Effect of calcium chloride and 1-methylcyclopropene combined treatment on pectin degradation and textural changes of Eureka lemon during postharvest storage

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ABSTRACT

During post-harvest storage, the cell wall properties are closely associated with the physical, chemical, and biological properties of the fruit. The degradation of pectin in the cell walls and middle lamella is critical to these properties. The effects of calcium chloride (CaCl₂) and 1-methylcyclopropene (1-MCP) combined treatment on the pectin degradation, texture, and peel color of Eureka lemon were investigated during post-harvest storage. The in-situ light microscope analysis, rapid method, and FTIR test were used to investigate the spatial distribution, the pectin content, and its degradation. The results showed a reduction in pectin degradation, by 42 d the CaCl₂ and 1-MCP combined treated fruits presented a 36.7% pectin content loss which was lower than the control which was 48.3%. The treated fruits significantly exhibited enhanced textural properties, delayed weight loss, higher total acids, and improvement of other physicochemical properties in comparison to the control. The treatment deaccelerated the fruit peel color change from green to yellow and also had a better visual appearance on the final day. Overall, the results suggest that the control treatment for pectin degradation can reduce the fruit texture decline and peel color change and maintain a good visual appearance. The influence of pectin degradation on the texture and physicochemical properties of lemon provides a theoretical basis for fruit storage optimization, quality control, and shelf-life extension.

1. Introduction

Citrus are non-climacteric fruits with great importance throughout the world, with lemon being the third most important species (Gonzalez-Molina et al., 2010). *Citrus limon* (L.) Burm (Eureka lemon) is the main lemon variety cultivated with a wide range of economical, medicinal, and biological properties and is rich in important natural compounds including, phenolic compounds, vitamins, minerals, dietary fiber, essential oils, and carotenoids (Gonzalez-Molina et al., 2010; Makni et al., 2018).

The texture and storage of fruits are two of the main problems which affect consumption and economic benefits (D. Li et al., 2019). Also, the appearance of the fruit significantly impacts buyers, color is considered to be one of the most important external factors, and it relates to maturity or tastes and influences commercial activity on the market (Li et al., 2020). Previous studies found that among fruit cell components, the cell walls have the most important influence on the texture of the tissues, with pectin being a major component (Chatjigakis et al., 1996; C. Zhang et al., 2019). Changes and degradation of pectin have been proposed as the primary cause of the softening of fruits during ripening which led to the cell wall loosening and disintegration (Defilippi et al., 2018). Over the years pectin has attracted a lot of interest due to its biological, physical, and chemical properties. Citrus fruits are known for the abundance of pectin in the cell walls of their peels with varied composition and structure which makes it useful in various fields and it is one of the main sources of commercial pectin (Adetunji et al., 2017). In this study, a microscopic in-situ analysis of pectin was applied to give a better understanding of the intrinsic changes that occurred in the peels of the fruit. This is because, in ex-situ pectin analysis, several processes such as extraction and drying are implored which degrades it to a certain

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degree during the process.

Many research works have been focused to develop the best and most affordable method to preserve different kinds of fruits. Approaches such as treatment with methyl jasmonate and salicylic acid (Habibi et al., 2019; Serna-Escolano et al., 2021), CaCl₂ (Tsanitli et al., 2015), and 1-MCP (Dou et al., 2015; Baswal et al., 2021) have been investigated for citrus and other fruits. Individual or combined application of these treatments has been observed and surmised to have anti-ripening and/or anti-senescent activities on fruits during postharvest storage.

