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ORIGINAL RESEARCH PAPER in HORTICULTURAL PLANTS

The Effect of Nanosilver on Postharvest Longevity of *Thalictrum aquilegifolium* L. Foliage

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Abstract

Thalictrum aquilegifolium L. 'Black Stockings,' with its interesting foliage, is used as a cut greenery. We tested the postharvest longevity of the foliage after different 24-hr conditioning treatments with nanosilver (0, 5, 10, 15, 20 mg dm^{-3}) and 20 g dm^{-3} sucrose and compared the results with those obtained using the standard preservative (200 mg dm^{-3} 8-hydroxyquinoline citrate + 20 g dm^{-3} sucrose) and Floralife 200 Clear. The longevity of the foliage and the content of assimilative pigments were evaluated and the functioning of the photosynthetic apparatus (F_0, Fm, Fv/Fm) was analyzed. We found that leaf senescence, as determined by chlorophyll *a* and carotenoid content after 14 days of holding, was most effectively inhibited by the solution containing 5 mg dm^{-3} nanosilver and sucrose. This solution increased the maximal quantum efficiency of photosystem II (Fv/Fm) in the leaves.

Keywords

carotenoids; chlorophyll content; chlorophyll fluorescence; Floralife 200 Clear; nanoparticles; standard preservative

1. Introduction

The highly competitive market for cut flowers and greenery requires consistently high-quality cuttings with the highest possible longevity. For this reason, the conditioning of inflorescences or foliage is performed immediately after harvest (Skutnik, 1998). The most commonly used conditioning agents are 8-hydroxyquinoline citrate (8-HQC), benzyladenine (BA), gibberellic acid (GA_3) (Koziara & Poręba, 2009; Krzymińska & Czuchaj, 2006), and commercial preparations, such as Chrysal Clear (Koziara & Poręba, 2009). Skutnik (1998) reports that the standard preservatives do not always prolong the postharvest longevity of cut greenery, and in some species, they may actually negatively affect quality. Therefore, it is worth testing new solutions. With recent advances in nanobiotechnology, it has been found that nanoparticles have antibacterial and antifungal properties (Rostami & Shahsavar, 2012), as demonstrated in studies on cut inflorescences of *Gerbera jamesonii* (Oraee et al., 2011) and *Rosa hybrida* 'Yellow Island' (Hashemabadi et al., 2014). Of all the nanocompounds, nanosilver deserves particular attention. Antimicrobial properties of silver have been recognized since ancient times, when silver vessels were used to contain food and water and silver was used to dress wounds (Łysakowska & Denys, 2009).

The use of nanosilver for the conditioning of cut flowers significantly limits the growth of bacteria on the cut surface of stalks and prolongs the longevity of cut flowers, including *Gerbera* (Liu et al., 2009; Mohammadiju et al., 2014), *Rosa* (Hashemabadi et al., 2014; Liu et al., 2009; Mortazavi et al., 2011), *Alstroemeria* (Alimoradi et al., 2013), and *Dianthus* (Hamidimoghadam et al., 2014; Sedaghathoor, 2015). Nanosilver was also found to limit wilting and accelerate flowering in *Polianthus tuberosa* (Bahrehmand et al., 2014) and *Rosa hybrida* 'Royal' (Mortazavi et al., 2011) and inhibited water loss in *Rosa* 'Movie Star' (Lü et al., 2010). According to Jowkar et al. (2013), nanosilver treatment resulted in an increase in the chlorophyll content of *Rosa hybrida* 'Cherry Brandy.' However, it is worth remembering that sucrose should be used together with the nanocompounds in the conditioning solutions because cut flowers are subjected to a rapid drop in the level of sugars, which can significantly shorten their longevity (Bahrehmand et al., 2014).

