Relative Salt Tolerance of Eight Japanese Barberry Cultivars

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Abstract. Relative salt tolerance of eight *Berberis thunbergii* (japanese barberry) cultivars (*B. thunbergii* ‘Celeste’, ‘Kasia’, ‘Maria’, ‘Mini’, and ‘Talago’; *B. thunbergii* var. *atropurpurea* ‘Concorde’, ‘Helmond Pillar’, and ‘Rose Glow’) was evaluated in a greenhouse experiment. Plants were irrigated with nutrient solution at an electrical conductivity (EC) of 1.2 dS·m⁻¹ (control) or saline solutions at an EC of 5.0 or 10.0 dS·m⁻¹ (EC 5 or EC 10) once a week for 8 weeks. At 4 weeks after treatment, all barberry cultivars in EC 5 had minimal foliar damage with visual scores of 4 or greater (visual score 0: dead, 5: excellent). At 8 weeks after treatment, in EC 5, ‘Helmond Pillar’, ‘Maria’, ‘Mini’, and ‘Rose Glow’ plants exhibited slight foliar salt damage with an average visual score of 3.5, whereas ‘Celeste’, ‘Concorde’, ‘Kasia’, and ‘Talago’ had minimal foliar salt damage with an averaged visual score of 4.4. However, most barberry plants in EC 10 exhibited severe foliar salt damage 4 weeks after treatment with the exception of ‘Concorde’ and were dead 8 weeks after treatment. Compared with control, at the end of the experiment (8 weeks of treatments), shoot dry weight (DW) of ‘Celeste’, ‘Helmond Pillar’, ‘Maria’, and ‘Rose Glow’ in EC 5 was reduced by 47%, 47%, 50%, and 42%, respectively, whereas shoot DW of ‘Concorde’, ‘Kasia’, ‘Mini’, and ‘Talago’ in EC 5 did not change. In EC 10, shoot DW of ‘Celeste’, ‘Concorde’, ‘Kasia’, and ‘Talago’ was reduced by 75%, 35%, 55%, and 46%, respectively. The averaged sodium (Na) concentration of all barberry cultivars in EC 5 and EC 10 was 34 and 87 times, respectively, higher than the control, whereas leaf chloride (Cl) concentration of all barberry cultivars in EC 5 and EC 10 was 14–60 and 29–106 times, respectively, higher than the control. Growth, visual quality, and performance index (PI) were all negatively correlated with leaf Na and Cl content in all cultivars, suggesting that excessive Na and Cl accumulation in the leaf tissue led to growth reduction, salt damage, and death. In summary, ‘Concorde’, ‘Kasia’, and ‘Talago’ were relatively salt tolerant; ‘Helmond Pillar’, ‘Maria’, ‘Mini’, and ‘Rose Glow’ were relatively salt sensitive; and ‘Celeste’ was in between the two groups. Generally, barberry plants had moderate salt tolerance and can be irrigated with marginal water at an EC of 5 dS·m⁻¹ or lower with slight foliar damage.

Water and soil salinization are global problems and are more severe in water-scarce areas such as arid and semiarid regions, where groundwater is the primary source of water. The increasing population has intensified the competition for high-quality water supply among urban and agricultural water users. Therefore, using alternative water sources such as municipal reclaimed water to irrigate nursery crops and landscape plants has drawn considerable attention (Grieve, 2011). Reclaimed water carries relatively high

levels of soluble salts, which negatively affect plant growth and development and impose foliar salt injury on sensitive plants (Niu and Cabrera, 2010; Veatch-Blohm et al., 2014). The salinity of groundwater, which is a primary water source for nursery crops in some areas, varies with location and rainfall (Niu and Cabrera, 2010). Overuse of groundwater leads to decline of water table and increases salinity (Smith et al., 2016). Therefore, information on salt tolerance of nursery and landscape crops is necessary to prevent

salt damage and maintain aesthetically appealing landscapes.