Calcium has wide applications such as extending the shelf life of fruits and maintaining its firmness for a long period (Shaheen et al., 2010, L. Zhang et al., 2019). CaCl₂ treatment retarded firmness loss and peel color changes of lemons without affecting the characteristics of the juice (Tsanitli et al., 2015). 1-MCP is a widely used endogenous ethylene inhibitor and suppresses the activity of cell wall-lysing enzymes, thereby delaying the softening (Wei et al., 2020). It is an effective, low-cost option, hazardous-free in its application with revealed economic value and commercial potential, but mainly used in the treatment of climacteric fruits due to its mode of action (Watkins 2006; Sozzi and Beaudry 2007). In apples, 1-MCP curtailed the decomposition of cell walls, and did not require further purification. They were supplied by Kelong Co. Ltd., and Tianjin Zhiyuan Chemical Reagent Co., Ltd. Aladdin Biochemical Technology Co., Ltd. (Shanghai, China), Chengdu grade and did not require further purification. They were supplied by Kelong Co. Ltd., and Tianjin Zhiyuan Chemical Reagent Co., Ltd.

2. Materials and method

2.1. Materials

For this study, physiologically mature green Eureka lemons (260–400 g) with similar shape and skin color were harvested retaining a small button of the stalk in September, and immediately transported to the laboratory. They originated from an orchard in the Dongxing District, Neijiang, China. All chemical reagents used were of analytical grade and did not require further purification. They were supplied by Aladdin Biochemical Technology Co., Ltd. (Shanghai, China), Chengdu Kelong Co. Ltd., and Tianjin Zhiyuan Chemical Reagent Co., Ltd.

2.2. Pre-treatment

All fruits were carefully inspected and all bruised and wrinkled fruits were removed from the lot. The 360 fruits selected were then divided into four lots based on their sizes. All the four lots were then further divided into two groups. Lemons in the first group were thoroughly washed, rinsed under running water to reduce surface contamination, fully immersed in distilled water for 25 min, air-dried, and then stored as control. The second group was subjected to the CaCl₂ treatment as described by Tsanitli et al. (2015) with some modifications. They were fully immersed in a 0.18 M CaCl₂ solution, gently rubbed, and left in the solution fully immersed for 25 min with the help of a net. The fruits were taken from the solution and then air-dried; these treatments were completed within 12 h after receiving them. The 1-MCP treatment was performed as described by Baswal et al. (2021) with some modifications. The fruits were treated with 1-MCP (1250 ppb), which was placed in the center of the fruits in a controlled-atmosphere acrylic box. The boxes were sealed and stored in a thermostatic room at 20 °C for 24 h. The control fruits were also completely sealed in empty boxes and stored in a thermostatic room at 20 °C for 24 h. The control and treated fruits were stored in two separate thermostatic rooms under ambient temperature for 42 days. Fruits were selected from all four lots of both control and treated for every assay.

2.3. Physicochemical properties

Weight loss (WL) was measured by weighing the fruit on the first day (W₁), and at different sampling dates (7, 14, 21, 28, 35, and 42 d) during storage (W₂). WL was calculated according to equation (1):

\[
WL \cdot (\%) = \frac{W_1 - W_2}{W_1} \times 100 \%
\]

The moisture content (MC) of the peels of the fruits was evaluated based on losing weight in an oven at 105 °C for 24 h (Hosseini et al., 2019). MC was calculated according to equation (2):

\[
MC\% = \frac{W_1 - W_2}{W_1} \times 100 \%
\]

where W₁ is the initial weight of the lemon and W₂ is the final weight after drying.

Drying Rate was also expressed on the fresh weight bases per the dry weight and time, gH₂O kg⁻¹ h⁻¹.

The total acid content (TA) was determined by titrating the juice with 0.1 M NaOH to the endpoint. TA was calculated according to equation (3):

\[
TA (\text{g} / L) = \frac{V \times C \times f \times B}{b \times A}
\]

where V is the volume of NaOH used; C is the concentration of NaOH used; f is the conversion coefficient, which is 0.064 in terms of the main acid containing citric acid; b is the volume of diluted sample; B is the volume of the sample prepared; A is the volume of juice used.