Thalictrum aquilegifolium L. is a decorative perennial herb belonging to the family Ranunculaceae. It is a plant with raised, hollow stems, reaching 40 to 150 cm in height (Grabowska & Kubala, 2012). Due to the original shape, the leaves can be used in floristic compositions. Single leaf blades can be successfully used in small compositions such as bouquets or wedding ornaments, while the whole foliage is used in large decorations in a dish and as a background or filler in bouquets. *Thalictrum* can be successfully grown for cut greenery, and appropriate postharvest treatment of the foliage will prolong their vase life.

The aim of the experiment was to evaluate the effect of three types of conditioning – nanosilver, standard preservative, and commercial product Floralife 200 Clear – on the postharvest quality of *Thalictrum aquilegifolium* L. foliage. The quality of plant material was determined based on the analysis of selected physiological parameters, including the content of assimilative pigments and chlorophyll *a* fluorescence indicators.

2. Material and Methods

The experiment was carried out twice in 2016–2017. The plant material consisted of *Thalictrum aquilegifolium* L. 'Black Stocking' foliage. Foliage approximately 50 cm long, with three composite leaves, were obtained in mid-June from plants growing in an unheated foil tunnel at the time when they were at the beginning of the flowering stage. Leaf blades were healthy, with no mechanical damage or symptoms of infection by diseases and pests. Foliage were cut in the morning and immediately transferred to the laboratory, where, after the inflorescences were removed, they were subjected to a conditioning treatment. The conditioning took place over 24 hr in nanosilver (NS) solutions (NanoBiotech) with a particle size of 6–12 nm, at concentrations of 0, 5, 10, 15, and 20 mg dm^{-3}. Sucrose (20 g dm^{-3}) was added to each solution. In addition to the solutions of nanosilver with sucrose, the standard preservative (8-HQC – 200 mg dm^{-3} supplemented with 20 g dm^{-3} sucrose) and Floralife 200 Clear at a concentration of 10 mL per L water and distilled water with 20 mg dm^{-3} sucrose were used. After conditioning, the foliage was placed in distilled water. The controls were also placed in distilled water.

Foliage were held in a growth room at 21 °C, 12-hr photoperiod and 35 µmol m^{-2} s^{-1} quantum irradiation, and a relative humidity of 60 ± 5%. Every other day during the storage period the water was changed and the foliage was shortened by approximately 0.5 cm with a floristic knife.

The postharvest longevity of foliage was determined in days. The point at which 30% of the leaf surface on the foliage showed wilting or yellow coloring was assumed to be the point at which the decorative qualities are lost. The experiment included eight variants in triplicates of seven stems in each replicate.

In order to determine the effect of the conditioning solutions on the quality of *Thalictrum aquilegifolium* L. 'Black Stocking' foliage, assimilation pigments such as chlorophyll *a* and *b* and carotenoids were measured from one leaf of each replicate. The analyses were performed three times at weekly intervals, in each year of the study; for the first time, immediately after the 24-hr conditioning treatment (0 days),

then after 7 and 14 days. Seven discs from each variant in triplicate, were randomly collected with a 9-mm (diameter) corkscrew. Collected material was weighed on an analytical balance with an accuracy of two decimal places, and then ground in a porcelain mortar with a small amount (2–3 mL) of 80% acetone. We transferred the ground material to a Schott funnel, with G4 pores and filtered the material several times, rinsing the mortar with 80% acetone each time. The collected filtrate was poured into measuring flasks with acetone up to 25 mL and placed in the dark. The absorbance measurements were made at three wavelengths (λ): 470, 646, and 663 nm, using a Cecil CE 9500 spectrophotometer. The concentration of individual pigments was calculated according to the method of Lichtenthaler and Wellburn (1983).

Using the Opti-Sciences OS30p+ fluorometer, we analyzed the functioning of the photosynthetic apparatus. The analysis of minimal fluorescence (F_0) and maximum fluorescence (Fm) of chlorophyll as well as maximal quantum efficiency (Fv/Fm) of photosystem (PS) II were performed on three leaves of plants from each variant. The meadow-rue leaves were adapted to the dark for 20 min by using shading clips prior to taking the measurements.

