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Effect of the Substrate Water Content on the Postharvest Quality and Shelf Life of Potted *Kalanchoe blossfeldiana*

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Abstract

In this study, we investigated the effects of the substrate water content on potted kalanchoe (*Kalanchoe blossfeldiana*) in an export distribution simulation. Potted kalanchoe plants were treated either with the optimum substrate water content (OSW, 50−60%) or a low substrate water content (LSW, ≤ 20%) and the postharvest quality and shelf life were assessed at farm or wholesale, export, auction, and consumer stages. The shelf life of the LSW flowers was shorter than that of the OSW flowers by 36%. The primary reason for the short shelf life after the LSW treatment was an increase in leaf chlorosis. The plant height was shorter with the LSW treatment at all stages, while the plant width was longer before the export stage. The fresh and dry weights of the root with the LSW treatment were lower at all stages. The chlorophyll content and the Fv/Fm of the leaves were lower during the auction stage for the LSW treatment. The Fv/Fm of the OSW treatment and LSW treatment were 0.79 and 0.77, respectively, during the auction stage. The change in the size of the stomatal pores and complexes was higher for the LSW treatment at all stages, but this difference was not significant. The difference between the air temperature and the petal or leaf surface temperature did not differ between treatments at the auction stage and consumer stage. The correlation between the shelf life and plant height was positive for all stages. There was no correlation between shelf life and the temperature of the flowers or leaves on auction stage and consumer stage. At the end of the shelf life, there was a high positive correlation between the shelf life and the substrate water content (r = 0.8**), the number of flowers (r = 0.8**) or buds (r = 0.6**), and flowering rate compared to the shipment (r = 0.5*) at the consumer stage. The findings here indicates that the substrate water content affects the postharvest quality and shelf life of potted kalanchoe.

Additional key words: morphological factor, physiological factor, soil moisture, soil water, substrate moisture

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Introduction

The market for potted plants has recently increased in Korea because they are easy to grow and inexpensive (Kim et al., 2014). Potted kalanchoe is a CAM plant that opens its stoma at night, closes it during the day to photosynthesis, and has various flower colors and cultivars (Kwon, 2003). It is a

popular potted plant among consumers due to its long flowering period and ability to be cultivated indoors (Park et al., 2011). The domestic cultivation area was 7.5ha in 2021 (Leonard and Nell, 1998; MAFRA, 2022). Producers and consumers are increasingly interested in improving the quality of potted plants, extending their shelf life, and exporting them due to increased levels of consumer interest (Cho et al., 2020).

In Korea, the export distribution process for potted plants generally involves sorting and packaging at a farm or public cooperative sorting facility followed by air or ship transport (Park et al., 2011; GARES, 2018). Potted kalanchoe is imported from the Netherlands and Denmark (Kim et al., 2014; Cho et al., 2020), and cultivars have been exported to Japan from 2012 (28 cases) to 2022 (26 cases), with Taiwan, Singapore, and Thailand also becoming stable export markets (APQA, 2023). China and Costa Rica have also recommended potted kalanchoe as an exportable product (APQA, 2022). In this process, kalanchoe is exported under the condition that the plants are free of disease and insects such as *Frankliniella occidentalis* and *Spodoptera litura*. GARES packaged domestic kalanchoe in 10 cm pots in a paper box with horticultural bed soil between 2015 and 2017, similar to the packing and sorting methods used for domestic distribution, and exported them to a Japanese OTA floriculture auction by air (GARES, 2018). Kalanchoe plants are distributed within Japan at around 45−50% flowering, which requires more technical know-how pertaining to the flowering stage during the transportation of Japanese exports (Kim, 2003).

Research on the potted plant quality of kalanchoe before transport has primarily focused on certain aspect of the cultivation environment, such as light, air temperature, relative humidity, CO_2, fertilizer, and growth retardant treatments (Leonard and Nell, 1998; Kim et al., 2014; Coelho et al., 2018; Cho et al., 2020; Park et al., 2021). It has been found that the shelf life and quality of potted plants are improved when 1-methylcyclopropene (1-MCP), 1-hexylcyclopropene (1-HCP), and 1-octylcyclopropene (1-OCP) are used as ethylene inhibitors before the exporting of kalanchoe to Japan, as kalanchoe is an ethylene-sensitive plant (Kebenei et al., 2003; Park et al., 2011). In addition, the strength of vibrations had no effect on the potted quality during simulated exports, but the number of flowers was higher at the consumer stage when the transportation temperature was 18°C rather than 12°C. As the transport temperature increased, flowering was promoted, and the potted flower life was shortened (Kwon, 2003; Kwon et al., 2003b; Sohn et al., 2003).