The color measurement of lemon peels was conducted by Color Meter Max (CHNSpec Technology Co., Ltd, Zhejiang, China) at four opposite points along the fruit’s equator. This was per the internationally accepted standard of CIE L*, a*, b* values, where L* denotes lightness, a* denotes chromaticity on a green (−) to red (+) axis, and b* indicates chromaticity on a blue (−) to yellow (+) axis (Pannitteri et al., 2018). Chroma (C*) which indicates color purity was calculated according to equation (4) and the citrus color index (CCI), was calculated according to equation (5),

\[
C^* = (a^*^2 + b^*)^1/2
\]
\[
CCI = -1000 \times \frac{a^*}{L^* \times b^*}
\]
2.4. Texture profile analysis

The texture of the fruits was measured using the double compression test with a TA.XT plus Texture Analyser (Stable Micro Systems) using a P100, 100 mm compression platen probe (Frempong et al., 2022). For every test day, 12 parallel measurements were made under the same experimental conditions for both the control and treated fruits. From each lot, 3 fruits were selected and the tests were performed in the stem-calyx axis orientation in the horizontal direction to the base. The operating conditions were: test speed 5 mm/s, trigger force 10 g, and compression distance 10 mm. The force deformation curve obtained from each test was interpreted using the software Exponent v.6 (Stable Micro Systems). For credible data, both the minimum and maximum values of the measured fruits were removed and the remaining 10 data were averaged and recorded for the fruits on every test day.

2.5. Pectin content

A rapid and quantitative method was employed with some modifications (Shelukhina and Fedichkina 1994). Approximately 0.2 g of dried pulverized peels were moistened with 1 mL ethanol. Then 10 mL distilled water was added, followed by the addition of 1 mL of 1 M NaOH which was mixed for 20 min at 20 °C. The solution was then acidified with 1.5 mL of 1 M HCl. Afterward, 50 mL of 0.1 M HCl was added to precipitate the solution and then stirred and kept for 5 min at room temperature. The final volume was measured and the mixture was filtered. Then 10 mL were pipetted from the filtrate into a flask, with the residue of the filter pooled together with the remaining filtrate. The funnel and vial were washed twice with distilled water and added to the residue-filtrate mixture and thoroughly stirred. The filtrate and mixture were separately titrated with 0.1 M NaOH using Hinton’s indicator. The HCl content of the original volume was calculated from the results of the titration of the 10 mL filtrate. Results obtained from the titration of the pooled mixture and 10 mL filtrate was used to determine the pectin content. The total amount of pectin was calculated according to equation (6):

\[ \text{Pectin Content} \% = \left( \frac{V_2 - V_1}{1000 \times W} \times 176 \times 0.1 \times K \times 100 \right) \]

where \( V_1 \) is the calculated volume of 0.1M NaOH required for the titration of HCl in the entire reaction mixture, (mL); \( V_2 \) is the volume of 0.1M NaOH for the titration of the entire reaction mixture, (mL); \( K \) is the coefficient to the NaOH concentration; 176 is the gram equivalent of the pectic acid; \( W \) is the weight of sample, (g); 0.1 is the concentration of NaOH, (M).

2.6. Pectin extraction

Peels were finely cut into small pieces and then dried in an oven at 45 °C to a constant weight. Afterward, the dried peels were pulverized and sieved. Pectin was extracted using 50 LSR and Citric acid (pH 1.5) as extractant. The mixture was microwaved, with operating conditions as follows; duration of exposure set for 8 min and 0.45 kW for power. After extraction, the glass vessel was cooled and the mixture was centrifuged at 10,000 rpm for 20 min to remove impurities. The filtrate was coagulated using a volume equal to one and a half of 96% ethanol and left for 16 h. The coagulated pectin was centrifuge at 10,000 rpm for 15 min and washed thrice with 96% ethanol. It was dried at 50 °C in a laboratory oven to a constant weight.