The values obtained for each feature were subjected to statistical analysis. Leaf longevity was subjected to one-way analysis of variance, and the content of assimilative pigments and chlorophyll fluorescence to a two-factor analysis of variance for orthogonal data. Differences between means were determined using multiple Tukey confidence intervals at the significance level of $\alpha = 0.05$. The tables give average results from two years of research.

3. Results

As shown in Table 1, the longest vase life was obtained in foliage conditioned with nanosilver (all concentrations) together with sucrose. The longevity of treated foliage was increased by almost 7 to 9 days, depending on concentration, in comparison to the controls (stems in distilled water). The shortest longevity was found in the *Thalictrum* foliage subjected to the conditioning treatment in a standard preservative. These stems retained their ornamental value for a period 3.1 days shorter than the controls.

Table 1 Effect of conditioning on the postharvest longevity of *Thalictrum aquilegifolium*.

Conditioner	Postharvest longevity (days)
H_2O	18.4 b*
H_2O + sucrose	21.1 b
5 mg dm^{-3} NS + sucrose	26.4 a
10 mg dm^{-3} NS + sucrose	27.3 a
15 mg dm^{-3} NS + sucrose	26.1 a
20 mg dm^{-3} NS + 20 sucrose	25.6 a
200 mg dm^{-3} 8-HQC + sucrose	15.3 c
Floralife 200 Clear	18.5 b

* Means followed by the same letter do not differ significantly at $\alpha = 0.05$.
NS – nanosilver; HQC – 8-hydroxyquinoline citrate.

Immediately after the conditioning, the highest content of chlorophyll *a* was found in foliage treated with 20 and 15 mg dm^{-3} nanosilver with sucrose (23.9% and 22.2% higher, respectively, compared to the control) (Table 2). Significantly, the highest content of chlorophyll *a* after 14 days of holding, compared to the control, was found in foliage treated with 15 and 20 mg dm^{-3} nanosilver with sucrose (increase by 32.7% and 28.6%, respectively).

During the 2-week holding period of foliage, the content of chlorophyll *a* in leaves decreased. In the control, between 0 and 14 days after the conditioning, the decrease in the chlorophyll *a* content was 30.9% (Table 2). A significant reduction in the content of this pigment during the holding period was also observed after using a

nanosilver solution at 10, 20, and 15 mg dm^{-3} with sucrose, and Floralife 200 Clear. Neither nanosilver at the concentration of 5 mg dm^{-3} with the addition of sucrose nor the standard preservative produced any significant effect on the degradation of chlorophyll *a* after 14 days.

With respect to the chlorophyll *b* content in the controls, a significant drop (41.5%) in the content of this pigment was observed between 0 and 14 days after the conditioning (Table 2). As shown in the table, chlorophyll *b* also significantly decreased in the foliage conditioned in the following solutions: water and sucrose (35.4% decrease), 15 and 20 mg dm^{-3} nanosilver with sucrose (27.0% decrease), standard preservative with sucrose (27.0% decrease), Floralife 200 Clear (23.3% decrease), and 5 mg dm^{-3} nanosilver with sucrose (17.2%).

In the comparison of the effects of the solutions after 7 days of holding, the highest chlorophyll *b* content was found in foliage conditioned in solutions of 15 and 20 mg dm^{-3} nanosilver and sucrose, with the values being 22.4% and 18.9%, respectively, higher than that in the control. After 14 days of holding, the highest content of the tested pigment, compared to the control, was recorded in the foliage treated with 10, 15, and 20 mg dm^{-3} nanosilver with sucrose, Floralife 200 Clear, and 5 mg dm^{-3} nanosilver with sucrose. With these treatments, pigment content was 47.4%, 42.1%, 41.1%, 34.2%, and 26.3% higher, respectively, than that in the control (Table 2).