It is also important to manage the substrate water content before transportation to ensure the quality of potted plants. For begonia, wick and mat irrigation leads to a shorter flowering factor compared to overhead irrigation, and the growth rates for the leaf width and the number of lateral shoots were higher before shipment (Son et al., 2002). Research has also been conducted on the soil moisture levels in automatic plant irrigation systems using soil moisture sensors in a cultivation environment and propagation for potted chili, cymbidium, english lavender, petunia, salvia, and vinca (Nemali and van Lersel, 2006; Priandana and Wahyu, 2020; An et al., 2021a, 2021b; Rock et al., 2022).

Kalanchoe is a succulent plant that stores moisture in its leaves and can therefore, grow well in dry moisture but it decays under high temperatures and high humidity (RDA, 2019). However, irrigation management is still required before or after packaging and transport to prevent deterioration of the quality of potted plants (Jeong et al., 2021; Lee and Lee, 2023). Although a significant volume of research has been conducted on the transport temperature of various potted plants such as kalanchoe, carnation, chrysanthemum, gerbera, cyclamen, begonia, hydrangea, and lisianthus, analysis of the substrate water content and potted plant quality of kalanchoe have been insufficient (Kwon et al., 2003a; An et al., 2022; Lee et al., 2023). Therefore, this study investigated the postharvest quality and shelf life of potted kalanchoe upon variations in the substrate water content during the export distribution process.

Materials and Methods

Plants, Substrate Water Content Treatment, and Export Simulation

Potted *Kalanchoe blossfeldiana* 'Queen bell' plants (10 cm pots, horticultural bed soil, EC 1.0, and pH 5.2) was grown in a greenhouse in Goyang-si, Gyeonggi-do, Korea, during the summer of 2022. The export distribution environment was simulated in the growth chamber (VS-91G09M-1300, VISIONBIONEX, Korea) at Chonnam National University's horticultural crop quality management laboratory by dividing the export distribution process into four stages: farm or wholesale, export, auction, and consumer stages (Park et al., 2011; Lee and Kim, 2019; Fig. 1). The substrate water content for the potted plants had two treatments: optimum (OSW, 50 − 60%) and low (LSW, ≤ 20%) by irrigating the plants for twenty or five min, respectively, 1.5L of water per ten pots, with the water content measured using a soil moisture meter (DM300L, YIERYI, China; Jeong et al., 2021; Lee and Lee, 2023). The potted plants were sorted at 45 − 50% flowering and packaged in an exported paper box (40 × 90 × 40 cm; 24 pot plants per box) at the farm or wholesale stage (GARES, 2018). They were controlled by a dark environment with an air temperature of 24 ± 2°C and relative humidity of 50 ± 4%, with irrigation suspended for three days at the export stage. During the auction and at the consumer stage, the plants were removed from the packaging and stored at an air temperature of 24 ± 2°C, a relative humidity of 50 ± 4%, and a light intensity of 35.2 $\mu mol \cdot m^{-2} \cdot s^{-1}$ PPFD with a 12-h photoperiod. To investigate the effects of the substrate water content and the morphological and physiological factors of the potted plants on shelf life, the analysis was conducted in three stages: (1) before export, (2) auction, and (3) consumer. The consumer stage was the end of the shelf life which was the action stage after four weeks (Fig. 1).

Shelf Life and Morphological and Physiological Characteristics of Potted Plants

The shelf life of potted kalanchoe was defined as the duration in days during the consumer stage (day 1) until the flowers began to exhibit shelf life termination symptoms such as the wilting of 75% of the petals or the yellowing of more than 20% of the leaves (Leonard and Nell, 1998). The quality of the potted kalanchoe was analyzed based on their morphological characteristics, including the plant height, plant width, fresh and dry weight of the shoots and roots, the number of inflorescences, flowers, flower buds and leaves, flowering rate, and leaf thickness, and their physiological

