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 (CaCl₂), 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.

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 (Batha et al., 2020). It is also
used as a medicinal plant to treat and relieve pain
due to its antioxidant, immune-modulating, antibac-
terial, 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, antiobiotic, and antihyperten-
sive 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 dress-
ing, 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 pep-
per-producing countries (Melgar-Lalanne et al.,
2017). It also contains vitamin C, phenolic com-
pounds, 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 arti-
ficial products such as Sudan dyes, water and oil solu-
bles, oils, and Rhodamine (Osman et al., 2019).
The colour fade is also caused by improper post-har-
vest 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 gen-
erated during grinding, drying techniques, red pep-
per powder particle size, water activity and interaction
with moisture, type of packaging materials, stor-
age 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 paper, 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 arti-
cles, books, book chapters, workshop proceedings,
FAO reports, AOAC official methods of analysis, bul-
etins, legal papers, and unpublished reports, includ-
ing 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 web-
sites. 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 tetraterpenephane (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 pro-
cess 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 O₂, H₂O₂ 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 hₐb 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 vapourisation 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 (Daoood 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 -cryptoxanthin, capsanthin, capsorubin, -carotene, anteraxanthin, violaxanthin lutein and α-carotene, while yellow colored peppers contains -carotene, zeaxanthin, anteraxanthin, violaxanthin lutein and α-carotene, but
brown colored peppers have green color (chlorophyll b) and lutein (Mohd-Hassan et al., 2019). Ripe pepper fruits of various varieties exhibit 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 paprika contained more carotenoids than paprika dried in a hot air oven, reflective window, or freeze drier (Topuz et al., 2011). The conventional 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 (CaCl2) (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% K2CO3 solution dip pretreatments at 50°C during hot air drying 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

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

<table>
<thead>
<tr>
<th>Pretreatments</th>
<th>Drying method</th>
<th>Recommendation</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>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</td>
<td>Sundrying</td>
<td>The powder without pedicle, sliced into two parts along the length and treated with 0.01% KMS maintained better sensory quality</td>
<td>Sarker et al. (2012)</td>
</tr>
<tr>
<td>Blanching at 93°C in plain or in 2% NaCl solution for 4 min</td>
<td>Solar drying and in the open sun</td>
<td>Blanching followed by drying in natural convection solar dryer scored better color acceptability</td>
<td>Owusu-Kwarteng et al. (2017)</td>
</tr>
<tr>
<td>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</td>
<td>Refractancewindow™ drying; oven drying; sun drying</td>
<td>Blanching prior to refractance window drying enhanced stability of pepper color for 12 months storage period</td>
<td>El-Hamzy and Ashour (2016)</td>
</tr>
<tr>
<td>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</td>
<td>Greenhouse drying; open sun drying</td>
<td>Dipping red peppers in 2% ethyleoleate + 2% NaOH + 4% K2CO3 solution at 60°C resulted in best color retention</td>
<td>Ergüneş and Tarhan (2006)</td>
</tr>
<tr>
<td>Blanching with hot water; blanching with steam at 98°C for 3 minutes; Ultrasonic Treatment (US); Pulsed Electric Field Treatment (PEF); combined methods</td>
<td>Vacuum drying (10 mPa, 70°C for 24 h)</td>
<td>Better retention of vitamin C and carotenoids content was observed for the treatment combination based on sonication with a pulsed electric field</td>
<td>Rybak et al. (2020)</td>
</tr>
<tr>
<td>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%</td>
<td>Dehydrator a 58±2°C till constant weight obtained</td>
<td>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</td>
<td>Sharma et al. (2015)</td>
</tr>
</tbody>
</table>
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-Sebaei, 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 aflatoxin 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 (Weill et al., 2017). This is due to the low light transitivity through the laminated aluminium foil, which results in less reduction of the photodegradable 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.
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 capsaisin, heat level, and colour quality of known pepper genotypes revealed that genotypes have a significant effect on capsaisin 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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