A comparison of the effect of the different solutions on the content of carotenoids in the leaves of *Thalictrum* showed that immediately after conditioning and after 7 days, the foliage treated with 15 mg dm^{-3} nanosilver with sucrose showed the highest content of carotenoids compared with the control (Table 2). On day 14 after the conditioning treatment, no statistically significant differences in the content of the examined pigment in *Thalictrum* leaves were found.

In the control group, there was a significant decrease in the content of carotenoids (25.9%) between day 0 and day 14 of foliage holding (Table 2). No breakdown of carotenoids was found in foliage conditioned in a solution of 5 mg dm^{-3} nanosilver with sucrose. In this treatment, no significant differences were found in the value of the examined features between days 0, 7, and 14. A significant decrease (22.4%) in the content of the tested pigments between day 0 and day 7 was observed in foliage conditioned in the standard preservative. After 14 days of holding, the largest decrease (31.9%) in carotenoid content was found in the foliage treated with 15 mg dm^{-3} nanosilver with sucrose (Table 2).

Table 2 Effect of conditioning on chlorophyll *a* and *b* and carotenoids content in leaves of *Thalictrum aquilegifolium* (mg g^{-1} fresh weight) after 0, 7, and 14 days holding time in water after the 24-hr postharvest treatment. Means from 2016–2017.

Conditioner	Content of chloprophyll *a*			Content of chloprophyll *b*			Content of carotenoids		
	0	7	14	0	7	14	0	7	14
H_2O	2.43 di*	2.28 c–h	1.68 a	0.65 h–k	0.58 e–h	0.38 a	0.58 e–g	0.51 c–e	0.43 a–c
H_2O + sucrose	2.43 d–i	2.18 b–e	1.81 a–b	0.65 h–k	0.55 c–g	0.42 a–b	0.55 d–f	0.45 a–c	0.39 a
5 mg dm^{-3} NS + sucrose	2.29 c–h	2.09 a–e	1.93 a–c	0.58 e–h	0.55 c–g	0.48 b–d	0.50 b–e	0.47 a–d	0.44 a–c
10 mg dm^{-3} NS + sucrose	2.73 h–k	2.67 f–k	1.89 a–c	0.63 f–j	0.60 e–i	0.56 d–k	0.60 f–g	0.55 d–f	0.48 b–d
15 mg dm^{-3} NS + sucrose	2.97 j–k	2.67 f–k	2.23 b–f	0.74 k	0.71 j–k	0.54 c–f	0.69 h	0.60 f–g	0.47 a–d
20 mg dm^{-3} NS + sucrose	3.01 k	2.53 e–j	2.16 b–e	0.74 k	0.69 i–k	0.54 c–f	0.65 g–h	0.54 d–f	0.47 a–d
200 mg dm^{-3} 8-HQC + sucrose	2.24 b–g	2.00 a–d	1.98 a–d	0.60 e–i	0.55 c–g	0.46 a–c	0.58 e–g	0.45 a–c	0.42 a–b
Floralife 200 Clear	2.69 g–k	2.26 b–g	2.03 a–d	0.64 g–j	0.58 e–h	0.51 b–e	0.60 f–g	0.54 d–f	0.43 a–c

* Means followed by the same letter do not differ significantly at $\alpha = 0.05$. NS – nanosilver; HQC – 8-hydroxyquinoline citrate.

From the comparison of the effects of solutions on the value of F_0, after 14 days of holding, the smallest value of F_0 was found in foliage conditioned in Floralife 200

Clear (Table 3). Accordingly, in the present experiment, the application of nanosilver at concentrations of 5, 15, and 20 mg dm^{-3} together with sucrose did not prevent the reduction of excitation energy transfer efficiency after 14 days of foliage holding.

When comparing the effects of solutions on the examined traits at specific measurement dates, no significant differences were found between the mean values of minimal fluorescence obtained after the use of individual substances and the mean for the control (Table 3).