2.7. In-situ analysis of pectin (microscopic assay)

This method operates on the principle of staining esterified pectin as described by (Hornatowska 2005) with some modifications. Thin slices of the peel were cut and placed in 70% ethanol. The slices were then placed on a slide and covered with a few drops of freshly mixed alkaline hydroxylamine solution for 10 min. Afterward, 10 drops of a solution containing 1-part concentrated HCl and 2 parts of 95% ethanol were added. The solution was then removed from the material, then a few drops of ferric chloride solution in 60% ethanol containing 0.1 N HCl were added to stain it. The slide was dehydrated and observed under a microscope. The microscope was linked to a computer that took images of the samples. Micrographs of the samples observed were obtained by the software Leica Application Suite (LAS, Version 4.8.0) and the length of the micrographs was 500 μm.

2.8. FTIR

FT-IR spectra of the dry pectin powder were carried out using a Fourier transform infrared spectroscopy (FTIR; Nicolet-6700; Perkin Elmer Instruments Corporation) with the KBr method in the wavenumber range of 4000–500 cm⁻¹ and resolution of 4 cm⁻¹.

2.9. Statistical analysis

The results were analyzed using Excel 2016 (Microsoft) and Origin Pro 9.0 (Origin Lab Corporation, Northampton, USA). All data are expressed as the mean ± standard error of 3–10 replicates. Data were subjected to analysis of variance (ANOVA) and a multiple range test (Tukey’s HSD test) was carried out to find significant differences (P < 0.05) among treatments and storage time.

3. Results

3.1. Pectin analysis

The changes in the pectin content for the lemon fruits were monitored from 1 d to 42 d. The effect of treatment of the lemon fruits with CaCl₂ and 1-MCP on pectin is illustrated in Figs. 1–3. The results obtained from the rapid test showed that the pectin degraded with an increase in storage time. From Fig. 1, the pectin content significantly decreased from 25.9% to 13.4% by 42 d for the control and 25.9%–16.4% for the treated fruits. The final pectin content of the treated fruits
**Fig. 2.** Light microscope micrographs of changes in the sections of Lemon peel stained with Hydroxylamine-ferric chloride for esterified pectin during storage. Showing pectin in the middle lamella and cell walls in different gradients of red. Data is from 1 d to 21 d, for both control and treated fruits. The length of the micrograph is 500 μm.
by 42 d was in a similar range to that recorded for the control by 28 d. This decline in the pectin content in both the cell wall and middle lamella was confirmed from the micrographs obtained from the microscopic assay. From both Figs. 2 and 3, it can be seen that the intensity of the red color was very high on 1 d. The intensity of the red color declined with an increase in storage time. The rate of decline in intensity between the control and treated peels was different. The micrographs of the control peels showed a higher rate of decline in the intensity of the red color, while that of the treated showed a more gradual decline. The somehow orange color observed from 28 d to 42 d indicates that the amount of pectin and the degree of esterification had decreased. It should be noted that the colors observed directly in the light microscope during the study are significantly better visible than those shown in the micrographs presented in the figures.

### 3.2. FTIR

FTIR test was performed on the pectin molecules from the lemon fruit at the various stages to depict the changes that occurred in the pectin during storage. From Fig. 4 there were broad bands observed between 3500 and 2800 cm\(^{-1}\) and bands at 3000 to 2800 cm\(^{-1}\). The peaks found in the region between 2000 and 1000 cm\(^{-1}\) represent the major chemical functional groups in pectin. Bands at 1749 cm\(^{-1}\) correspond to the absorption of esterified carboxylic groups whilst those observed at 1630 cm\(^{-1}\) corresponded to the non-esterified carboxylic groups (Chatjigakis et al., 1998). These peaks were seen in all the pectin

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**Fig. 3.** Light microscope micrographs of changes in the sections of Lemon peel stained with Hydroxylamine-ferric chloride for esterified pectin during storage. Showing pectin in the middle lamella and cell walls in different gradients of red-orange. Data is from 28 d to 42 d, for both control and treated fruits. The length of the micrograph is 500 μm and 100 μm for 35 d.
molecules at the various stages during storage. From Fig. 4, the intensity of the transmittance of the bands at 1749 cm\(^{-1}\) was observed to reduce while the intensity of the band at 1630 cm\(^{-1}\) increased from 1 d to 42 d with an increase in storage time for both the treated and control fruits.