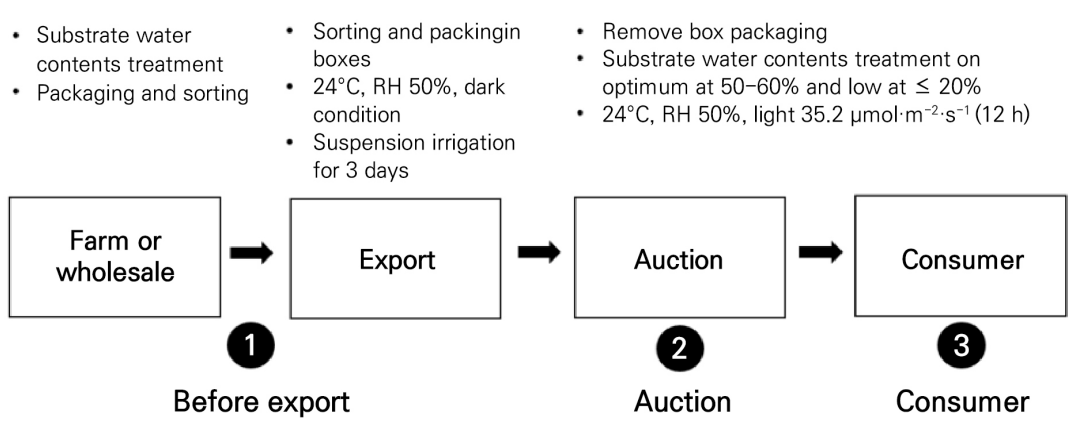

Fig. 1. Simulation of exports to Japan of potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content: (1) before export, (2) auction, and (3) consumer.

characteristics, including the chlorophyll content, Fv/Fm, the rate of change in the stomatal size of the leaves, and the temperature of the petals and leaves. The plant height and width were based on the maximum length and width of the shoot, respectively. The fresh and dry weight of the shoots and roots were measured, and the dry weight was measured by drying the plants at 50°C for 72 h (Vieira and Ferrarezi, 2021). The flowering rate compared to shipment was calculated according to the equation proposed by Cho et al. (2020), and the flowering rate was defined as the percentage of flowers that bloomed compared to the total.

The chlorophyll content of the leaves was measured using SPAD (Chlorophyll contents, SPAD-502PlusMinolta, Japan) for the outer leaves of the second and third nodes of each plant. Chlorophyll fluorescence (Fv/Fm) was measured on the same leaves with a portable chlorophyll fluorometer (MINI-PAM-II, Walz, Germany) after 20 min of dark treatment using a leaf-chip holder (Walz, Germany; An et al., 2022). The rate of change in the pore size on the first edge of three leaflets was calculated as follows: Rate of change in the pore size = (Pore size under dark conditions for 12 h / Pore size under light conditions for 12 h) × 100 (Yi et al., 2018; Choi and Lee, 2020). The temperature of each potted plant and the surrounding air was measured using a thermal infrared camera (FLIR T560, FLIR Systems Inc., USA) at 640 × 480 pixels for a temperature range of −20 to 1500°C. Thermal imaging was conducted in the dark, and krypton lamps (60 W) were used for ten min before measurement to release heat energy from the plant. The average spot temperature was recorded for the petals and leaves. The images taken by the thermal imaging camera were analyzed using the FLIR Tools + program (FLIR Systems Inc., USA; Choi and Lee, 2020).

Experimental Design and Data Analysis

The potted plants were placed in a chamber using a completely randomized block design. Analysis of variance (ANOVA) was used to analyze the data, and *t*-test were conducted as a post hoc analysis (p = 0.05). To clarify the relationships between the shelf life, physiological / morphological characteristics, and the substrate water content, Pearson correlation analysis was conducted. Based on the results of the correlation analysis, multiple regression analysis was also employed to determine the most influential determinant of shelf life. Statistical analysis was conducted using SAS software (Statistical Analysis System, version 9.4, SAS Institute Inc., Cary, NC).

Results and Discussion

The plant quality and shelf life were analyzed according to the substrate water content for potted plants in the simulated export distribution process. The shelf life for the plants subject to the LSW treatment was shorter than the OSW treatment by 36% (Table 1). Both treatments led to 100% petal wilting as a senescence symptom, while the LSW treatment increased leaf chlorosis (yellowing), which strongly influences the value of commercial plants because it is easily noticeable (Zaicovski et al., 2008). According to Funamoto (2003) and Zaicovski et al. (2008), high soil water stress produces ethylene and increases the respiration rate, which is related to yellowing. Kalanchoe is an ethylene-sensitive plant, and it is possible that the high water stress caused by the low substrate water content increased leaf yellowing (Kebenei et al., 2003). When CAM plants are exposed to water stress, their ABA levels increase, affecting the occurrence of yellowing leaves (Table 1; Hou et al., 2010; Jeong et al., 2021).