With respect to the Fm in the leaves of *Thalictrum aquilegifolium*, the Fm value for the control leaves, as well as those conditioned in other solutions, did not change during the 14 days of holding (Table 3). In the assessment of the effect of individual substances used for conditioning the foliage on the test feature on the day of treatment and after 7 days of the experiment, no significant differences were found between mean values of the tested parameter. After 14 days of holding, the lowest Fm was obtained in foliage conditioning with Floralife Clear 200, and the value was 19.1% lower than that in the control (distilled water with sucrose).

As shown in Table 3, immediately after *Thalictrum aquilegifolium* conditioning treatment, the highest value of the Fv/Fm was recorded (9.1% higher than control) for foliage conditioned in the solutions containing 15 and 20 mg dm^{-3} nanosilver with sucrose. Between day 0 and day 14, the Fv/Fm of foliage conditioned in a solution of 5 mg dm^{-3} nanosilver with sucrose was 8.9% higher and that of foliage treated with 15 mg dm^{-3} nanosilver with sucrose.

Table 3 Effect of conditioning on minimal fluorescence (F_0), maximal fluorescence (Fm), and maximal quantum efficiency of PSII (Fv/Fm) in leaves of *Thalictrum aguilegifolium* after 0, 7, and 14 days holding time in water after the 24-hr postharvest treatment. Means from 2016–2017.

Conditioner	F_0			Fm			Fv/Fm		
	0	7	14	0	7	14	0	7	14
H_2O	225 ab*	256 b	219 ab	1,101 ab	1,181 b	1,084 ab	0.795 a–c	0.781 a–c	0.797 a–c
H_2O + sucrose	261 b	248 b	239 b	1,079 ab	1,208 b	1,180 b	0.782 a–c	0.794 ab	0.797 a–c
5 mg dm^{-3} NS + sucrose	215 ab	234 ab	233 ab	1,025 ab	1,113 ab	1,074 ab	0.758 ab	0.789 a–c	0.826 cd
10 mg dm^{-3} NS + sucrose	235 ab	256 b	249 b	1,121 ab	1,166 ab	1,134 ab	0.749 ab	0.779 a–c	0.780 a–c
15 mg dm^{-3} NS + sucrose	245 b	247 b	246 b	1,143 ab	1,168 ab	1,015 ab	0.867 d	0.812 b–d	0.746 a
20 mg dm^{-3} NS + sucrose	230 ab	213 ab	228 ab	1,008 ab	1,047 ab	1,172 ab	0.867 d	0.796 a–c	0.804 a–d
200 mg dm^{-3} 8-HQC + sucrose	239 b	236 ab	249 b	1,151 ab	1,146 ab	1,118 ab	0.806 a–d	0.781 a–c	0.776 a–c
Floralife 200 Clear	233 ab	226 ab	182 a	1,116 ab	1,141 ab	954 a	0.790 a–c	0.801 a–c	0.777 a–c

* Means followed by the same letter do not differ significantly at $\alpha = 0.05$. NS – nanosilver; HQC – 8-hydroxyquinoline citrate.

4. Discussion

Hansen et al. (1996) report that *Thalictrum* positively responds to the silver solution in the conditioning preservative, extending the period of decorative value of the plant material. According to the author, treatment with silver thiosulphate (STS) resulted in *Thalictrum delavayi* 'Hewitts Double' inflorescences remaining decorative for 7 days longer than the control. Lin et al. (2019) investigated the efficacy of pretreatment with nanosilver at 10, 15, 20, 25, and 30 mg dm^{-3} in enhancing

the vase life of cut gardenia foliage. The authors reported that the most effective nanosilver concentration was 15 mg dm^{-3}, which promoted the longest vase life extension (310% higher than control). The results of our experiment are similar to those from the study by Lin et al. (2019) in which the longest period of decorative value was demonstrated by foliage conditioned in the experiment concentrations of nanosilver (5 to 20 mg dm^{-3}) (Table 1).

