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Research Article

Effects of sachet-type 1-methylcyclopropene (1-MCP) treatment on fruit quality during ambient and cold storage of *Hongro* apples

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Abstract This study evaluated the effectiveness of sachet-type 1-methylcyclopropene (1-MCP) treatment in preserving the quality of *Hongro* apples during ambient storage and subsequent cold storage. Four treatments were applied: a control and three SFIS-based treatments - SFIS (sachet placed with fruit for 24 h, then removed), SFIS-S (sachet placed with fruit and retained throughout the storage period), and SFIS-PE (sachet sealed with fruit in a polyethylene liner for 24 h, then liner removed). In control fruits, firmness and titratable acidity (TA) declined markedly over 30 days of ambient storage, from 66.7 N and 0.22% at harvest to 48.5 N and 0.19%, respectively. In contrast, all SFIS treatments effectively maintained quality parameters at levels comparable to those at harvest, with firmness ranging from 64.0 to 65.2 N, TA from 0.21% to 0.22%, and IEC from 0.4 to 14.4 μL/L. Following an additional 30 days of cold storage after 10 days of ambient storage, SFIS-treated fruits continued to exhibit high firmness and TA and significantly suppressed IEC levels, indicating prolonged quality preservation. These findings suggest that SFIS treatment is a promising approach for maintaining *Hongro* apple quality during both short-term ambient distribution and extended cold storage, with strong potential for commercial postharvest application.

Keywords *Hongro* apple, fruit firmness, internal ethylene concentration, titratable acidity, 1-MCP

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1. Introduction

In Korea, apples (*Malus domestica* Borkh.) represent a major fruit crop, cultivated across approximately 33,298 ha, accounting for roughly 20% of the nation's total fruit production area (Statistics Korea, 2024). Among the various cultivars, *Hongro* apples have experienced a consistent increase in cultivation and market demand, particularly due to their popularity as a seasonal gift during the Chuseok holiday period (Choi and Mcguire, 2021). However, post-Chuseok market saturation often results in a surplus of fruit, necessitating effective short- or long-term storage strategies to preserve postharvest quality.

As a climacteric fruit, the ripening of apples is characterized by a climacteric rise in ethylene production and respiration rate, which accelerates softening and senescence, thereby diminishing fruit quality (Busatto et al., 2017). To mitigate these effects, ethylene action inhibitors are frequently employed to delay ripening and extend shelf life. Among these, 1-methylcyclopropene (1-MCP) has been extensively studied and shown to effectively preserve fruit firmness and titratable acidity by inhibiting ethylene perception during storage (Khan and Singh, 2007; Rahman et al., 2024; Watkins, 2006; Yoo et al., 2023).

Despite its proven efficacy, conventional 1-MCP gas formulations (e.g., SmartFresh™) are often cost-prohibitive and logistically demanding, requiring controlled environments and strict application protocols (Kwon et al., 2024). These constraints can pose challenges for small-scale producers, such as individual growers of *Hongro* apples, who typically harvest comparatively less quantities from limited yield (Statistics Korea, 2024), making fumigation-type 1-MCP treatments economically and practically unfeasible. Therefore, the development and adoption of a cost-effective and user-friendly alternative are essential for maintaining fruit quality in decentralized or small-scale postharvest handling systems.

To overcome these limitations, a sachet-based formulation of a 1-MCP product (SmartFresh™ InBox Sachet, SFIS) has been introduced. This product, enclosed in an air-permeable tea bag, is designed for direct placement into individual packaging boxes, allowing for simplified and scalable application. Recent studies have demonstrated the efficacy of SFIS in extending the postharvest life of mangoes by approximately 20 days (Chomba et al., 2025); however, limited research is available regarding its effectiveness in apples.

Therefore, the present study aimed to evaluate the efficacy of SFIS treatment in preserving the postharvest quality of *Hongro* apples under ambient storage conditions simulating commercial distribution. Furthermore, the feasibility of subsequent cold storage following ambient exposure was assessed to determine the potential of SFIS as a practical postharvest management tool for use in commercial and small-scale apple supply chains.

