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Original Article

Improving postharvest life, quality and bioactive compounds of strawberry fruits using spermine and spermidine

Melhorando as condições de vida pós-colheita, qualidade e compostos bioativos de frutos de morango usando espermina e espermidina

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Abstract

Small fruits such as strawberries, are a good source of natural antioxidants. In recent decades, many efforts have been made to increase the shelf life of strawberries and maintain its nutritional value in post-harvest conditions. In the present study, the effects of spermine (Spm) and spermidine (Spd) (0, 1.0 and 1.5 mM) on the post-harvest life and quality of strawberry fruits during the 3rd, 6th, and 12th days of storage, were investigated. Applications of Spm and Spd decreased the rate of weight loss, fruit decay, soluble solids content, fruit juice pH and taste index during the storage period in compared to the control. However, titratable acids and vitamin C contents, tissue stiffness, phenolic compounds and antioxidant activity increased in compared to the control. These growth regulators prevented the aging and loss of bioactive compounds of the fruit by increasing the antioxidant activity and preventing the destruction of the fruit tissue. Among the studied treatments, applications of 1.5 mM of Spm and Spd were the most effective treatments to enhance the storage life and quality characters of strawberry fruits.

Keywords: antioxidant activity, decay percentage, soluble solids, taste index, titratable acid, total phenol.

RESUMO

Frutas pequenas como morangos são uma boa fonte de antioxidantes naturais. Nas últimas décadas, muitos esforços têm sido feitos para aumentar sua vida útil e manter seu valor nutricional em condições de pós-colheita. No presente estudo, foram investigados os efeitos da espermina (Spm) e espermidina (Spd) (0, 1,0 e 1,5 mm) pós-colheita e na qualidade dos frutos de morango durante o 3º, 6º e 12º dias de armazenamento. Aplicações de Spm e Spd diminuíram a taxa de perda de peso, podridão dos frutos, teor de sólidos solúveis, pH do suco de frutas e índice de sabor durante o período de armazenamento em comparação com o controle. No entanto, os teores de ácidos tituláveis e vitamina C, rigidez tecidual, compostos fenólicos e atividade antioxidante aumentaram em relação ao controle. Esses reguladores de crescimento preveniram o envelhecimento e a perda de compostos bioativos da fruta, aumentando a atividade antioxidante e evitando a destruição do tecido da fruta. Entre os tratamentos estudados, as aplicações de 1,5 mm de Spm e Spd foram os tratamentos mais eficazes para aumentar a vida de armazenamento e as características de qualidade dos frutos de morango.

Palavras-chave: atividade antioxidante, porcentagem de decomposição, sólidos solúveis, índice de sabor, ácido titulável, fenol total.

1. Introduction

Postharvest loss of fruits and vegetables is one of the most important economic worldwide. Strawberry (*Fragaria annanasa*) is one of the most widespread fruit species grown in almost every country. It is one of the most rapidly deteriorating fresh produce and thus prone to significant losses during the whole supply chain (Chen et al., 2023).

Several factors cause damage to horticultural products, among which mechanical injuries are the most important factors that cause to attack and development of fungi (Sun et al., 2020; Yoon et al., 2020). Applications of some growth regulators on harvested fruits can be highly effective to increase the fruits life. Polyamines are among the growth regulators that have a high ability to increase the shelf life of some products (Serrano et al., 2016).

Polyamines are aliphatic carbohydrates with low molecular weight, and a chain structure that has imino and amino groups (Handa and Mattoo, 2010). Polyamines are found in the apoplast, plasma membrane, vacuoles, chloroplast, and cell nucleus (Serrano and Valero, 2018).

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The free form of polyamines has been introduced as an anti-aging agent. In plant tissues, polyamines have an inhibitory effect on the ripening and aging process (Sharma et al., 2017). The polyamines play a significant role in increasing the storage life of fruits (Serrano and Valero, 2018; Sharma et al., 2017). The loss of firmness of peach fruit tissue during the storage period is known to be associated with a decrease in internal polyamines and an increase in ethylene biosynthesis (Liu et al., 2006). It was reported that the Japanese pears varieties which had longer shelf life had higher internal polyamine content and there was an inverse relationship between the internal polyamines and ethylene contents (Franco-Mora et al., 2005). Transgenic tomatoes which accumulated higher amounts of Spd and Spm in the fruit, represented higher postharvest life (Mehta et al., 2002). In nectarine fruits, the exogenous applications of putrescine (Put) and Spd caused a decrease in the ethylene production, a delay in tissue softening, maintaining the amount of titratable acid and preventing an increase in the total soluble solids content (Torrigiani et al., 2004).