### 3.3. Texture profile analysis

The variation in the texture of the treated fruits and the untreated fruits was revealed during the period of study from 1 d to 42 d. The hardness was 433.37 N on 1 d and it gradually decreased with an increase in storage time. There was a significant difference in the rate of decline for both the treated and control fruits. Within the first 7 d, there were no significant differences in the changes of hardness, but the differences were observed afterward till the final day. By 42 d the control lemon had lost 72.10% of its hardness during storage. From Fig. 5 the average hardness decreased to 121.01 N in the control and 151.81 N in the treated fruits by 42 d which was in a similar range as the control on 28 d.

The treatment also affected the cohesiveness, springiness, and resilience and it could be seen from Fig. 5 that the decline was retarded by the treatment. From Fig. 5 the cohesiveness gradually decreased in value from 0.84 to 0.70 and 0.84 to 0.74 for the control and treated fruits respectively with an increase in storage time. The springiness gradually decreased from 0.89 to 0.72 and 0.89 to 0.76 respectively for the control and treated fruits. The resilience also decreased from 0.59 to 0.32 and 0.59 to 0.36 for the control and treated fruits respectively. Comparatively, the fruits treated exhibited better resistance to loss in the textural properties.

### 3.4. Physicochemical properties

The WL during 42 days of storage under ambient conditions increased for both the control and treated fruits as shown in Fig. 6. By 42 d, the cumulative loss of weight was 28.7% and 23.2% for the control and treated fruits respectively. A significant WL occurred during storage. The final weight loss of the treated fruits by 42 d was in a similar range to that recorded for the control by 28 d.

The MC for the lemon fruits on 1 d was 83.3% as shown in Fig. 6. The moisture content of control decreased to 69.4% by 42 d. Loss of moisture remained without significant changes until 14 d of storage for the control and then strongly declined until the end of the study. But that of the treated remained without significant changes until 21 d of storage and then declined until the end of the study. The moisture content for the treated fruits decreased to 73.4% by day 42 d. Also, the drying rate was significantly reduced from 5.76 to 2.63 g H\(_2\)O kg\(^{-1}\) hr\(^{-1}\) and 5.76 to 3.20 g H\(_2\)O kg\(^{-1}\) hr\(^{-1}\) by 42 d for both control and treated respectively (Fig. 6).

Though there was a decline in both cases, the control was faster and had a lower final drying rate by 42 d as compared to the treated.

The effect of CaCl\(_2\) and 1-MCP treatment on the external color of lemon fruits during storage was evaluated. There was a significant difference observed in the external peel color and CCI between the treated and control fruits during storage. The color mostly remained green within the first 14 d of the treated fruits whereas that of the control faded substantially within the first 14 d. The external peel colors of both batches gradually turned yellow during storage, but the color change of the treated fruits was delayed over the period. Control fruits displayed a considerably higher CCI value than the treated fruits. At 42 d the CCI had increased from −9.27 to 1.04 and −9.27 to 0.31 for the control fruits and treated fruits respectively. The changes in the CCI correlated with the visual sense of changes in the color from green to yellow. The C\(^{+}\) also corresponded to the visual observation. The control increased from 29.20 on 1 d to 73.38 by 42 d whilst that of the treated fruits increased from 29.20 to 66.47.

TA content for both control and treated fruits increased during storage. There was no major difference in the TA values in both the control and treated fruits until 14 d. TA decreased from 7.39 g/L on 1 d to 6.31 g/L on 7 d before increasing to 7.51 g/L on 42 d in the control. Whereas the TA decreased from 7.39 g/L on 1 d to 6.35 g/L before increasing to 8.03 g/L on 42 d.