2. Materials and methods

2.1. Plant materials

Fruit samples were collected from 9-year-old *Hongro*/*M.9* apple trees grown in a commercial orchard located in Gogeong-myeon, Yeongcheon-si, Gyeongsangbuk-do, Korea. Fruits were harvested on September 10, 2024, and immediately transported to the Horticultural Crop Quality Management Laboratory at Kyungpook National University. Uniform, undamaged, and disease-free fruits were selected for the experiment.

2.2. Treatment and storage conditions

2.2.1. 1-MCP treatment

The 1-MCP treatment was conducted using sachets containing powdered 1-MCP [SmartFresh™ InBox Sachet (SFIS); 0.014% 1-MCP, 99.986% inert ingredients; AgroFresh, Yakima, WA, USA], packaged in a tea bag-like format. Two sachets (equivalent to 1.25 g of 1-MCP) were applied per 10 kg corrugated fruit box, based on the recommended dose of one sachet per 5 kg of fruit. To initiate fumigation, the tip of each sachet was moistened with water prior to placement in the fruit box, which was then sealed with tape. Four treatment groups were established as follows:

- Control: Fruits were placed in 10 kg boxes without SFIS and sealed.
- SFIS: Fruits and SFIS were placed in 10 kg boxes and sealed. SFIS sachets were removed after 24 h of treatment, and the boxes were resealed.
- SFIS-S: Fruits and SFIS were placed in 10 kg boxes and sealed. The sachets remained in the boxes throughout the storage period.
- SFIS-PE: Fruits and SFIS were enclosed together in a polyethylene (PE) film liner (18-20 μm thickness; Taebang Patec Co., Ltd., Seoul, Korea) within the 10 kg boxes, which were then sealed. The PE liners and sachets were removed after 24 h of treatment, and the boxes were resealed.

Each treatment group contained 30 fruits per 10 kg box, with three replicates per treatment.

2.2.2. Storage conditions

Two storage regimens were employed in this study. In the first regimen, fruits were stored under ambient conditions [20±2°C, 50-55% relative humidity (RH)] for up to 30 days. Fruit quality parameters were assessed at 10 days intervals (0, 10, 20, and 30 days).

In the second regimen, fruits were initially stored under ambient conditions for 10 days and then transferred to cold storage (0±0.5°C, 85-90% RH) for 30 days. Prior to analyis, cold-stored fruits were equilibrated to room temperature (20±2°C) for 24 h.

For each measurement, five fruits per replicate were used, with three replicates per treatment.

2.3. Fruit quality assessments

Weight loss during storage was evaluated for both control and SFIS-treated fruits. Percentage weight loss was calculated based on changes in the average fruit weight over time, using an initial sample of 30 fruits per treatment.

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Fruit firmness was determined using a fruit firmness tester (Compac-100II, Sun Scientific Co., Tokyo, Japan) equipped with an 11 mm plunger. Measurements were taken at three points on the peeled equatorial zone of each fruit and averaged, with results expressed in Newtons (N). Titratable acidity (TA) was measured using a potentiometric titrator (DL-15, Mettler Toledo Co., Greifensee, Switzerland) by titrating 5 mL of juice with 0.1 N NaOH to pH 8.1, with results expressed as malic acid equivalents. Soluble solids content (SSC) was assessed using a digital refractometer (PR-201α, Atago Co., Ltd., Tokyo, Japan), and the SSC/TA ratio was subsequently calculated. Peel color was measured at three points on the sun-exposed side of each fruit using a chromameter (CR-400, Konica Minolta Inc., Tokyo, Japan), and average values were recorded.

Internal ethylene concentration (IEC) was measured by extracting a 1 mL gas sample from the core cavity via the calyx using a syringe. The sample was analyzed using gas chromatography (GC 7820A, Agilent Technologies Inc., Santa Clara, CA, USA) equipped with a flame ionization detector and a Porapak Q column (80/100, 1 m; RASTEK, Bellefonte, PA, USA). Injector, oven, and detector temperatures were set at 100°C, 90°C, and 250°C, respectively. Helium served as the carrier gas at a flow rate of 25 mL/min.