Berberis thunbergii (japanese barberry) is a species native to Japan and eastern Asia, although widely naturalized in China and North America (Wikipedia, The Free Encyclopedia, 2017). It is a multibranched dense shrub that can grow up to 2.5 m tall with shiny green to burgundy alternate leaves along its thorny stems (Dirr, 1998). It has solitary yellow flowers that bloom from March to April and produces round or elliptical red berries (Dirr, 1998). Japanese barberry is a widely grown landscape plant that was awarded the prestigious Royal Horticultural Societies Annual Award of Garden Merit in 1993 (Davis Landscape Architecture, 2017). In the United States, an estimated \$30 million in barberry plants are sold annually (U.S. Department of Agriculture, 2009). Previous breeding efforts have led to numerous cultivars that offer different foliage colors (yellow, dark red to violet, or variegated foliage) and forms (erect growth or dwarf size) (Dirr, 1998). For example, *B. thunbergii* var. *atropurpurea* ‘Concorde’ is extremely slow growing with a compact habit and small deep red or purple leaves that hold color in heat (Dirr, 1998). *Berberis thunbergii* var. *atropurpurea* ‘Helmond Pillar’ is a distinct upright with fastigate form and reddish purple leaves that usually grows up to 1.5 m tall and 0.6 m wide forming a slow-growing column (Dirr, 1998). *Berberis thunbergii* var. *atropurpurea* ‘Rose Glow’ can grow about 1.5–1.8 m tall and produces new foliage in rose-pink mottled with deeper red-purple splotches that gradually mature to a deep reddish purple (Dirr, 1998).

Salt tolerance of barberry species has been reported in extension articles. For example, Beckerman and Lerner (2009) reported that *Berberis* species are sensitive or have intermediate tolerance to aerial salt spray, whereas they are sensitive to soil salinity. On the list of salt-tolerant plants compiled by Chalet Nursery (2013), *Berberis* species have high aerial salt tolerance and low soil salt tolerance. *Berberis thunbergii* has poor soil salt tolerance (Gilman, 2014) and high tolerance to aerial salt spray (Jull, 2009). *Berberis koreana* also has high tolerance to aerial salt spray (Jull, 2009), but its tolerance to soil salinity is yet to be determined. *Berberis julianae* and *Berberis bealei* have moderate salt tolerance (Glen et al., 2004; Harrison, 2009). However, these reports are mostly based on anecdotal observations without defined thresholds for categories of salt tolerance. Only a few research-based studies have been conducted to evaluate the responses of barberry plants to salinity. Monk and Wiebe (1961) reported that *B. thunbergii* was not salt tolerant based on the study in salinized field plots. *Berberis thunbergii* is listed as a very salt-sensitive plant because a 25% growth reduction occurred when the EC of a saturation extract of growing medium was 1.8 dS·m⁻¹, whereas *Berberis xmentorensis* is listed as a salt-sensitive plant tolerating a saturation extract of EC up to 3–4 dS·m⁻¹ (Costello et al.,

2003; Handreck and Black, 2002). Two-year-old seedlings of *B. thunbergii* 'Atropurpurea' showed no significant difference in annual growth when irrigated with tap water, tap water containing 3.3 g·L⁻¹ NaCl, 6.0 g·L⁻¹ CaCl₂, or 10.5 g·L⁻¹ Na₂CO₃ for eight times at 7-d intervals (Marosz, 2012).

Given that salt tolerance varies considerably among species and even cultivars within a species, a systematic study is needed to investigate the salt tolerance of different barberry cultivars. The objectives of this study were to evaluate the relative salt tolerance of eight barberry cultivars in a greenhouse study using the parameters of shoot growth, visual quality, chlorophyll content, PI, and mineral concentration in response to elevated salinity of irrigation solution.

Materials and Methods

Plant materials and growing conditions.