Pomegranate fruit treated with Put or Spd had higher amounts of vitamin C, phenolic compounds and total anthocyanins in their arils than untreated fruits during 60 days of cold storage (Mirdehghan et al., 2007).

Polyamines by restricting ethylene biosynthesis in plants prevent the activation of polygalactronase gene transcription that occurs after ethylene synthesis (Sharma et al., 2017). The application of putrescine before and after harvesting delays and stops ethylene production and respiration rate (Khan et al., 2008). Polyamines affect the production of ethylene by preventing the transcription, production and activity of ACC synthase enzyme. The ability of polyamines to stop the activity of the ACC oxidase enzyme by eliminating superoxide free radicals, which are necessary for the conversion of ACC to ethylene, leads to a decrease in ethylene production (Bitrián et al., 2012). It has been proven that the reduction of three types of polyamines (Put, Spm, Spd) is related to the increase in ethylene production (Abu-Kpawoh et al., 2002). The prevention of fruit softening with the application of polyamines may be due to the decrease in the activity of cell wall degrading enzymes, including polygalactronase, exopolygalactronase, and methylesterase (Khan et al., 2008). Polyamines can act as inactivators of free radicals and protect cell membranes from oxidation, thereby increasing the resistance of membranes (Bitrián et al., 2012). Their ability to eliminate free radicals is related to the number of amino groups (positive charges).

Therefore, the present study was aimed to evaluate the effect of exogenous applications of Spm and Spd on optimizing the storage life of strawberry fruit.

2. Materials and Methods

2.1. Plant material and experimental design

Strawberry fruits of cv. Camarosa were obtained from a hydroponic greenhouse located in Jiroft city (Kerman provinces) and transported to the laboratory in 2022. Uniform fruits at the commercial mature stage were immersed in solutions containing spermine and spermidine at concentrations of 0.0, 1.0, and 1.5 mM. After immersion, the fruits were air-dried in the laboratory

The fruits were stored in a refrigerator at 4 °C and various traits were measured on the 3rd, 6th and 12th days of storage. The experiment was a factorial experiment based on a completely randomized design with three replications. For each treatment, 20 fruits were considered in each replication.

2.2. The fruit weight loss

The weight of the fruits was measured with a digital scale. Percentage of weight loss was calculated by Formula 1 given by (Ali et al., 2011).

$$Weight\ loss\ = \left(Weight\ before\ storage\ -\ Weight\ on\ the\ purpose\ day\right) / \ Weight\ before\ storage\ \times\ 100 \quad (1)$$

2.3. The fruit firmness

To measure the firmness of strawberry fruits, 5 fruits were randomly selected from each replication and measured using a pentometer (LUTRON FR-5120, made by Taiwan).

2.4. Total soluble solids

A digital refractometer (ATAGO – N1 and made by Japan) was used to measure total soluble solids. A few drops of fruit juice extract were poured on the device's detector and the amount of total soluble solids was recorded.

2.5. Titratable acidity content

To measure titratable acidity, the titration method was used with 0.1 normal NaOH until the pH of the extract reached 8.1 to 8.3. The titratable acidity was calculated according to the following Formula 2 and expressed as a percentage of citric acid (the dominant organic acid of strawberry).

$$Total\ acidity\ = \left(NaOH\ volume\ \times\ 0.064\right)\ /\ sample\ volume \quad (2)$$

2.6. Vitamin C content

Vitamin C content was determined using the Malik and Singh (2006) method, by titration with potassium iodide. The amount of vitamin C was calculated using the following Formula 3 in terms of milligrams per 100 g:

$$Vitamin\ C\ = amount\ of\ consumed\ iodine\ solution\ \times\ 0.88\ \times\ 100\ /\ 25 \quad (3)$$

2.7. Total anthocyanin content

To measure the total anthocyanin content, two buffers with pH 1 and 4.5 were first prepared and then 1.5 mmol (mL) of each sample was mixed with 2.5 mmol of the prepared buffers and their absorbance was read at 520 and 700 nm wavelengths. Finally, the total absorption of each extract was calculated using the following Formula 4:

$$A = \left[\left(A_{520} - A_{700}\right)_{pH1} - \left(A_{520} - A_{700}\right)_{pH\,4.5}\right] \quad (4)$$

where: A = Absorption rate.

2.8. Taste index and juice pH

The taste index was obtained by dividing the soluble solids by the titratable acidity. The pH of fruit juice was measured with a pH meter (110, Jenway and made by UK).

2.9. The fruit decay

The decay percentage was evaluated by observation. After observing the spread of mold mycelium on strawberries and the formation of brown spots on the surface, the fruits were removed. The amount of spoilage was calculated as a percentage of all fruits.