2.4. Statistical analysis

All statistical analyses were performed using SPSS software (IBM SPSS Statistics 27, IBM Co., Armonk, NY, USA). Mean values of treatment groups were compared with one-way analysis of variance (ANOVA) using Duncan's test at a significance level of $p<0.05$. Differences in weight loss between the control and SFIS-treated groups were analyzed using an independent t-test ($p<0.05$).

3. Result and discussion

3.1. Changes in fruit quality during ambient storage after treatment

The effects of sachet-type 1-MCP (SFIS) treatment on fruit quality parameters of *Hongro* apples during ambient storage are presented in Figs. 1-3.

Fruit firmness in the control group declined significantly from 66.7 N at harvest to 56.5 N after 20 days, further decreasing to 48.5 N by 30 days (Fig. 1A). In contrast, SFIS-

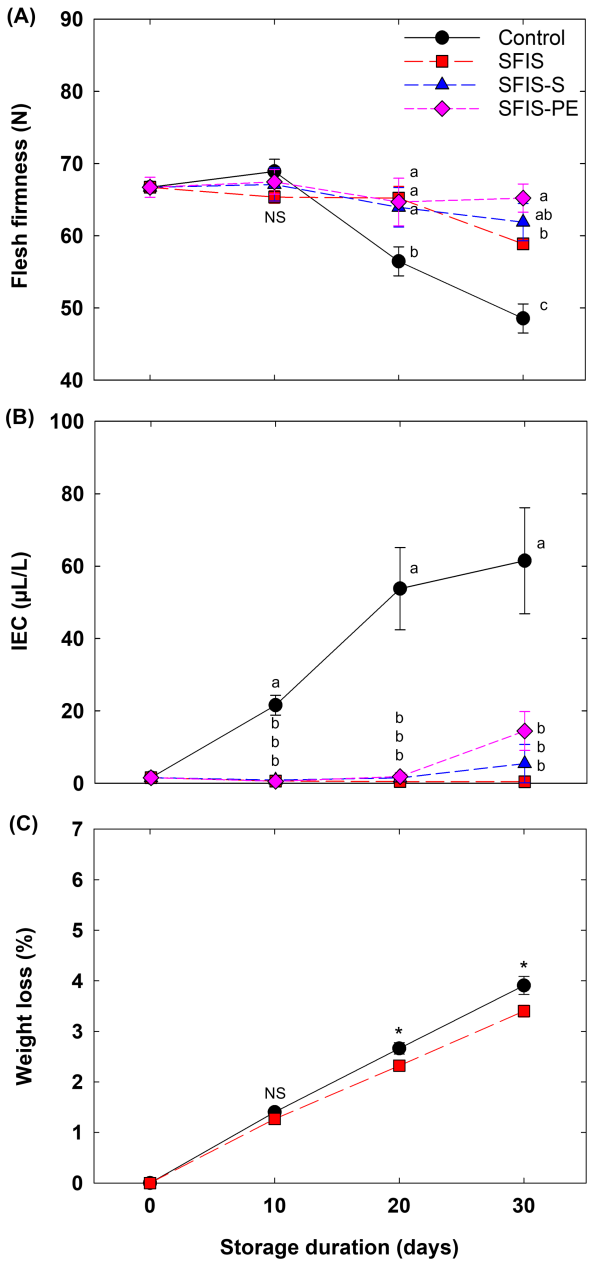

Fig. 1. Effect of SmartFresh™ InBox Sachet (SFIS) treatments on flesh firmness (A), internal ethylene concentration (IEC, B), and weight loss rate (C) of *Hongro* apples at harvest and after 30 days of storage at 20±2°C and 50-55% relative humidity (RH). All values are mean±SE (n=15). Means with different superscript letters at the same time point are significantly different at $p<0.05$ by Duncan's multiple range test. Asterisks in panel (C) indicate significant differences between Control and SFIS treatments (t-test, $p<0.05$). Treatment groups: Control (no treatment), SFIS (sachet placed with fruit for 24 h, then removed), SFIS-S (sachet placed with fruit and retained throughout the storage period), and SFIS-PE (sachet sealed with fruit in a polyethylene film liner for 24 h, then film removed).

treated fruits retained significantly higher firmness, ranging from 58.9 to 65.2 N after 30 days of ambient storage.