Rooted cuttings (≈6 cm) of barberry cultivars [*B. thunbergii* 'Celeste' (Sunjoy® Cinnamon), 'Kasia' (Sunjoy® Mini Saffron), 'Maria' (Sunjoy® Gold Pillar), 'Mini' (Sunjoy® Mini Salsa), and 'Talago' (Sunjoy® Gold Beret); *B. thunbergii* var. *atropurpurea* 'Concorde', 'Helmond Pillar', and 'Rose Glow'] were received from Spring Meadow Nursery Inc. on 3 Mar. 2016. On 8 Mar., the cuttings were transplanted into 2.7-L black polyethylene injection-molded containers (C-650; Lerio Corp., Mobile, AL) containing Metro-Mix 360 RSI [canadian sphagnum peatmoss 45% to 55%, vermiculite, composed bark, dolomite limestone, 0.0001% silicon dioxide (SiO₂); SunGro Hort., Bellevue, WA]. All barberry plants were placed in a greenhouse in El Paso, TX (lat. 31°41'45"N, long. 106°16'54"W, elev. 1139 m). They were irrigated to saturation initially and then watered as needed afterward with reverse osmosis (RO) water-based nutrient solution

to avoid salt accumulation in the root zone until treatments started. Three weeks after transplanting (i.e., 29 Mar.), uniform plants were chosen for salt tolerance screening, and treatments were started. The average air temperature in the greenhouse was 26.7 ± 4.1 °C (mean and SD) during the day and 18.1 ± 4.6 °C at night. The average daily light integral was 9.6 ± 1.5 mol·m⁻²·d⁻¹ and the average relative humidity was 35.6% ± 12.9% during the experiment period.

Treatments. A nutrient solution at an EC of 1.2 ± 0.1 dS·m⁻¹ was used as the control. The nutrient solution was prepared by adding 1 g·L⁻¹ 15N–2.2P–12.5K (Peters 15–5–15 Ca–Mg Special; Scotts, Marysville, OH) to RO water. Saline solutions at an EC of 5.0 ± 0.1 dS·m⁻¹ (EC 5) and 10.0 ± 0.1 dS·m⁻¹ (EC 10) were prepared by adding 20.6 mM sodium chloride (NaCl) and 10.4 mM calcium chloride (CaCl₂), and 47.8 mM NaCl and 24.0 mM CaCl₂, respectively, to the nutrient solution mentioned previously. The pH of all solutions was adjusted to 6.6–6.8 using potassium hydroxide. Both nutrient and saline solutions were prepared in 100-L tanks with confirmed EC using an EC meter (Model B173; Horiba, Ltd., Kyoto, Japan) before irrigation.

From 29 Mar. to 26 Apr., barberry plants were irrigated weekly with treatment solutions, 1 L/plant, resulting in a leaching fraction of ≈38%. In addition, plants were irrigated with nutrient solution whenever substrate surface became dry between treatments. The irrigation frequency depended on environmental conditions, plant size, and treatments. For example, plants in the control often use more water and need to be irrigated more frequently than those at high salinity levels. On 10 May, five plants were harvested per treatment per cultivar (first harvest). From 13 May to 3 June, treatment solutions were applied weekly to the remaining barberry plants as described previously. On 13 June, all remaining five plants in each treatment were harvested (second harvest).

Leachate EC. The leachate EC was measured using the pour-thru technique as described by Cavins et al. (2008) and Wright (1986). One plant per treatment per cultivar was randomly selected for measurement after irrigating with treatment solution and EC readings were pooled across cultivars.

Visual quality and growth data. At harvest time, salt damage was rated by giving a visual score based on a reference scale from 0 to 5, where 0 = dead; 1 = more than 90% foliar damage (salt damage: burning, necrosis, and discoloration); 2 = moderate (50% to 90%) foliar damage; 3 = slight (less than 50%) foliar damage; 4 = good quality with minimal foliar damage; and 5 = excellent with no foliar damage (Sun et al., 2015b). The foliar salt damage rating did not consider plant size. Shoots were severed at the substrate surface, and leaf area was determined using an LI-3100C area meter (LI-COR® Biosciences, Lincoln, NE). Shoot DW was determined after oven-drying at 70 °C for 4 d.

Leaf relative chlorophyll content. Relative chlorophyll content [soil plant analysis

development (SPAD) reading] was recorded using a handheld chlorophyll meter (measured as the optical density; Minolta Camera Co., Osaka, Japan) on 4 May and 7 June. Healthy and fully expanded leaves in the middle of shoots were chosen for measurement, and five plants per treatment per cultivar were measured.