### 4. Discussion

The treatment retarded the rate of degradation of pectin in the peels of the lemon fruits. The decline in pectin content results in the decline of the primary cell wall’s firmness, increase in porosity, and strength of the intercellular connections between the cells. Therefore, a decrease in the degradation of pectin led to a decline in the rate of loss of these properties. 1-MCP is known to curtail the decomposition of the cell wall and suppress the cell wall degradation-linked genes and their associated enzyme activities (Watkins 2006; Win et al., 2019; Baswal et al., 2020). Also, the decline in the degradation of the pectin could be associated with the crosslink that was formed between Ca\(^{3+}\) and the carbonyl groups present in the pectin after the treatment with CaCl\(_2\). The calcium pectate formed during this reaction heightens the molecular bonding between the other cell wall components and pectin which increases the hardness of the fruit (Roushesh Saba and Sogvar, 2016; Liu et al., 2017; Jain et al., 2019). This could be the underlying reason for the decline in the rate of degradation of pectin during storage as shown in Fig. 1. The decline in the rate of pectin degradation is associated with the treatment of the fruits with both chemicals. A similar trend was observed in the combined treatment of new queen melons with CaCl\(_2\) and 1-MCP (Q. Zhang et al., 2019). The synergistic effect of both compounds greatly reduced the rate as compared to the individual treatments during the study period as reported by Zhang. Other studies also, confirmed that individual treatment of fruits with CaCl\(_2\) or 1-MCP delayed pectin degradation during storage (Liu et al., 2017; Win et al., 2019; L. Zhang et al., 2019; Baswal et al., 2020). Therefore, the observed decline in the rate of degradation is associated with the combined treatment of the fruits. The intensity of the red color is dependent on the amount of esterified pectin present since it stains primarily esterified pectin red (Hornatowska 2005). The high-intensity red color observed on 1 d,
represented a high pectin content in the peels of the lemon. The red color was mainly observed in the middle lamella and the cell walls. From the micrographs in Figs. 2 and 3 the intensity of the red color weakened with an increase in storage time which represented pectin degradation and a decline in DE during storage. Previous studies showed a strong relationship between pectin degradation and decline in DE of citrus fruits during postharvest storage (Frempong et al., 2022). Contrary to reports on the effect of the postharvest application of 1-MCP or CaCl$_2$ on PME and other cell wall enzymes activities, fruits such as Mandarin, two varieties of Ber fruit, and red raspberry showed a reduction in PME activities during storage after treatment (Jain et al., 2019; Baswal et al., 2020; Lv et al., 2020). This could support the reason why the rate of decline in the intensity of red color to the somewhat orange color for the control fruits was higher than that of the treated fruits. This showed that the combined treatment was effective in controlling the degradation of pectin. The decline in the intensity of color showed correlation with the decline in pectin content determined by the rapid test in Fig. 1. The micrographs showed the spatial distribution of the pectin molecules in the peels of the lemon fruit. With most of the pectin localized in the middle lamella as shown in Figs. 2 and 3 from 1 d to 42 d. The changes that occurred in the height or area absorbance peaks of the FTIR spectrum during storage gave further insight into the modification that occurred in the pectin molecules as shown in Fig. 4. Two of the most important peaks in pectin are found in the bands centered around 1749 and 1630 cm$^{-1}$. The peak area of the esterified carboxylic group and the sum of peaks of esterified (1749 cm$^{-1}$) and non-esterified carboxylic groups (1630 cm$^{-1}$) can be considered as DE (Chatjigakis et al., 1998; Hosseini et al., 2019), changes in these peaks give an estimation of the decline in the DE. From the FTIR spectrum, there was an obvious decline in the esterified carboxylic regions and an increase in the non-esterified carboxylic region over time, which confirmed the degradation of pectin. Also, the rate of decline in the control was more drastic as compared to the treated fruits and this confirmed the efficacy of the treatment on the fruits.