IEC increased markedly in control fruits, rising from 1.5 μL/L at harvest to 61.5 μL/L after 30 days (Fig. 1B). Conversely, SFIS-treated fruits maintained substantially lower IEC values, between 0.4 and 14.4 μL/L, demonstrating effective suppression of ethylene accumulation. Additionally, SFIS-treated fruits exhibited slightly lower weight loss compared to the control group (Fig. 1C). Ethylene plays a pivotal role in accelerating fruit softening by enhancing the expression and activity of cell wall-degrading enzymes (Gwanpua et al., 2018). Previous studies have demonstrated that 1-MCP effectively inhibits ethylene action by blocking receptor sites, thereby delaying ripening processes such as firmness loss and acidity decline in climacteric fruits, including apple cultivars such as *McIntosh* and *Empire* (Watkins et al., 2000). Similar trends have been reported in Korean cultivars such as *Summer Prince*, *Summer King*, and *RubyS* apples, where 1-MCP treatments at concentrations of 0.5-1.0 μL/L reduced ethylene perception and maintained fruit firmness (Yoo et al., 2020; Yoo et al., 2023). A strong correlation between ethylene production and firmness loss has been widely reported, with this relationship notably weakened under 1-MCP treatment (Yoo et al., 2021).

Despite the non-airtight storage conditions, sachet-type 1-MCP (SFIS) effectively suppressed IEC and preserved fruit firmness in *Hongro* apples, highlighting its efficacy even in semi-open environments. Therefore, the increased ethylene production and firmness reduction in control fruits are likely attributable to unregulated ethylene activity, whereas the inhibition of ethylene action in SFIS-treated fruits contributed to the delayed firmness loss observed in this study.

SSC showed no significant difference among treatments throughout the storage period (Fig. 2A). However, TA declined from 0.22% at harvest to 0.19% in control fruits after 30 days, while SFIS-treated fruits maintained higher TA levels (0.21-0.22%) (Fig. 2B). This resulted in a markedly higher SSC/TA ratio in the control group due to reduction in TA, while the SFIS-treated fruits exhibited stable SSC/TA ratios, indicating better maintenance of overall fruit quality (Fig. 2C).

These findings align with previous reports by Kim et al. (2018) and Park et al. (2012) in *Gamhong* and *Jonathan* apples, as well as by Kwon et al. (2021) in *Arisoo* and *Picnic* apples. Tomala et al. (2020) observed improved retention of acidity in 1-MCP-treated *Idared* apples during storage. The stable acidity levels in SFIS-treated fruits in the present