2.10. Statistical analysis

The experiment was a factorial experiment based on a completely randomized design with three replications. The data were analyzed using MSTAT-C software and the mean values were compared with Duncan's Multiple Range Test at the probability level of 1%. Also, the heat map correlation analysis was visualized by MetaboAnalyst

3. Results

The interaction effect of polyamines and storage time on all measured indicators was significant. The fruit weight loss increased during the storage period. Throughout the experiment, the highest amount of fruit weight loss was related to the control treatment. On the third and sixth days, the lowest amount of fruit weight loss were observed in the plant treated by 1 and 1.5 mM Spm and 1.5 mM Spd. On the 12th day, the fruits treated by 1.5 mM Spm showed the lowest weight loss (Table 1). The fruit decay increased during the storage period. No decay was observed on the third day. On the sixth and twelfth days, the fruits of the control treatment showed the highest rate of decay. On the 6th and 12th day, the fruits treated with 1.5 mM Spm and Spd had the lowest decay rate (Table 1). Also. the results of correlation analysis showed different positive and negative significant correlation among the studied characters (Figure 1).

The fruit soluble solids increased during the storage period. On the third and sixth days, the highest soluble solids content was observed in the fruits of the control treatment (Figure 2a). On the third day, fruits treated with Spm and Spd 1.5 mM had the lowest amounts of soluble solids. The lowest amount of soluble solids was observed on the sixth day in the fruits treated by 1.5 mM Spd and on the twelfth day in the fruit treated by Spd treatments.

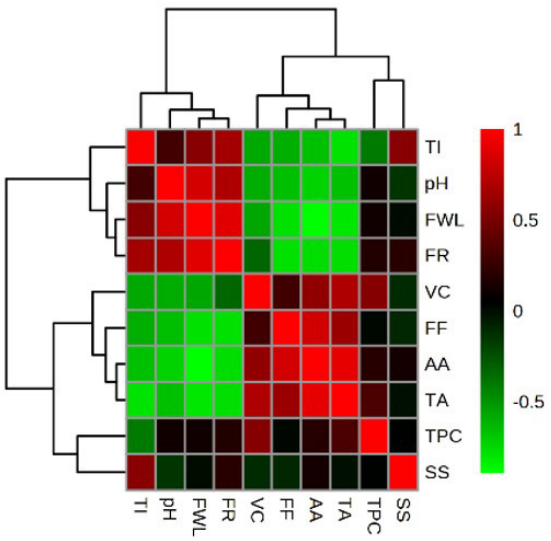

Figure 1. Heat map correlation among the measured characters. Each square indicates r (Pearson's correlation coefficient). TI: taste index; FWL: fruit weight loss; FR: fruit rot; VC: vitamin C; FF: fruit firmness; AA: antioxidant activity; TA: titratab acid; TPC: total phenolic content; SS: soluble solids.

Table 1. The interaction effect of storage period (0, 3, 6, and 12 days after harvest) and Spm and Spd on fruit weight loss and fruit rot.

Treatments	Fruit weight loss (%)			
	0	3	6	12
Control	-	14.56^{f}	40.85^{b}	100.00^{a}
Spm 1 mM	-	3.65^{h}	23.37^{de}	38.22^{b}
Spm 1.5 mM	-	1.02^{h}	19.82^{e}	26.39^{d}
Spd 1 mM	-	9.90^{g}	29.02^{c}	40.85^{b}
Spd 1.5 mM	-	1.15^{h}	19.82^{e}	31.65^{c}
	Fruit rot (%)			
Control	-	0.00^{g}	50.00^{b}	100.00^{a}
Spm 1 mM	-	0.00^{g}	20.00^{d}	27.00^{c}
Spm 1.5 mM	-	0.00^{g}	7.33^{f}	14.33^{e}
Spd 1 mM	-	0.00^{g}	21.33^{d}	28.30^{c}
Spd 1.5 mM	-	0.00^{g}	8.66^{f}	15.66^{e}

Means with the same letter in each column and row do not have a significant difference at the one percent level of Duncan's Multiple range test.

The amount of titratable acids decreased during the storage period. On the third and sixth day, Spm and Spd (1 and 1.5 Mm) treatments had the highest titratable acids contents (Figure 2b). On the twelfth day, the highest amounts of titratable acid were observed in the fruits treated by 1 and 1.5 mM Spm and 1.5 mM Spd. The fruit taste index increased during the storage period (Figure 2c). On the third and sixth days, the highest amount of taste index was observed in the fruits of the control treatment. On the third day of storage, Spd and Spm (1.5 mM) had the lowest taste index. On the sixth and twelfth days, the fruits of the 1.5 mM Spd treatment had the lowest taste index.