Performance index. The PI (Strasser et al., 2000, 2004) was measured at 1000 and 1400 HR using a Hansatech Pocket PEA chlorophyll fluorimeter (Hansatech Instruments Ltd., Norfolk, UK) to examine the effect of elevated salinity on leaf photosynthetic apparatus of barberry plants at 36 d of treatment (i.e., 4 May) and 70 d of treatment (i.e., 7 June). Healthy and fully expanded leaves in the middle of shoots were chosen for measurement, and five plants per treatment per cultivar were measured. The leaves were dark adapted for at least 30 min before the measurements. Performance index was calculated as follows (Strasser et al., 2000; Živčák et al., 2008): $PI = \frac{1 - (F_0/F_M)}{M_0/V_J} \times \frac{F_M - F_0}{F_0} \times \frac{1 - V_J}{V_J}$, where minimal fluorescence values in the dark-adapted state (F_0) were obtained by application of a low-intensity red light-emitting diode light source (627 nm) at 50 μs, whereas maximal fluorescence values (F_M) were measured after applying a saturating light pulse of 3500 μmol·m⁻²·s⁻¹. The parameter F_J is the fluorescence intensity at the J step at 2 ms and V_J is the relative variable fluorescence at 2 ms calculated as $V_J = (F_J - F_0)/(F_M - F_0)$, M_0 represents the initial slope of fluorescence kinetics, which can be derived from the equation:

$$M_0 = 4 \times (F_{300\mu s} - F_0)/(F_M - F_0).$$

Mineral analysis. Shoot Na, Cl, Ca, and potassium (K) concentrations were analyzed using the dried materials from the first harvest with four samples per treatment per cultivar. Mineral analysis was not conducted for those samples from the second harvest because most plants in EC 10 did not survive. Dried tissue was ground to pass a 40-mesh screen with a stainless Wiley mill (Thomas Scientific, Swedesboro, NJ). The dried tissue samples were extracted with 2% acetic acid (Fisher Scientific, Fair Lawn, NJ) to determine Cl using the method described in Gavlak et al. (1994). The concentration of Cl was determined using a M926 Chloride Analyzer (Cole Parmer Instrument Company, Vernon Hills, IL). The dried tissue samples were submitted to the USDA-ARS (Toledo, OH) for analyses of foliar Na, Ca, and K. In brief, the dried tissue samples were digested in nitric acid following the protocol described by Havlin and Soltanpour (1989). Sodium, Ca, and K in digested samples were analyzed using inductively coupled plasma-optical emission spectrometer (iCAP 6300 Duo View ICP-OES; Thermo Fisher Scientific, Waltham, MA) and reported on a dry plant basis as described by Isaac and Johnson (1975).

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Experimental design and statistical analysis. The experiment used a split-plot design with the salinity treatment as the main plot and eight cultivars as the subplot with 10 replications per treatment per cultivar. Because of different plant growth habits, a one-way analysis of variance was performed separately for each cultivar. Means separation among treatments was conducted using Tukey's honestly significant difference multiple comparison at $\alpha = 0.05$. When plants in EC 10 treatment were dead, mean comparison between control and EC 5 was analyzed by Student's *t* test.

Relative shoot DW was calculated for each plant in EC 5 or EC 10 treatment as follows: relative shoot DW (%) = shoot DW in salt treatment/shoot DW in control $\times$ 100%. Similarly, relative values for leaf area and SPAD were calculated. These relative values and visual scores were used as salt tolerance indices for hierarchical cluster analysis (Zeng et al., 2002). The dendrogram and clustering of the eight barberry cultivars was obtained based on the Ward's linkage method and squared Euclidean distance on the means of the salt tolerance indices for four multivariate parameters including all relative values and visual scores. All statistical analyses were performed using JMP (Version 12; SAS Institute Inc., Cary, NC).

Results and Discussion

Leachate EC. Average leachate EC from 29 Mar. to 26 Apr. ranged from 2.5 to 3.1 $\text{dS}\cdot\text{m}^{-1}$ for control, 4.7 to 8.4 $\text{dS}\cdot\text{m}^{-1}$ for EC 5, and 6.5 to 14.8 $\text{dS}\cdot\text{m}^{-1}$ for EC 10 (Fig. 1). From 13 May to 3 June, the average leachate EC of the control was 3.2–3.8 $\text{dS}\cdot\text{m}^{-1}$, whereas that in EC 5 and EC 10 increased from 9.8 to 9.9 $\text{dS}\cdot\text{m}^{-1}$ and from 15.5 to 17.3 $\text{dS}\cdot\text{m}^{-1}$, respectively. The higher EC values of leachate indicated salt accumulation in the substrate.