The texture change is highly dependent on pectin and its modification in the cell walls (Defilippi et al., 2018; Frempong et al., 2022). The treated fruits exhibited some level of delay in the degradation of the pectin and a similar trend was observed in the textural changes. The treatment gave further insight and confirmation to the claim that pectin played a major role in textural changes. Treatment of the fruits slowed down the degradation of pectin during storage, and this led to the decline in the rate of weakening of the cell walls and middle lamella which in turn retarded the loss of moisture as seen in Fig. 6. This contributed to the slower decline in hardness as observed for the treated fruits. According to the reference (Win et al., 2019; Baswal et al., 2020), 1-MCP was efficient in slowing down the loss of firmness of mandarin. The crosslink formed between pectin and Ca ions was reported to significantly increase the texture of lemons during storage after postharvest treatment with CaCl$_2$ (Valero et al., 1998, Koushesh Saba and Soqvar, 2016). These trends were similar to what was observed in this study. The difference in the cohesiveness, springiness, and resilience of both the control and the treated fruits can also be associated with the differences in the rate of degradation of pectin that occurred during storage. The degradation of pectin weakened the cell wall and its

![Fig. 5. Changes in the textural properties include (A) Hardness, (B) Springiness, (C) Cohesiveness, and (D) Resilience of Lemon during storage. Data represent the mean ± SE (n = 10). The sampling date interval is 7 d. Cohesiveness, springiness, and resilience were all expressed as a ratio, hence no units. Different letters above the error bars indicate a significant difference at P < 0.05.](image-url)
mechanical strength. This led to the decline in cohesiveness during storage because it is dependent on the structural integrity of the cell wall. Since the treatment slowed down the degradation of pectin, it can be seen in Fig. 5 that the decline in cohesiveness was retarded during storage in the fruits as compared to the control. The ability of the lemon fruits to resist and fight back to regain their original position and the rate of returning to the undeformed state is directly linked to the turgor pressure in cells in the epicarp, mesocarp, and endocarp. The improvement in retaining the pectin structure and content over a longer period due to the treatment with CaCl₂ and 1-MCP, led to the decline in the rate of loss of moisture, as shown in Figs. 1 and 6. Despite the textural changes being mainly controlled by the pectin degradation, a correlation can also be seen between the color of the peels and the texture. It can be seen that all the textural parameters dropped rapidly on 14 d after the fruits’ color significantly changed from green to yellow in the control fruits. But that of the treated fruits was not so because they experienced a relatively longer green color period.