The acidity of fruit juice increased during the storage period (Figure 2d). The fruits of the control treatment had the highest acidity on the third and sixth days, and the fruits treated with 1.5 mM Spm had the lowest acidity on the third day. On the sixth day, the fruits treated with Spm and Spd had significantly less acidity than the control treatment. On the twelfth day, the acidity of the fruits of the 1.5 mM Spm and Spd treatment was significantly lower than the other treatments (the control treatment was removed from the experiment and the corresponding number was considered zero).

The vitamin C content of the fruits decreased during the storage period (Figure 3a). On the third and sixth days, the fruits of the control treatment had the lowest amount of vitamin C, and the fruits of the 1 mM Spm and 1.5 mM Spd treatments had the highest amount of vitamin C. On the twelfth day, the highest amount of vitamin C was observed in the fruits of 1 mM Spm treatment.

The firmness of the fruit texture decreased during the storage period. During the storage period, the fruits of the control treatment had the lowest level of firmness. On the third and sixth days, fruits treated with Spm 1.5 mM and on the twelfth day, fruits treated with Spd 1.5 mM had the highest firmness (Figure 3b).

The phenolic compounds content in the fruits of the control treatment was significantly lower than the other treatments during the storage period (Figure 3c). On the third and sixth day, no significant difference was observed between Spm and Spd treatments. On the twelfth day, fruits of 1.5 mM Spm treatment had lower content of phenolic compounds than other polyamine treatments. The highest values of antioxidant activity were observed in fruits treated with 1.5 M of Spm and Spd (Figure 3d). The fruits of the control treatment had the lowest antioxidant activity during the storage period.

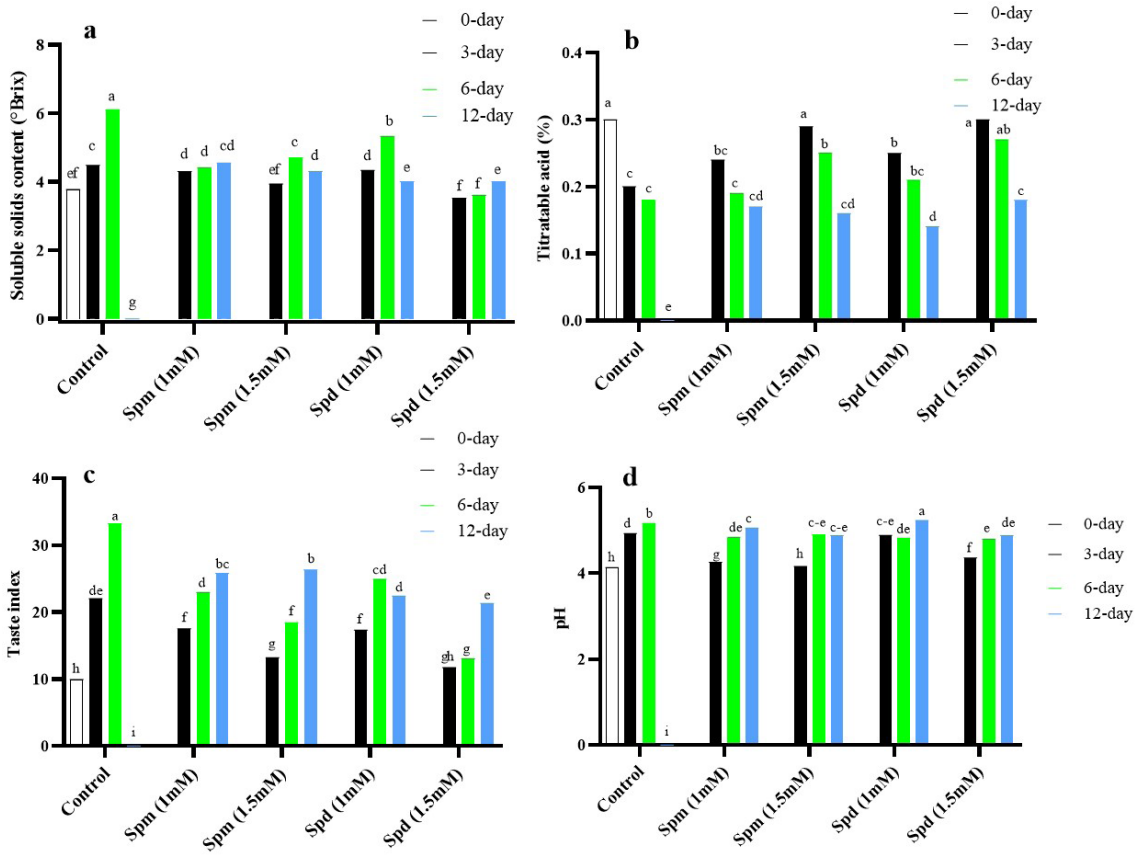

Figure 2. The interaction effect of storage time and Spm and Spd on soluble solids content (a), titratab acid (b), taste index (c), and pH (d). Means with the same letter in each column and row do not have a significant difference at the one percent level of Duncan's Multiple range test.