The plant height was shorter for the LSW treatment at all stages (Table 2, Fig. 2A and 2B). The plants were shorter and wider under the LSW treatment than the OSW treatment due to water stress before the export stage, which caused the plants to droop (Table 2). Potted kalanchoe has a high ornamental value because it has a short height, the result of dwarfing chemicals used to inhibit growth during cultivation (Son et al., 2002). In the present study, the plants were more horizontal than vertical because of the lack of substrate water content before the export stage (Table 2). The fresh and dry weights of the root for the LSW treatment were lower than those for the OSW treatment, but those of the shoots were not significant (Fig. 2C to 2F). The total fresh and dry weights of the potted plants tended to decrease under the LSW treatment due to the restricted carbohydrate transport arising from lower photosynthesis during all stages (Table 2, Fig. 2C to 2F; Zaer-Ara et al., 2016; Vieira and Ferrarezi, 2021). A previous study has also reported that the total fresh and dry weights of potted kalanchoe were higher at a substrate water content of more than 80% compared with less than 40% (Lee and Lee, 2023). The quality of the flowers, such as the number of inflorescences and flowers, and the budding/flowering rate, is an important factor in determining the quality of potted plants (Kim, 2003). The flowering rate, chlorophyll contens, Fv/Fm, and stomatal size change rate of leaves were not significantly different between the two treatments (Tables 2 and 3, Fig. 3B). In contrast, the flowering rate for Bougainvilla increased when moisture stress was applied (pF 2.7), while that of Dendrobium and Neofinetia also increased when moisture stress was applied during autumn (Lee, 2008). In this study, the flowering rate compared to shipment for the plants in the LSW treatment increased by 26.1% compared with the OSW treatment during the auction stage (Fig. 3A). The chlorophyll content of the leaves was measured using the SPAD values, which are used as an indirect indicator of plant nitrogen (Hoel and Solhaug, 1998). The chlorophyll content and Fv/Fm of the leaves were lower for the LSW treatment at the auction stage (Fig. 4A and 4B).

Table 1. Shelf life and senescence symptoms for potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content in the simulated export distribution process

Substrate water content treatment[z]	Shelf life (days)	Senescence symptom (%)		
		Petal		leaf
		Wilting	Abscission	Chlorosis
OSW (50−60%)	33.2	100	80	70
LSW (≤ 20%)	21.0***	100	70	100

[z]Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50−60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively.

*** Significant difference between the OSW and LSW treatments in a *t*-test at $p < 0.001$ (n = 10).

Table 2. Morphological characteristics of potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content before export stage

Substrate water content treatment[z]	Plant height (cm)	Plant width (cm)	Fresh weight (g)		Dry weight (g)		No. of inflorescence	No. of flowers	No. of flower buds	Flowering rate	No. of leaves	Leaf thickness (mm)
			Shoot	Root	Shoot	Root						
OSW (50−60%)	18.8	18.6	175.0	7.7	75.3	1.7	9.9	9.0	89.7	9.05	48.9	1.89
LSW (≤ 20%)	17.4**	23.2**	163.2 ns	6.3*	68.7 ns	1.4*	9.2 ns	9.6 ns	83.7 ns	9.78 ns	44.1 ns	1.70 ns

[z]Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50−60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively.

ns, *, ** Non-significant or significant difference between the OSW and LSW treatments in *t*-test at $p < 0.05$ or 0.01, respectively (n = 10, except n = 5 for the fresh or dry weight).

A previous study reported that the chlorophyll content of wheat leaves was higher for irrigated plants than for rainfed plants exposed to low soil moisture (Sarker et al., 1999). The chlorophyll content also increased with the irrigation of mustard plants (Begum and Paul, 1993). In this study, the environment was controlled by the suspension of irrigation and dark conditions during the export stage (Fig. 1). Light significantly influences chloroplast development and chlorophyll biosynthesis (Mohanty et al., 2006), and the total chlorophyll content gradually fell during dark treatment for water dropwort (Zhang et al., 2018).