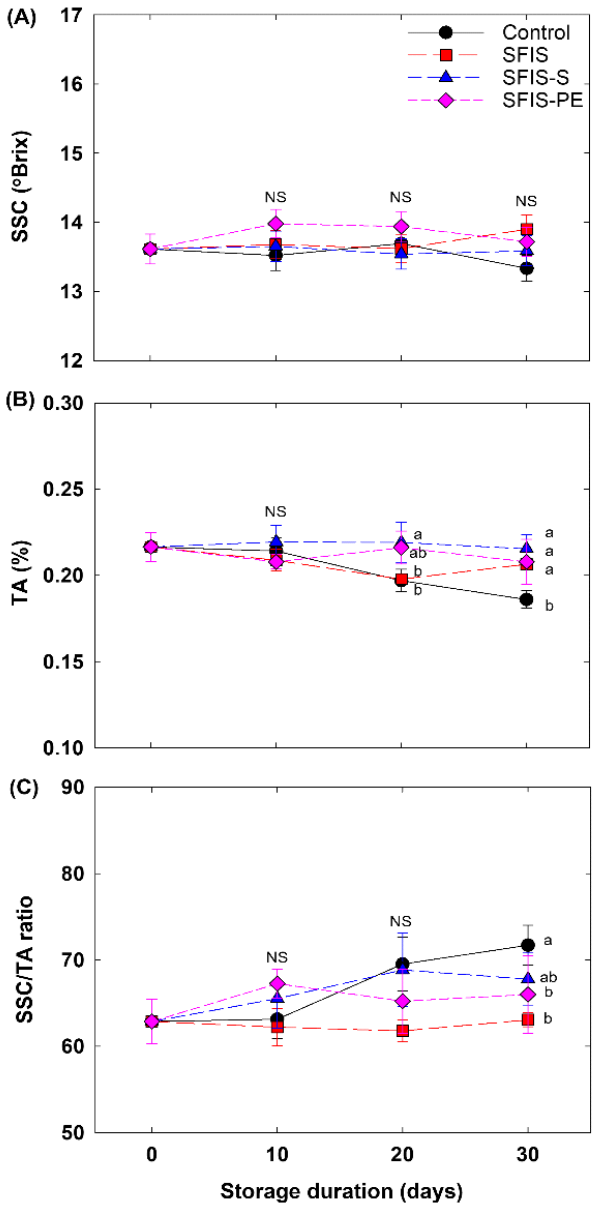

Fig. 2. Effect of SmartFresh™ InBox Sachet (SFIS) treatments on soluble solids content (SSC, A), titratable acidity (TA, B), and SSC/TA ratio (C) of *Hongro* apples at harvest and after 30 days of storage at 20±2°C and 50-55% RH. All values are mean±SE (n=15). Means with different superscript letters at the same time point are significantly different at $p<0.05$ by Duncan's multiple range test. Treatment groups: Control (no treatment), SFIS (sachet placed with fruit for 24 h, then removed), SFIS-S (sachet placed with fruit and retained throughout the storage period), and SFIS-PE (sachet sealed with fruit in a polyethylene film liner for 24 h, then film removed).

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study further suggest enhanced flavor preservation through reduced SSC/TA ratios.

Peel color analysis showed no significant differences in lightness (L*) or redness (a*) among treatments (Fig. 3). However, yellowness (b*) increased across all treatments during storage, with the control group exhibiting a more pronounced increase. SFIS-treated fruits showed a slower increase in yellowness, indicating a delay in skin senescence. Previous studies have shown that 1-MCP treatment delays chlorophyll degradation and color change in various fruits, including tomatoes, bananas, peaches, plums, and oranges (Blankenship and Dole, 2003; Porat et al., 1999), as well as in avocados (Feng et al., 2000; Jeong et al., 2002). However, in apples such as *Fuji* and *Honeycrisp*, 1-MCP had minimal effects on color development (Mattheis et al., 2017; Yoo and Kang, 2021). Thus, the impact of 1-MCP on fruit color development may vary depending on the crop, maturity stage, and storage conditions.

In this study, SFIS treatment reduced the increase in yellowness (b*) but did not affect lightness (L*) or redness (a*), suggesting a partial delay in the background color development of *Hongro* apples. Therefore, the overall impact of SFIS treatment on fruit color changes was minimal under the tested conditions.

3.2. Fruit quality after cold storage following simulated distribution

To assess the effectiveness of SFIS treatment in preserving fruit quality during commercial distribution, *Hongro* apples treated with SFIS were stored at ambient temperature for 10 days - simulating the typical 'Chuseok' distribution period - and subsequently transferred to cold storage at 0°C for 30 days (Fig. 4). After 10 days at ambient temperature, the firmness of control fruits measured 68.9 N, but it declined to 59.1 N following the subsequent 30 days of cold storage. In contrast, all SFIS-treated fruits retained markedly higher firmness values, ranging from 63.3 to 69.3 N (Fig. 4A). Similarly, the IEC in control fruits increased to 25.0 μL/L, while SFIS-treated fruits maintained significantly lower levels (0.4-1.7 μL/L) throughout the 10+30 storage period (Fig. 4B). Although no significant differences were observed in SSC among treatments (Fig. 4C), TA in the control fruits decreased to 0.18%. In contrast, SFIS-treated fruits maintained TA levels between 0.21% and 0.22%, closely resembling the values observed at harvest (Fig. 4D).