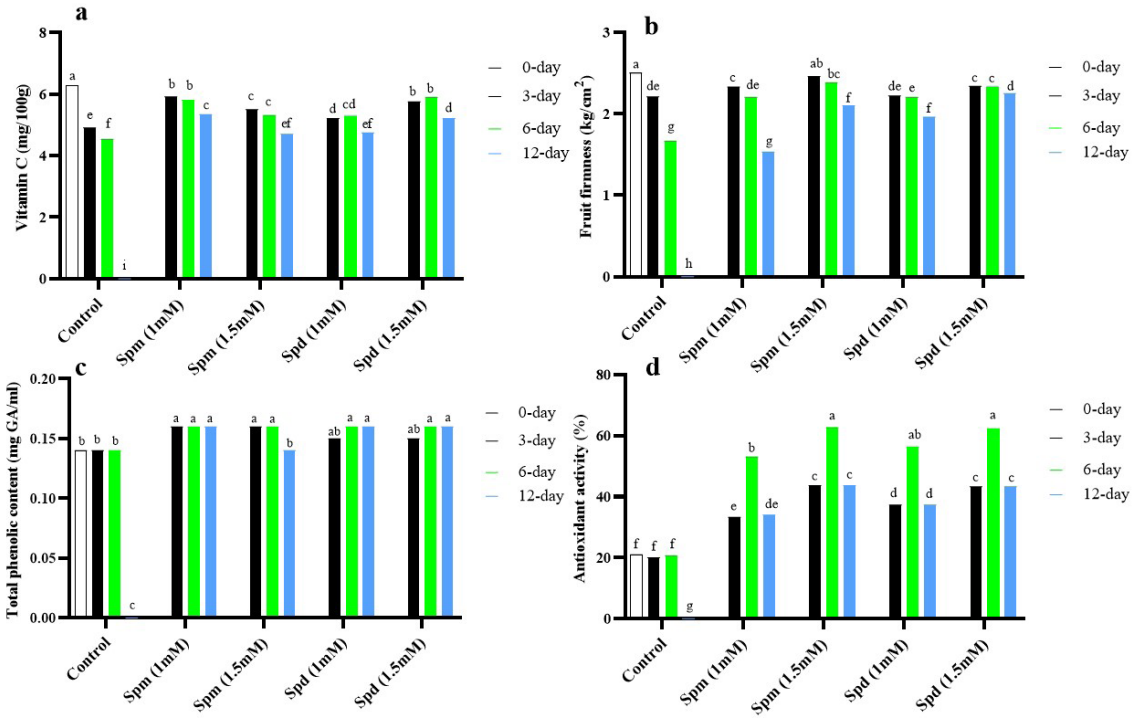

Figure 3. The interaction effect of storage period and Spm and Spd on vitamin C content (a), fruit firmness (b), total phenolic content (c), and antioxidant activity (d). Means with the same letter in each column and row do not have a significant difference at the one percent level of Duncan's Multiple range test.

4. Discussion

During storage, the weight loss percentage of strawberry fruits significantly increased. Weight loss is a common issue after harvest and can result in significant economic losses due to reduced fruit weight and quality. Strawberries are particularly susceptible to weight loss and fungal contamination due to their fragile structure and thin coating (Sun et al., 2020). Additionally, high metabolic activity causes rapid weight and quality loss in post-harvest conditions (Yoon et al., 2020; Shafiee et al., 2010).

The application of Spm and Spd significantly prevented fruit weight loss during storage, as evidenced by a decreasing trend in weight loss with increasing concentrations of Spm and Spd. Similar results have been reported in various fruits treated with polyamines, including strawberry (Mortazavi et al., 2012), peach and nectarine (Bregoli et al., 2002) and pomegranate (Mirdehghan et al., 2007). Mirdehghan et al. (2007) suggested that polyamines improve membrane fluidity, enhance plasma membrane health, and prevent water loss during storage. In addition, the prevention of fruit weight loss may be attributed to the increase in tissue antioxidant activity following the application of Spm and Spd, which limits oxidative damage to the plasma membrane (Zahedi et al., 2019). This is crucial for preventing water loss and minimizing respiration intensity during storage.