The use of nanosilver at a concentration of 5 to 20 mg dm^{-3} for the conditioning of *Thalictrum aquilegifolium* L. 'Black Stocking' foliage positively affected the longevity of cuttings (Table 1). Prolonged longevity of the tested foliage most probably results from the bactericidal and fungicidal action of nanosilver. Oleszkiewicz et al. (2008) report that silver interacts with the thiol groups of the bacterial cell walls, increasing the permeability of the cell membranes and causes disturbances in ionic balance and DNA structure damage, resulting in the inhibition of protein synthesis.

Results of this experiment confirm the desirability of using nanosilver for postharvest treatment of ornamental plants. Low doses of this substance (i.e., 5 mg dm^{-3}) were used to increase the longevity of *Rosa hybrida* 'Royal' (Mortazavi et al., 2011), *Dianthus caryophyllus* 'Pinkcastellaro' (Hamidimoghadam et al., 2014), and *Dianthus caryophyllus* 'Express' (Sedaghathoor, 2015). In studies on *Gerbera jamesonii*, the efficacy of nanosilver has been demonstrated at a concentration of 6 mg dm^{-3} (Oraee et al., 2011) and 10 mg dm^{-3} (Mohammadiju et al., 2014). Nanosilver at higher concentration (15 mg dm^{-3}) significantly increased the longevity of *Alstroemeria* flowers. Byczyńska and Salachna (2017) showed that the use of nanosilver at a concentration of 200 mg dm^{-3} increased the longevity of *Chrysanthemum* ×*morifolium* 'Feeling Green.'

In the present study, the shortest longevity shown by *Thalictrum* foliage was achieved by the conditioning treatment of 8-HQC with sucrose (Table 1), confirming the negative effect of the standard preservative on the longevity of many cut greenery species (Skutnik & Łukaszewska, 2001; Skutnik et al., 2016). Janowska and Jerzy (2003) showed that holding *Zantedeschia elliottiana* leaves in 8-HQC solution adversely affected plant material quality, causing the tops of leaf blades to dry. According to Solgi et al. (2009), 8-HQC reduced the longevity of *Gerbera jamesonii* 'Dune' inflorescences. Different results were obtained by Krzymińska and Czuchaj (2006), who recorded an increase in the longevity of the alumroot 'Plum Pudding' leaves after conditioning in 200 mg dm^{-3} 8-HQC solution.

The green color of cut greenery is an important determinant of foliage quality (Alimoradi et al., 2013). Loss of leaf decorativeness is related to metabolic changes occurring in chloroplasts, among others, chlorophyll degradation and chloroplast protein degradation (Jackowski, 1998). The compounds used for conditioning should delay senescence processes by, for example, inhibiting protein and chlorophyll degradation (Skutnik et al., 2016). In our experiment, the highest content of chlorophyll *a* after 14 days of holding, compared to the control, was found in foliage treated with 15 and 20 mg dm^{-3} nanosilver with sucrose (Table 2).

Michałek et al. (2006) reported that the content of chlorophyll *a* and *b* in the leaves of *Paeonia lactiflora* decrease by more than one-third the initial value during the first 6 days after the harvest. In the present experiment, significant reductions in the chlorophyll *a* content between day 0 and day 14 was observed after treatment with all conditioners, except the standard preservative and the solution of 5 mg dm^{-3} nanosilver and sucrose. Differing results due to the use of 8-HQC have been demonstrated by Skutnik et al. (2001) and Skutnik and Rabiza-Świder (2004). Studies have also reported that the standard preservative accelerated the breakdown of chlorophyll in the leaves of *Zantedeschia aethiopica* (Skutnik & Łukaszeska, 2001) and inflorescences of *Molucella laevis* (Skutnik & Rabiza-Świder, 2004).