During the auction stage, the Fv/Fm of the OSW and LSW treatment was 0.79 and 0.77, respectively (Fig. 4B). Neither treatment damaged the reaction center of photosynthetic photosystem II, given that Fv/Fm is typically in the range of 0.75 to 0.85 for non-stressed plants (Bolhar-Nordenkampf et al., 1989; Jung, 2002; Hou et al., 2010). The stomatal pore and

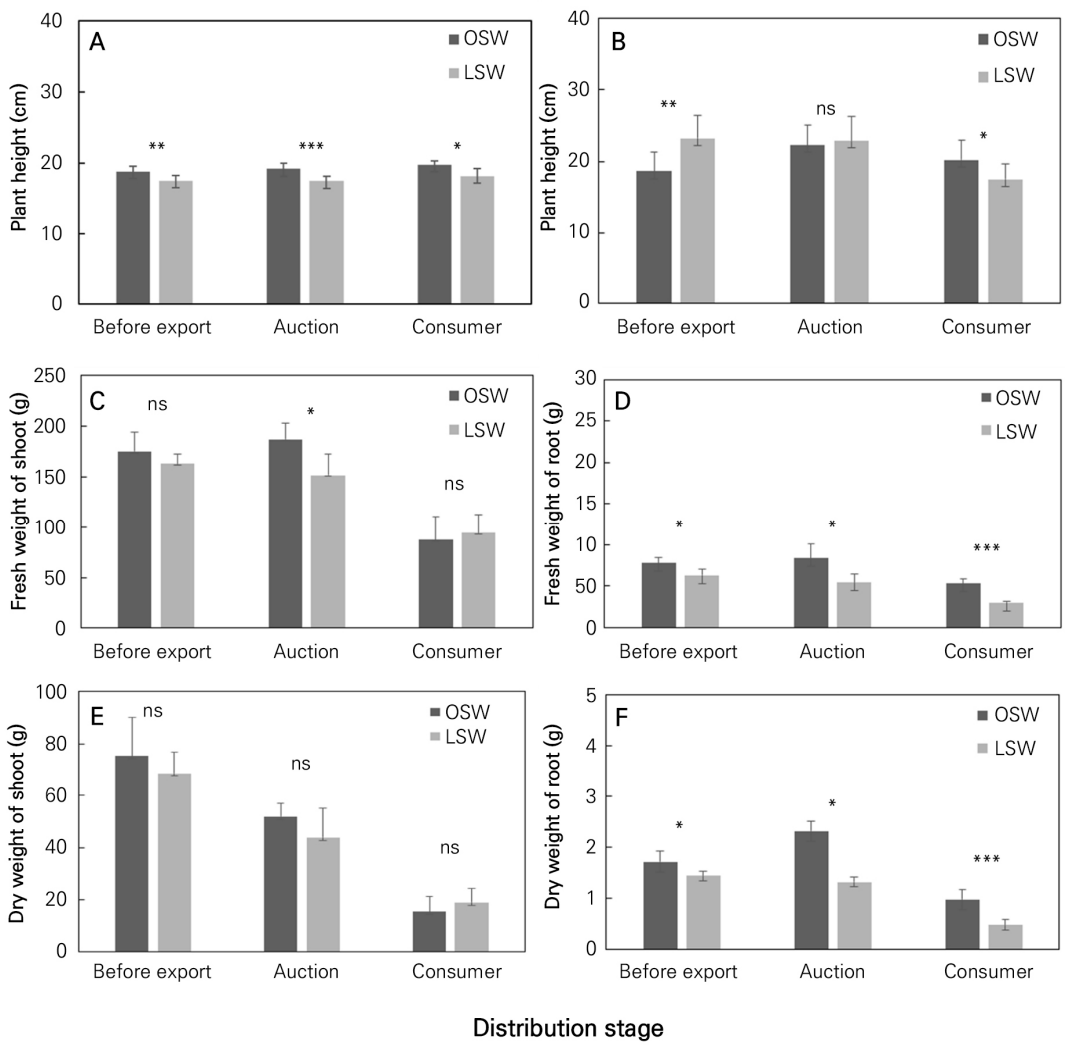

Fig. 2. Morphological characteristics on (A) plant height, (B) plant width, (C) fresh weight of shoots and (D) roots, (E) dry weight of shoots and (F) roots of potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content for three simulated export distribution stages. Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50–60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively. $^{ns, *, **, ***}$ Non-significant or significant difference between the OSW and LSW treatments in a *t*-test at $p < 0.05$, 0.01, and 0.001, respectively. Vertical bars indicate the standard error (n = 5, except n = 10 for the plant height and width).