Fruit firmness is an important indicator of product freshness and quality (Yoon et al., 2020).

A decrease in tissue firmness was observed in harvested fruits with increasing storage time. Strawberry softening during storage reduces its postharvest life and increases its susceptibility to fungal contamination (Sogvar et al., 2016). Since strawberry fruit is a non-climacteric product, the reduction in texture hardness indicates product aging and deterioration under storage conditions (Hernandez-Munoz et al., 2008). Strawberry softening is associated with the destruction of the middle layer of cortical parenchyma cells, which results in a significant increase in pectin solubilization, with minor changes in pectin molecular weight and a slight decrease in hemicellulose content (Koh and Melton, 2002). The decrease in firmness during storage is linked to the conversion of insoluble pectin proportions to soluble forms, resulting from ripening and aging (Parveen et al., 2015). In addition to cell wall destruction, the loss of tissue stiffness in postharvest conditions is due to the loss of cell turgor (Shafiee et al., 2010).

The application of Spm and Spd increased fruit firmness during storage. Increasing the concentration of Spm or Spd enhanced firmness in fruit tissue, with the best results observed at a concentration of 1.5 mM. Mortazavi et al. (2012) also demonstrated that Spm and Spd application preserved the firmness of strawberry fruit tissue during storage. The role of polyamines in delaying fruit softening can be attributed to their effects on increasing cell wall stability (Bonghi et al., 1998). Leiting and Wicker (1997) showed that Put and Spd treatment decreased pectinesterase enzyme activity, thereby preventing grapefruit softening.

Valero et al. (2002) suggested that polyamines may help maintain fruit quality by making cell walls less accessible to degrading enzymes, such as pectinesterase and polygalacturonase. Khan et al. (2007) demonstrated that pre-storage Put application delayed fruit softening during cold storage by suppressing ethylene biosynthesis. Due to their positive charge, polyamines strengthen cell walls by cross-linking with the carboxyl group (COO-) of pectic substances in the cell wall, resulting in wall strengthening and reinforcement (Champa et al., 2014). This binding also hinders the access of cell wall-degrading enzymes, including pectin methylesterase (PME), pectinesterase (PE), and polygalacturonase (PG), and slows the rate of softening during the storage period (Valero et al., 2002). Champa et al. (2014) reported lower PME activity in fruit treated with Put or Spd. PME-induced pectin chain modifications determine the accessibility of galacturonans to degradation by polygalacturonases (Barnavon et al., 2001).

Fungal contamination can contribute to the loss of fruit firmness and weight during cold storage, as well as affect the quality of the product (Mirdehghan and Rahimi, 2016). Due to its structure and lack of protective coating, strawberry fruit is susceptible to post-harvest diseases (Jamali et al., 2013). In this study, the spread of fungi in the treated fruits during storage showed an increasing trend, leading to complete rotting of all fruits in this treatment group by the end of the experiment. Given the susceptibility of strawberry fruit to post-harvest diseases, it is crucial to identify methods to reduce contamination and maintain product quality.

The results of the present study demonstrate a reduction in fungal contamination of strawberries treated with polyamines during storage. These effects were enhanced by increasing the concentration of Spm and Spd, with the most inhibitory effects observed at a concentration of 1.5 mM. Khosroshahi et al., (2007) also showed that polyamines may affect the fungal contamination of strawberry fruit during storage. They demonstrated that Put-treated fruits had less fungal infection than the control group, resulting in an increase in the shelf life of strawberry fruit from 7 to 14 days. These findings are consistent with those of Mirdehghan and Rahimi (2016), who showed that the application of polyamines limited postharvest fungal contamination of grapes.

Although there are few reports on the antimicrobial activity of polyamines on horticultural products and their interaction with pathogens, increased levels of polyamines have been associated with reduced oat leaf contamination by brown rust (*Puccinia hordei*) and powdery mildew (*Blumeria graminis* F.sp. Hordei) fungi. Therefore, it can be concluded that polyamines may play a role in plant defense against pathogens. Increasing cell wall stability after polyamine application is not ineffective in this regard. As explained regarding the effects of polyamines on increasing fruit tissue firmness, these compounds can enhance the stability and strength of the cell wall during storage, which is crucial as a barrier limiting fungal penetration into the fruit. Due to their positive charge, polyamines can attach to the wall and make it less accessible to degrading enzymes, such as pectinesterase and polygalacturonase, thereby limiting fungal penetration into the fruit (Valero et al., 2002).