Alimoradi et al. (2013) showed that the use of nanosilver at a concentration of 15 mg dm^{-3} limited the decrease in chlorophyll content in the leaves of cut *Alstromeria*. In the present experiment, the solution of 10 mg dm^{-3} nanosilver together with sucrose maintained the chlorophyll *b* content throughout the 14 days of holding (Table 2). The effect of nanosilver solutions on the chlorophyll content in leaves depends on its concentration. Langroudi et al. (2019) reported

that the use of nanosilver at a concentration of 10 mg dm^{-3} limited the degradation of chlorophyll in *Alstroemeria*. Byczyńska and Salachna (2017) showed that nanosilver at a concentration of 400 mg dm^{-3} exerted positive effects on the green leaf index of cut *Chrysanthemum ×morifolium* 'Feeling Green' inflorescences. In *Dianthus caryophyllus* 'Pinkcastellaro,' a positive effect on the content of assimilative pigments was noted after using nanosilver at a concentration of 10 mg dm^{-3} (Hamidimoghadam et al., 2014). Jowkar et al. (2013) found that cuttings of *Rosa hybrida* 'Cherry Brandy' stems treated with high concentrations of nanosilver (50 and 25 g dm^{-3}) presented significantly higher chlorophyll content than that in control stems treated with distilled water. Byczyńska (2017) reported that the cut leaves of *Aspidistra elatior* conditioned in nanosilver solution showed significantly higher greening index values than the controls, regardless of the nanosilver concentration, whereas Solgi et al. (2009) reported that nanosilver at concentrations of 25 and 50 mg dm^{-3} did not significantly affect the chlorophyll content of *Dianthus caryophyllus*.

With senescence of plant organs and degradation of chlorophyll, carotenoids become visible (Kopcewicz & Lewak, 2012), and the yellowing of leaves is the most visible sign of their aging (Skutnik & Rabiza-Świder, 2004). Carotenoids, which are responsible for the yellow color of the leaves, have antioxidant functions and take part in singlet oxygen quenching and are degraded during the neutralization of harmful compounds (Packer, 2002). In the present experiment, after 14 days of holding, the largest decrease in the carotenoid content was found in the foliage treated with 15 mg dm^{-3} nanosilver with sucrose (Table 2). This result differed from that reported by Mattiuz et al. (2010), who showed that *Oncidium varicosum* 'Samurai' subjected to pulse conditioning with the silver thiosulphate complex (STS) had higher carotenoid content than that in controls on days 8 and 12 (Mattiuz et al., 2010).

Early detection of the influence of stressful conditions (before visual symptoms of stress occur) on the physiological state of plants is achieved by measuring chlorophyll *a* fluorescence (Cetner et al., 2016). Fluorescence intensity varies depending on the duration and intensity of stress (Lichtenthaler, 2007). This method of measuring the chlorophyll fluorescence can also be used to optimize flower holding conditions (Cetner et al., 2016).

In the experiment, the value of F_0, otherwise known as the initial fluorescence, which is the first point on the chlorophyll fluorescence curve (Cetner et al., 2016), was assessed. After 14 days of holding, the smallest value of F_0, compared to the control, was found in foliage conditioned in Floralife 200 Clear (Table 3). According to Kalaji and Łoboda (2010), high F_0 values indicate low efficiency of excitation energy transfer between pigment molecules in the PSII power antenna. Ferrante et al. (2009) showed that the increase in the F_0 indicator occurred in *Matthiola incana* plants held in distilled water for 7 days.

The Fm, which is the maximum fluorescence intensity of objects adapted to the dark (Cetner et al., 2016), of leaves of *Thalictrum aquilegifolium* (regardless of the variant) did not change during the 14 days of holding (Table 3). The decrease in the Fm value, according to reports by Kalaji and Łoboda (2010), is indicative of stress, which prevents all electron acceptors in PSII from being completely reduced. Kalaji and Łoboda (2010) reported that Fm values depend not only on chlorophyll content in the examined tissue but other factors as well; this might also be the case in the present experiment with *Thalictrum aquilegifiolium*.