complex size change rate of leaves was higher for LSW treatment at all stages, but this difference was not significant (Fig. 4C and 4D). Rogiers et al. (2011) and Hou et al. (2010) reported that stomatal sensitivity increased with dry soil, and ABA was simulated in the roots and transported to the leaves, resulting in a decrease in stomatal conductance. In addition, CAM plants close their stomatal pores, which reduces transpiration and prevents plant wilting. However, this study found no

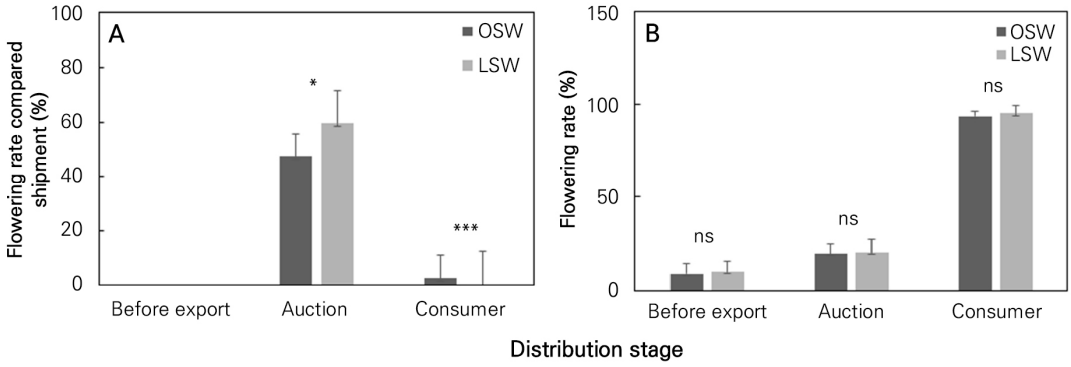

Fig. 3. Morphological characteristics on (A) flowering rate compared to shipment and (B) flowering rate for potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content for three simulated export distribution stages. Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50–60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively. ns, *, *** Non-significant or significant difference between the OSW and LSW treatments in a *t*-test at $p < 0.05$ and 0.001, respectively. Vertical bars indicate the standard error (n = 10).