Soluble solids content increased with storage time in the control fruits, contrary to the expected decrease in mature fruit due to respiration after ripening. A plausible explanation for this increase is the significant water loss suffered by strawberries during storage, particularly for those that experienced the most water loss. As water is lost, the cell sap becomes more concentrated, resulting in an increase in soluble solids content and subsequent calories per unit weight. Solubilization of polyuronides and cell wall hemicelluloses in mature strawberries may also contribute to increased soluble solids content (Hernandez-Munoz et al., 2008). Consistent with this hypothesis, the increase in soluble solids content was accompanied by a decrease in fruit firmness. The amount of fruit calories in the control treatment also increased during the storage period, likely due to an increase in sugar compounds resulting from cell wall destruction and fruit tissue softening, as well as the conversion of organic acids into simpler carbohydrates. The rate of organic acid decrease was higher in the control treatment than in other treatments.

The application of Spm and Spd decreased the amount of soluble solids compared to the control, with the lowest soluble solids observed at a concentration of 1.5 mM for both polyamines. Similar results have been reported for postharvest polyamine application on other fruits (Zokaee Khosroshahi and Esna-Ashari, 2008; Davarynejad et al., 2013). This effect can be attributed to a decrease in respiration rate and ethylene production, and delay in the ripening process (Davarynejad et al., 2013). Therefore, an inverse relationship between polyamine concentration and total soluble solids content during storage can be concluded. Asghari and Abdollahi (2013) suggested that the effects of polyamines in reducing ethylene synthesis and respiration rate may reduce the need for sugar consumption, leading to less conversion of organic acids into sugar.

The titratable acidity of strawberry fruit is directly related to the content of citric and malic acids (Saleem et al., 2021). In the present study, titratable acidity decreased during storage, with the control treatment showing the greatest decrease. These results are consistent with the findings of Khosroshahi et al., (2007) and Sogvar et al., (2016). The reduction in titratable acidity during storage may be due to metabolic changes in the fruit caused by the consumption and conversion of organic acids in the respiration process (Echeverría and Valich, 1989). Khosroshahi et al. (2007) concluded that the inhalation of untreated strawberries (due to rapid fungal infection growth, ethylene production, and fruit aging) stimulates the consumption of organic acids and reduces the titratable acidity of the fruit. Along with the degradation of titratable acids, the pH of fruit juice also increased during storage, consistent with the report of Khosroshahi et al. (2007). The increase in juice pH in the control treatment (with the highest acid degradation) was greater than in the other treatments, leading to a greater reduction in the sour taste of the fruit compared to other treatments.

The application of Spm and Spd increased the titratable acid content in stored fruits, consistent with similar results observed after post-harvest polyamine application in other fruits (Mirdehghan and Rahimi, 2016; Davarynejad et al., 2013). Maintaining or increasing the content of organic acids in the fruit indicates a delay in fruit ripening, one of the specific effects of polyamines that has been reported in many fruits such as mango (Malik and Singh, 2006). However, Cordenunsi et al. (2003) found no significant changes in titratable acidity or pH of strawberry cultivars during a one-week storage period, likely due to the short storage period in their study. Ishaq et al. (2009) suggested that the reduction of titratable acidity could be due to the consumption of organic acids in fruits during respiration. In the present study, it appears that polyamine treatments had a significant effect on the processes of respiration and ethylene biosynthesis, which can reduce or delay respiration and maintain titratable acidity (Davarynejad et al., 2013). Therefore, by maintaining the titratable acidity in the fruit, the increase in pH of the fruit juice was limited during the storage period. As a result, fruits treated with polyamines had a more sour taste than untreated fruits.

The change in fruit taste during storage is due to a slight sweetening and decrease in acidity, which can make the fruit tasteless (Mirdehghan and Rahimi, 2016). In the present study, an increase in soluble solids and decrease in titratable acidity of fruit juices were observed during cold storage. This significantly increased the ratio of soluble solids to titratable acidity of the fruit juice, as reported for grape and pomegranate fruits (Meighani et al., 2015) and consistent with the findings of Maraei and Elsawy (2017) and Yoon et al. (2020). However, different results have been reported in some studies. For example, Majeed et al. (2014) reported no significant changes in pH, soluble solids, or titratable acidity in 'Corona' strawberries treated with different doses of gamma radiation, as well as non-irradiated fruits that were stored at 16-18 degrees Celsius for 9 days. They suggested that this may be partly due to the non-secretory characteristics of strawberries and the relatively low temperature during the storage period. In the present study, the loss of water and decrease in titratable acidity, along with an increase in soluble solids, contributed to changes in fruit taste in the control treatment.