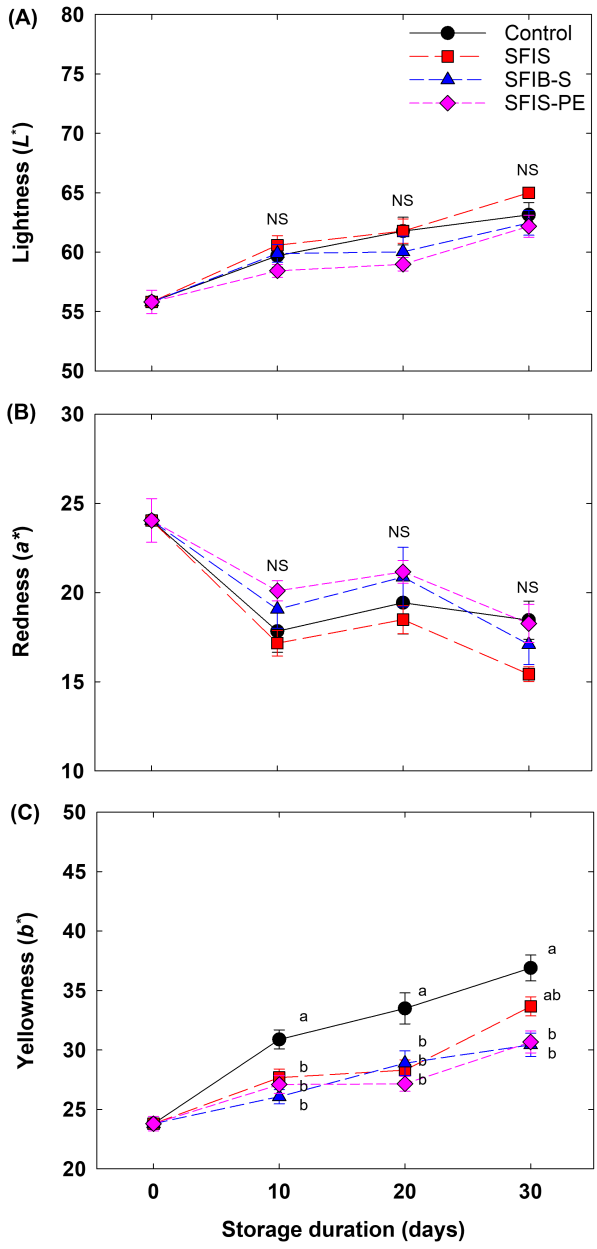

Fig. 3. Effect of SmartFresh™ InBox Sachet (SFIS) treatments on peel color parameters - lightness (L*, A), redness (a*, B), and yellowness (b*, C) - on the sunny side of *Hongro* apples at harvest and after 30 days of storage at 20±2°C (RH 50-55%). All values are mean±SE (n=15). Means with different superscript letters at the same time point are significantly different at $p<0.05$ by Duncan's multiple range test. Treatment groups: Control (no treatment), SFIS (sachet placed with fruit for 24 h, then removed), SFIS-S (sachet placed with fruit and retained throughout the storage period), and SFIS-PE (sachet sealed with fruit in a polyethylene film liner for 24 h, then film removed).