Another indicator of the physiological status of *Thalictrum aquilegifolium* foliage analyzed in the present experiment was the maximal quantum efficiency of PSII (Fv/Fm) (Table 3). This parameter can be used as a reliable indicator of photochemical activity of the photosynthetic apparatus (Kalaji & Łoboda, 2010). According to Matysiak (2003), the value of this parameter in optimal conditions should be 0.75–0.85, and lower values indicate the degradation of chlorophyll during holding of greenery cut under stress conditions. According to Johnson et al. (1999), the optimal level of Fv/Fm should not be less than 0.83. A value below this level indicates that the plant was previously exposed to stress factors that caused damage to PSII (Kalaji & Łoboda, 2010; Maxwell & Johnson, 2000). According to

Koziara (2005), disturbance in water intake and the limiting of continuous uptake of minerals from the substrate are also important factors that cause plant stress. The senescence of cut greenery is also largely due to oxidative stress, which is observed when the balance between the production of reactive oxygen species and their removal by antioxidant systems is disturbed (Bartosz, 2008). In the present study, the value of this indicator dropped below the limit given by Matysiak (2003) immediately after *Thalictrum aquilegifolium* was conditioned with 10 mg dm^{-3} nanosilver with sucrose. After a longer (14 day) period of foliage holding, this value (0.746) was recorded after conditioning the cutting in a solution of 15 mg dm^{-3} nanosilver with sucrose (Table 3).

With respect to the effect of nanosilver on Fv/Fm immediately after *Thalictrum aquilegifolium* conditioning treatment, the highest value of the tested indicator was recorded after application of 15 and 20 mg dm^{-3} nanosilver with sucrose (Table 3). Between day 0 and day 14, the Fv/Fm was higher for the foliage conditioned in a solution of 5 mg dm^{-3} nanosilver with sucrose than that for the controls. The obtained results are in line with those reported by Jowkar et al. (2013), who measured the longevity of the flower stems of *Rosa hybrida* 'Cherry Brandy' and found a positive effect of nanosilver on Fv/Fm, although they used significantly higher concentrations of nanosilver (10 g dm^{-3}) than those used in this work. In *Matthiola incana* (Ferrante et al., 2009) and *Peoania lactiflora* (Michałek et al., 2006), a significant decrease in Fv/Fm was observed in the control foliage (held in distilled water), which was not observed in the present study of *Thalictrum aquilegifolium*.

Fluorescence of chlorophyll *a* is used to assess the state of cut greenery. Skutnik et al. (2003) reported that the change in values of chlorophyll fluorescence parameters occurs as a result of degradation processes due to senescence of leaf blades and it gradually reduces the intensity of photosynthesis.

5. Conclusions

- In order to prolong the longevity of *Thalictrum aquilegifolium* L. 'Black Stocking' foliage, it is recommended that the foliage be conditioned for 24 hr in a solution of nanosilver at a concentration of 5 to 20 mg dm^{-3} with 20 g dm^{-3} sucrose.
- The standard preservative, used as a conditioner (200 mg dm^{-3} 8-HQC + 20 g dm^{-3} sucrose), negatively affects the longevity of cut *Thalictrum aquilegifolium* foliage.
- In nonconditioned foliage, senescence caused an approximately 40% decrease in the level of chlorophyll in the leaves of cut *Thalictrum aquilegifolium* foliage.
- The use of nanosilver at 5 mg dm^{-3} with sucrose slowed chlorophyll *a* and carotenoid decrease rate in *Thalictrum aquilegifolium* leaves and maintained the Fv/Fm of PSII after 14 days of holding.
- Chlorophyll fluorescence can be used to assess the physiological state of the leaves of cut *Thalictrum aquilegifolium* 'Black Stocking' foliage during 14 days of holding.

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