The vitamin C content decreased significantly in the control treatment during storage, consistent with the findings of Ishaq et al. (2009) and Davarynejad et al. (2013). Autoxidation, which occurs spontaneously when vitamin C combines with oxygen in the air, is a possible reason for the loss of vitamin C during storage (Sogvar et al., 2016). Additionally, vitamin C is used as an antioxidant agent to inhibit reactive oxygen species during storage (Nazoori et al., 2020).

The application of Spm and Spd significantly prevented the destruction of vitamin C in the fruit tissue, with the most efficient treatments being 1.5 mM Spm and Spd. Mortazavi et al. (2012) The application of Spm and Spd significantly prevented the destruction of vitamin C in the fruit tissue, with the most efficient treatments being 1.5 mM Spm and Spd. Malik and Singh (2006) who attributed this effect to the reduction of ascorbate oxidase enzyme activity in the presence of these nitrogenous compounds. Ishaq et al. (2009) suggested that the decrease in ascorbic acid content during storage could be due to the conversion of dehydroascorbic acid to dictogulonic acid by oxidation. The effect of Spm and Spd on vitamin C content may also be attributed to the reduction or delay of ascorbate oxidase activity (Zhang et al., 2018). Moreover, due to their strong antioxidant activity, polyamines can prevent the oxidation of vitamin C during fruit storage. The evaluation of the effects of polyamines on the fruit phenolic compound content and antioxidant activity of the tissue supports this hypothesis.

In the present study, the content of phenolic compounds in the control treatment did not show any significant difference during the storage period. Costa et al. (2006) reported an increase in phenolic content of broccoli with aging during storage, Ashtari et al., (2019) showed a decrease in total phenolic compounds and anthocyanins of pomegranate during storage. The use of different treatments caused a significant increase in these compounds compared to the control. The antioxidant activity of fruit is contributed by several bioactive compounds such as phenolics, flavonoids, ascorbic acid, anthocyanins, etc. The evaluation of antioxidant activity of whole fruits and vegetables has become increasingly important as people have become more health conscious, providing valuable information about the quality and nutritional value of fruits (Kumari et al., 2015).

Strawberries are an important source of bioactive compounds such as phenols, with primary phenolic compounds including anthocyanins, flavanols, and ellagic acid derivatives (Ariza et al., 2016), that have antioxidant, anti-inflammatory, anticoagulant, antimicrobial, and anti-cancer properties (Landete, 2011). Mortazavi et al. (2012) reported a clear relationship between the content of phenolic compounds and antioxidant activity, with the antioxidant activity of phenols being one of their most important biological properties (Sogvar et al., 2016). Therefore, it is important to maintain higher levels of these compounds during storage and shelf life. Consistent with the results of the present study, Hassanpour (2015) and Sogvar et al. (2016) reported an increase in phenolic content of stored strawberry fruits. The reduction in titratable acids and organic acids, through interconversion to carbohydrates, may provide carbon skeletons for phenolic synthesis, including anthocyanins and non-anthocyanin phenolics (Kalt, 2005).

The increase in antioxidant activity in fruits treated with Spm and Spd may be due to the effects of these compounds in increasing the phenolic compounds and vitamin C content of the fruit. Mirdehghan et al. (2007) reported an increase in phenolic compounds and antioxidants in pomegranate fruits treated with Spd or Put. Phenolic acids present in fruits are highly oxidative and produce brown-colored compounds that also exhibit antioxidant activity (Jimenez et al., 2002). The antioxidant properties of polyamines have been demonstrated in many studies. Therefore, the higher levels of these compounds in fruits treated with polyamines could be attributed to their antioxidant properties. Additionally, polyamines reduce the rate of respiration and ethylene production, preventing the breakdown of cell walls, which leads to a reduction in the production of reactive oxygen species and a lower need for vitamin C and phenolic consumption to remove them (Zhu et al., 2006).

5. Conclusion

In conclusion, this study demonstrated that the application of Spm and Spd can effectively extend the postharvest life of strawberry fruit and preserve its quality during storage. These compounds, when used in small quantities as plant growth regulators, do not have any harmful environmental effects or pose any risk to consumers. The optimal concentration of Spm and Spd was found to be 1.5 mM, which resulted in the best outcomes. The results of this study suggest that the use of Spm and Spd can be a promising approach to improve the postharvest quality and shelf life of strawberries, which could have significant economic and environmental benefits for the fruit industry. Further research is needed to explore the underlying mechanisms of the beneficial effects of Spm and Spd on strawberry fruit quality and to optimize their application methods to achieve the best outcomes.

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