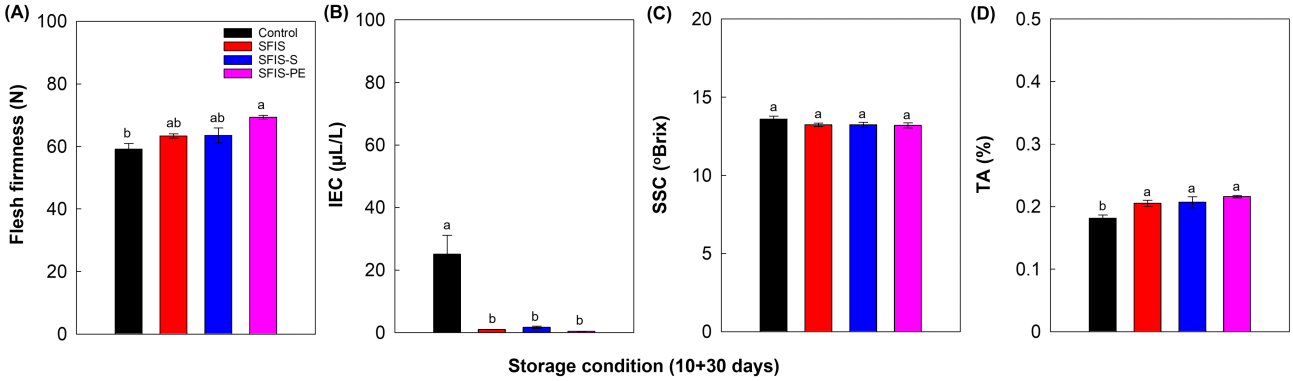

Fig. 4. Effect of SmartFresh™ InBox Sachet (SFIS) treatments on fruit quality attributes—flesh firmness (A), IEC (B), SSC (C), and TA (D)—of *Hongro* apples following 10 days at ambient conditions (20±2°C, 50-55% RH) and subsequent cold storage at 0±0.5°C and 85-90% RH for 30 days (10+30 days). All values are mean±SE (n=15). Means with different superscript letters above the bars within each parameter are significantly different at $p<0.05$ by Duncan's multiple range test. Treatment groups: Control (no treatment), SFIS (sachet placed with fruit for 24 h, then removed), SFIS-S (sachet placed with fruit and retained throughout the storage period), and SFIS-PE (sachet sealed with fruit in a polyethylene film liner for 24 h, then film removed).

The inhibitory effects of 1-MCP on ethylene action have been widely demonstrated in a range of horticultural crops. It also suppresses ethylene biosynthesis by downregulating the expression of ethylene-related genes such as *MdACS1* and *MdACO1* (Dal Cin et al., 2006; Varanasi et al., 2013). Gwanpua et al. (2017) reported that the efficacy of 1-MCP in *Jonagold* apples depended on fruit maturity and treatment timing; delayed application after the climacteric peak reduced binding efficiency to ethylene receptors, resulting in diminished quality retention. Similarly, Pre-Aymard et al. (2003) reported that 1-MCP exhibited limited efficacy when applied to *Anna* apples 8 d after harvest, highlighting the importance of treatment timing. Chomba et al. (2025) reported that, with appropriate exposure time and its concentration, SFIS treatment effectively suppressed ethylene rates and maintained it quality in *Tommy Atkins* mango fruits.

In the present study, SFIS treatment at harvest effectively preserved fruit firmness and TA, while suppressing IEC, even after an additional 30 days of cold storage following 10 days of ambient storage. These findings demonstrate that timely postharvest application of SFIS can effectively maintain the quality of *Hongro* apples under simulated commercial handling and distribution conditions.

4. Conclusions

The application of SFIS effectively delayed quality deterioration in *Hongro* apples, leading to better retention of fruit firmness and acidity compared to untreated fruit during 30 days of ambient storage. Moreover, this quality preservation effect was sustained after an additional 30 days of cold storage following 10 days at ambient conditions. These results support the potential of SFIS as a practical postharvest treatment for maintaining the commercial quality of *Hongro* apples during seasonal distribution periods such as Chuseok. However, further studies required to set optimal SFIS concentration to maximize efficacy to enable practical use by growers.

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Conflict of interests

The authors declare no potential conflicts of interest.

Author contributions

Conceptualization: Kim K, Han A. Methodology: Kim K, Han A, Kim E, Kwon JG, Win NM, Yoo J. Formal analysis: Kim K, Han A, Kwon JG, Win NM, Yoo J. Validation: Kim

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K, Han A, Yoo J, Kang IK. Writing - original draft: Kim K, Han A, Kang IK. Writing - review & editing: Kim K, Han A, Yoo J, Kang IK.

Ethics approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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