Visual quality. At the first harvest, all barberry plants in EC 5 had minimal foliar damage with visual scores of 4 or greater, whereas the visual scores of 'Helmond Pillar' and 'Mini' barberry were significantly reduced in EC 5 (Table 1). Treatment EC 10 reduced the visual quality of 'Concorde' barberry, but the visual score was still greater than 4. 'Celeste', 'Helmond Pillar', 'Kasia', 'Rose Glow', and 'Talago' in EC 10 had moderate foliar damage with visual scores of 2 to 3. 'Maria' and 'Mini' in EC 10 were severely damaged with visual scores near 1. At the second harvest, 'Celeste', 'Concorde', 'Kasia', and 'Talago' were still in good quality with visual scores of 4 or greater in EC 5, whereas in EC 10, plants exhibited severe foliar salt damage with an averaged visual score of 0.9. 'Helmond Pillar', 'Maria', 'Mini', and 'Rose Glow' in EC 5 had slight foliar salt damage with averaged visual scores of 3.5, but all were dead in EC 10. These results indicated that the degree of the foliar damage in response to salinity is cultivar dependent.

Visual quality is an important parameter for ornamental plants and, therefore, visual

Fig. 1. Time course of weekly leachate electrical conductivity (EC) during the experimental period. Control represents nutrient solution at an EC of 1.2 $\text{dS}\cdot\text{m}^{-1}$; EC 5 represents saline solution at an EC of 5.0 $\text{dS}\cdot\text{m}^{-1}$ and EC 10 represents saline solution at an EC of 10.0 $\text{dS}\cdot\text{m}^{-1}$. Vertical bars represent SE of eight samples, one sample per cultivar.

rating is always used as an important parameter in assessing salt tolerance of ornamental plants (Niu and Cabrera, 2010). Salinity may cause undesirable effects such as necrosis and leaf edge burn on ornamental plants that result in poor visual quality and eventually affect the marketability of ornamental plants (Wahome et al., 2001). As indicated by many researchers (Grieve et al., 2008; Niu and Cabrera, 2010), at elevated salinity conditions, salt-tolerant species, genotypes, or cultivars usually have less foliar salt injury compared with less salt-tolerant species. Based on this criterion, most of the tested cultivars of barberry were tolerant to an EC of 5.0 $\text{dS}\cdot\text{m}^{-1}$ of irrigation water with acceptable visual quality (greater than 4.0), provided that well-drained substrate or soils are used to reduce salt accumulation in the root zone. The substrate used in this study resulted in salt accumulation (Fig. 1) which could have been caused by the high portion of peatmoss (45% to 55%). Peatmoss has higher cation exchange capacity than pine bark (Altland et al., 2014), and thus may have retained higher salt levels than typical nursery substrates composed primarily of bark. Peatmoss also retains more water than bark with higher container capacity (Gabriel et al., 2009), and thus would drain less than typical substrates composed primarily of bark. To prevent salt accumulation, a substrate with lower peatmoss ratio should be used for long-term production.

Growth and relative chlorophyll content (SPAD). All barberry cultivars in EC 5 had similar leaf area to those in control at the first harvest (Table 1). Compared with control, in EC 10, 'Concorde', 'Helmond Pillar', and 'Talago' also had similar leaf area; however, 'Celeste', 'Kasia', 'Mini', and 'Rose Glow' had smaller leaf area. At the second harvest,

reduced leaf area was observed on all barberry cultivars in EC 5 with exception of 'Concorde', 'Kasia', and 'Talago'. Salinity affected the growth of barberry as indicated by reduced shoot DW (Table 2). At the first harvest, in EC 5, only 'Celeste' and 'Maria' had decreased shoot DW. Treatment EC 10 further reduced the shoot DW of all barberry cultivars except Concorde, Helmond Pillar, and Talago. At the second harvest, shoot DW of 'Celeste', 'Helmond Pillar', 'Maria', and 'Rose Glow' in EC 5 was reduced, and that of 'Celeste', 'Concorde', 'Kasia', and 'Talago' in EC 10 was further reduced. These results suggest that barberry cultivars responded differently to elevated salinity, and 'Concorde', 'Kasia', and 'Talago' were more tolerant than the other cultivars. Elevated salinity has been previously reported to reduce the shoot and leaf biomass in a variety of plant species (Cai et al., 2014; Niu and Rodriguez, 2006; Niu et al., 2012a, 2012b, 2013; Sun et al., 2013, 2015a, 2015b).