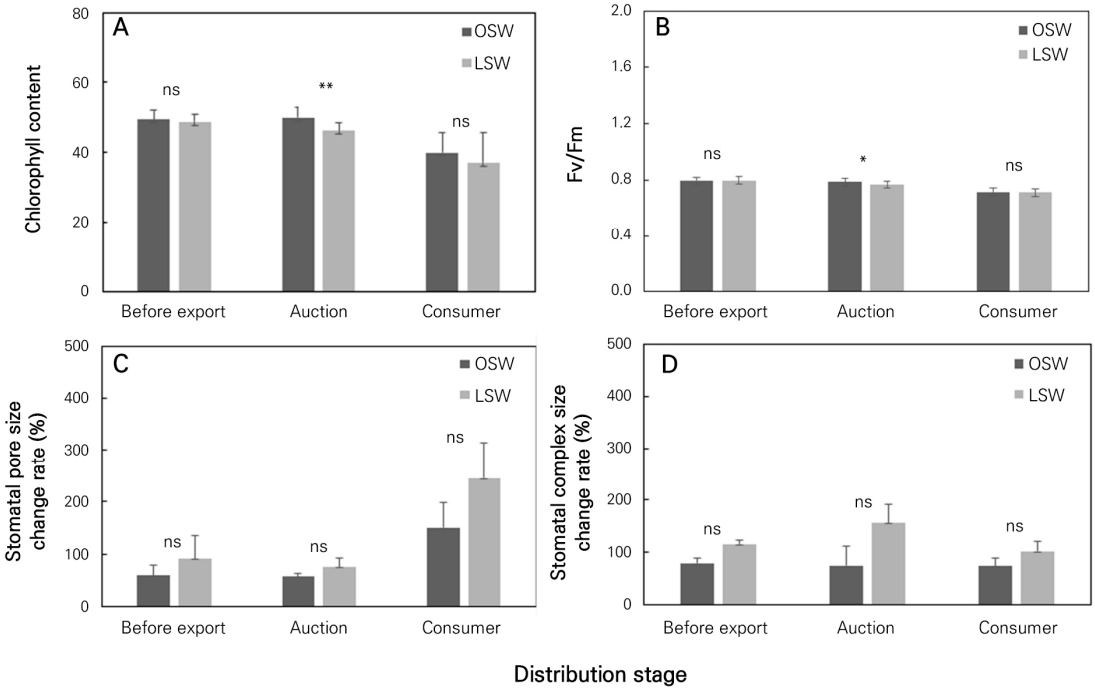

Fig. 4. Physiological characteristics on (A) chlorophyll content, (B) chlorophyll fluorescence, (C) stomatal pore size change rate or (D) complexes on the leaves of potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content for three simulated export distribution stages. The potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50–60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively. ns, * Non-significant or significant difference between the OSW and LSW treatments in a *t*-test at $p < 0.05$. Vertical bars indicate the standard error (A and B: n = 10; C and D: n = 3).

significant difference between the substrate water content treatments. Thermal imaging or index has widely been used to predict the vase life of cut rose flowers, determine the irrigation water needed by plants, run machine learning algorithms, and calculate plant stress indices (Choi and Lee, 2020; Vieira and Ferrarezi, 2021; Lee and Kim, 2021). The difference between the air temperature and the petal or leaf surface temperature did not differ between treatments at the auction stage and consumer stage (Table 4). In cut roses, the temperature of the flowers and leaves was higher than the external temperature (17°C) with the lasing stage exhibiting no visual signs of senescence (Choi and Lee, 2020; Lee et al., 2020). The plant temperature of maize, pistachio trees, potted citrus, and *Ascophyllum nodosum* has been found to be higher under water stress, but the temperature of plants under water stress was lower than OSW treatment before the export stage in this study (Table 4; Testi et al., 2008; Zia et al., 2011; Martynenko et al., 2016; Vieira and Ferrarezi, 2021).

The correlation between the shelf life and plant height was positive during all stages (Fig. 5). Vieira and Ferrarezi (2021) found a positive relationship between the temperature of plant leaves and substrate water content, indicating that thermal imaging is a reliable tool for assessing the water status of potted citrus plants in a greenhouse. However, there was no correlation between shelf life and the temperature of the flowers or leaves on auction stage and consumer stage (Fig. 5B and 5C). At the end of the shelf life, there was a high positive correlation between the shelf life and the substrate water content (r = 0.8**), the number of flowers (r = 0.8**) or buds (r = 0.6**), and flowering rate compared to the shipment (r = 0.5*) at the consumer stage (Fig. 5C).

Table 3. Physiological characteristics of potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content before export stage

Substrate water content treatment[z]	Chlorophyll contents	Fv/Fm	Stomatal size change rate (%)	
			Pore	Complex
OSW (50−60%)	49.4	0.79	59.0	80.1
LSW (≤ 20%)	48.7 [ns]	0.79 [ns]	91.3 [ns]	116.6 [ns]

[z]Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50−60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively.

[ns] Non-significant difference between the OSW and LSW treatments in a *t*-test (n = 10, except n = 3 for the stomatal size change rate).

Table 4. Difference between the temperature of the air and the petal and leaf surface in potted *Kalanchoe blossfeldiana* 'Queen bell' plants according to the substrate water content during three simulated export distribution stages

Distribution stages	Substrate water content treatment[z]	Difference in temperature	
		Petal	Leaf
Before export	OSW (50−60%)	−3.35 ± 0.24	−3.51 ± 0.19
	LSW (≤ 20%)	−2.41 ± 0.45***	−2.20 ± 0.42***
Auction	OSW (50−60%)	−1.69 ± 0.64	−2.10 ± 0.37
	LSW (≤ 20%)	−1.70 ± 0.66 [ns]	−1.82 ± 0.66 [ns]
Consumer	OSW (50−60%)	−2.03 ± 0.39	−1.53 ± 0.30
	LSW (≤ 20%)	−2.54 ± 0.41 [ns]	−1.98 ± 0.56 [ns]

[z]Potted kalanchoe plants were treated either with optimum substrate water content (OSW, 50−60%) or low substrate water content (LSW, ≤ 20%) by irrigation for twenty or five min, respectively.