The decline in loss of moisture during storage showed a strong correlation with pectin degradation. As the pectin degraded, the loss of moisture increased with storage time. But the treatment strengthened and helped maintain the cell wall integrity over a longer period. Also, it has been established that ethylene activities accelerate respiration in citrus fruits and 1-MCP is a known inhibitor of ethylene (Mayuoni et al., 2011; Wei et al., 2020). So, the reduction in loss of moisture can also be attributed to the treatment of the lemon fruits with 1-MCP which deaccelerated the rate of moisture loss in the fruits. Since moisture loss is the major cause of loss of weight, the decline in WL in the treated fruits is a result of the decline in pectin degradation which led to the declining loss of moisture (Frempong et al., 2022). The treatment of lemons with CaCl₂ and 1-MCP significantly slowed down the rate of loss in weight of the fruits and led to the extension of the shelf life of the lemon. Both control and treated fruits showed a similar trend to that observed for other citrus fruits previously studied (Singh and Reddy 2006; Habibi et al., 2020). The decline in moisture loss led to a decrease in the drying rate. According to Ghannem et al. (2012), when the outer cells in a tissue lose a considerable amount of moisture, the further loss of moisture by
diffusion through the cell walls encounters greater resistance. Therefore, it can be seen that as the loss of moisture increased the rate of drying also decreased. The drying rate slows down during a long storage period, this could be attributed to the progressive water activity reduction of the external cells, therefore when a great number of cell layers in the tissue have lost a considerable amount of moisture, dried cell layers offer much greater resistance to water diffusion through the interface (Ghanem et al., 2012). The treated fruits had a considerably higher drying rate as compared to the control, this was a result of the deceleration of loss of moisture from the cells over the same period as discussed. The reduction in the changes of these parameters due to the treatment considerably slowed down the loss of textural properties since they influence the texture of fruits greatly. And they were controlled mainly by the reduction in the degeneration of the pectin due to the treatment. Ethylene aids the degradation of the green chlorophyll pigments responsible for the green color of the fruits and increases the accumulation of carotenoids in the peels of the fruit (Watkins 2006; Li et al., 2016). This leads to the change in the color of citrus fruits from green to yellow. Aside from 1-MCP an endogenous ethylene inhibitor, Calcium also acts as an antagonist during the ethylene-induced ripening process and reduces the release of ethylene (Njorgoe et al., 1998; Q. Zhang et al., 2019; Wei et al., 2020). The combined postharvest application of 1-MCP and Ca²⁺ significantly deaccelerated the process of de-greening the fruits as shown in Fig. 6. It decreased the rate of increase of CCI and C* values of the lemon peels. The combined treatment preserved the green color of the fruits for a longer time and improved the visual appearance when they finally turned yellow, as compared to the control. These results for color were consistent with those previously reported for lemons (Mitalo et al., 2020) and mandarin (Lu et al., 2020). TA increased continuously at later stages of the lemon storage for the treated fruits. It showed a similar trend to previous reports for lemon fruits (Zhang and Zhou 2019). CaCl₂ treatment has the potential of reducing the acid oxidation in the fruits during storage (Liu et al., 2017, L. Zhang et al., 2019), therefore could be the cause for the higher values of TA in the treated fruits as compared to the control fruits. The major commercial maturity index in the citrus sector includes factors such as peel coloration and TA. Various preharvest or post-harvest variables, such as maturity stage, fertilization used, and post-harvest treatment or storage, influence the peel coloration levels or TA (Zhang and Zhou, 2019). These factors could have influenced the level of changes that were observed in the physicochemical properties that were analyzed during this study. Reference Zhang and Zhou (2019) determined that the lemon fruits which were analyzed during that study and had higher CCI values showed higher TA levels. A similar trend was observed in this study, where fruits that had higher CCI values showed higher TA levels.

5. Conclusion

The combined treatment of the lemon fruits with CaCl₂ and 1-MCP had a positive effect on the texture, pectin degradation, peel color maintenance, weight loss, moisture loss, and total acidity. There was a significant difference between the control and treated fruits in all the tests carried out. Compared with the control the treated fruits showed lower deterioration over the storage period. This was achieved by the reduction in the degradation of pectin which plays a major role in the cell wall, this led to a reduction in loss of cell wall integrity and an increase in porosity. The micrographs coupled with the rapid test indicated that the degradation of the pectin was delayed by the treatment. This delay caused a reduction in the rate of moisture loss, WL, and texture (hardness, cohesiveness, springiness, and resilience) of the fruits. The increase in the rate of deterioration of the treated lemon fruits after 28 d suggests that multiple treatments of the fruit before 28 d can extend the shelf life of the fruit further. Also, the treatment delayed the change in peel color from green to yellow and improved the visual appearance when it finally turned yellow, as compared to the control. These results suggest that softening of lemon follows the trend in pectin degradation during storage, and the well-detailed mechanism and different concentrations to control the degradation can be of interest for further studies.

Data availability statement

Data available on request from the authors.

CRediT authorship contribution statement

Kwame Eduam Baiden Frempong: Conceptualization, Methodology, Investigation, Writing – original draft, Visualization, Formal analysis. Yan Chen: Conceptualization, Resources, Supervision, Writing – review & editing. Lili Liang: Formal analysis. Xiaoyan Lin: Resources, Supervision, Project administration, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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