)
Polypropylene; polyvinyl chloride plastic film	'Yalova Charleston' Pepper	In normal atmosphere and MAP storage using 35µ PP and 35µ PVC at 7°C and 90±5% RH	Samples were successfully stored for 30 days using 35µ PP at 7°C and 90±5% RH	Akbudak (2008)
Polyethylene bag; jute sac; banana leaf; refrigerator; ambient condition; evaporative cooling system	Sweet pepperpod	Freshsealing	Combining an evaporative cooling system with a polythene bag proved to be a more effective storage method	Garuba *et al*. (2022)

Variety and breeding technologies

Developing breeding programs that effectively preserve the vibrant red color of peppers throughout the drying and processing stages plays a pivotal role in enhancing the appeal and desirability of red peppers. Furthermore, to prevent colour loss through breeding programs, the total carotenoid content of dried products from different cultivars should be compared and selected, and the cultivar with the highest total carotenoid content should be chosen (Paran and

Fallik, 2011). However, when comparing and selecting cultivars, one should consider not only the variety with the highest total carotenoid content but also the cultivar's carotenogenic capacity, which is manifested by a higher red-to-yellow isochromatic pigment fraction ratio (R/Y) and capsanthin to zeaxanthin ratio (Caps/Zeax) (Hornero-Méndez *et al.*, 2000).

Cultivar Mana had the highest total carotenoid content (13208 mg/kg dwt), but the lowest R/Y(1.25) and Caps/Zeax (3.38) ratios, so these parameters should be improved. Cultivar Negral, on the other hand, had a higher carotenoid content (8797 mg/kg wet), R/Y, and Caps/Zeax ratios, whereas cultivar Numex had the highest Caps/Zeax ratio (7.17) and lower total carotenoid content and should be improved by crossbreeding with Mana, which has a higher total carotenoid content (Hornero-Méndez *et al.*, 2000). Additionally, the capsaicin, heat level, and colour quality of known pepper genotypes revealed that genotypes have a significant effect on capsaicin and colour values. Furthermore, breeders should consider disease resistance as well as drying characteristics of peppers, as some genotypes are not suitable for drying, with increased pungency and colour loss during the drying process (Arpaci *et al.*, 2020). Gnayfeed *et al.* (2001) also reported that K-V2 variety had also the highest total carotenoids followed by F-03, SZ-178 and Cseresezenye, respectively.

The studies also revealed that the maturity stage has a significant impact on red pepper colour, with Candida red paprika having higher total carotenoids, b*, and L* values than Candida yellow paprika (Kim *et al.*, 2015). Different varieties considered for the study showed the same ripening-dependent pattern of b-carotene content increase, with the highest b-carotene content observed in the ripe red stage (Bhandari *et al.*, 2013). The total carotenoid content also decreased from 7966 to 1701 g/g in the break, faint red, and deep red stored pepper after three months, with faint red having the highest carotenoid content (Markus *et al.*, 1999). In general, breeding technologies, and varieties have a significant impact on the colour and other bioactive compounds of hot red pepper and should be considered in the management of red pepper colour loss (Martínez-Ispizua *et al.*, 2021).

6. Conclusions

In conclusion, the findings of this review paper indicated that colour fading hot red pepper is one of the major challenges in pepper production worldwide, which is highly determined by many factors such as genotype, maturity stage, exposure time to sunlight, higher temperature, relative humidity, moisture content and water activity, and oxygen during drying, processing techniques, storage methods, and product particle size. There is a need for significant effort to raise community awareness, engage stakeholders, and prioritize scientific research in order to address the inadequate attention given to preventing the fading of the bright red color in hot peppers. The use of light- and oxygen-permeable packaging materials, high-temperature drying, prolonged storage of the powder at high temperatures, and early and/or delayed harvesting were all noted in our review paper as contributing factors to the typical colour loss of red hot pepper powder. Based on the consulted literature, it is vital to employ techniques like low temperature drying, water blanching, and chemical dipping before the drying process in order to minimize color loss in red hot pepper powder. Furthermore, storing the peppers at a low temperature of 5°C, using packaging materials that are resistant to light, moisture, and air, and ensuring that the peppers are harvested at the appropriate maturity level are also essential steps to be taken in consideration.

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