[ns, ***] Non-significant or significant difference between the OSW and LSW treatments in a *t*-test at $p < 0.001$ (n = 10).

In conclusion, the shelf life of potted kalanchoe plants in the LSW treatment was shorter than that with the OSW treatment. Water stress due to the low substrate water content affected the postharvest quality of potted plants in the plant height and width, the fresh and dry weight of the roots, flowering rate compared to shipment, chlorophyll content, and Fv/Fm of the leaves. The correlation between the shelf life and plant height was positive at all stages. This study indicates that substrate water content affects the postharvest quality and shelf life of potted kalanchoe.

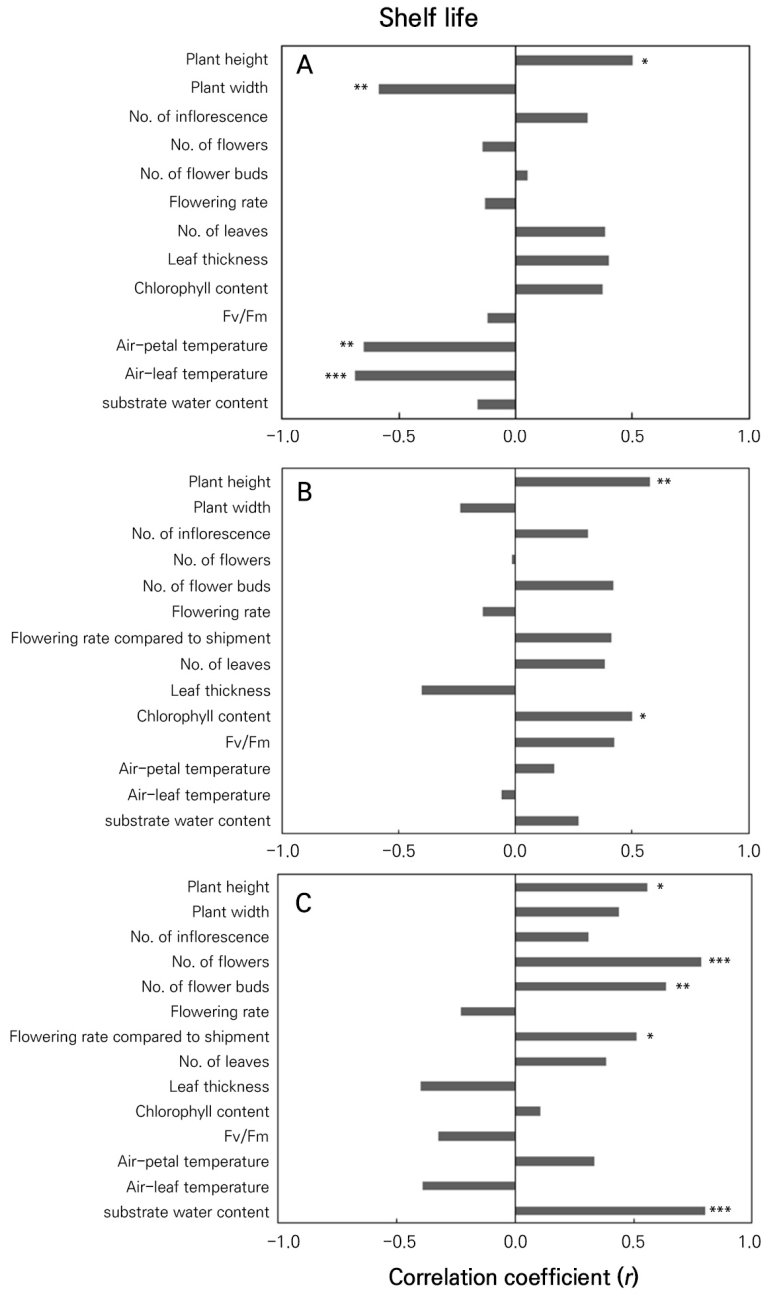

Fig. 5. Correlation coefficients for the relationships between the shelf life and the physiological/ morphological characteristics, and substrate water content of potted *Kalanchoe blossfeldiana* 'Queen bell' plants for three simulated export distribution stages: (A) before export, (B) auction, and (C) consumer. *,**, *** Significant difference at $p < 0.05$, 0.01, or 0.001, respectively (n = 10).

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