Salinity negatively affected SPAD readings at both harvests (Table 2) with variations among cultivars. At the first harvest, saline solutions at EC 5 did not affect SPAD readings of all barberry cultivars with the exception of 'Celeste' and 'Maria' (Table 2). In EC 10, compared with control, reduced SPAD readings were observed on all barberry cultivars except Kasia. At the second harvest, elevated salinity reduced the SPAD readings of all barberry cultivars.

Based on the visual score and the reduction of shoot DW, 'Helmond Pillar', 'Maria', 'Mini', and 'Rose Glow' could be classified as salt sensitive, whereas 'Concorde', 'Kasia', and 'Talago' were more salt tolerant. 'Celeste' was in between the two groups. These conclusions were further

Table 1. Visual score and leaf area of eight barberry cultivars irrigated with nutrient solution [electrical conductivity (EC) = 1.2 dS·m⁻¹; control] or saline solution [EC = 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10)] in the greenhouse. Plants were harvested after the fourth (first harvest) and eighth treatment (second harvest).

Cultivars	Visual score						Leaf area (cm ²)					
	First harvest			Second harvest			First harvest			Second harvest		
	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10
Celeste	5.0 a ^z	4.7 a	2.9 b	5.0 a	4.0 a	0.6 b	637 a	571 a	239 b	1121 a	358 b	— ^y
Concorde	5.0 a	4.7 ab	4.3 b	5.0 a	4.6 a	0.8 b	375 a	396 a	420 a	433 a	468 a	—
Helmond Pillar	5.0 a	4.1 b	2.0 c	5.0 a	3.4 b	0.0 c	453 a	532 a	294 a	557 a	191 b	—
Kasia	5.0 a	4.5 a	2.3 b	5.0 a	4.6 a	1.6 b	602 a	677 a	288 b	811 a	764 a	169 b
Maria	5.0 a	4.6 a	0.6 b	5.0 a	3.4 b	0.0 c	1177 a	1000 a	—	1511 a	512 b	—
Mini	5.0 a	4.1 b	1.2 c	5.0 a	3.8 b	0.0 c	550 a	575 a	193 b	700 a	417 b	—
Rose Glow	5.0 a	4.2 a	2.1 b	5.0 a	3.4 b	0.0 c	642 a	458 ab	228 b	811 a	179 b	—
Talago	5.0 a	4.3 a	2.3 b	5.0 a	4.2 a	0.6 b	386 a	327 a	318 a	378 a	425 a	—

^zMeans with same letters within a row and harvest are not significantly different among treatments by Tukey's honestly significant difference multiple comparison or between treatments by Student's *t* test at *P* < 0.05.

^yData not collected because of dead plants.

Table 2. Shoot dry weight (DW) and relative chlorophyll content [soil plant analysis development (SPAD)] of eight barberry cultivars irrigated with nutrient solution [electrical conductivity (EC) = 1.2 dS·m⁻¹; control] or saline solution [EC = 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10)] in the greenhouse. Plants were harvested after the fourth (first harvest) and eighth treatment (second harvest).

Cultivars	Shoot DW (g)						SPAD					
	First harvest			Second harvest			First harvest			Second harvest		
	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10
Celeste	7.5 a ^z	5.1 b	4.1 b	15.0 a	7.9 b	3.8 b	24.0 a	19.3 b	18.7 b	30.1 a	27.1 a	—
Concorde	4.3 a	3.8 a	3.8 a	7.1 a	6.7 a	4.6 b	46.3 a	42.0 ab	39.2 b	53.4 a	40.4 b	—
Helmond Pillar	5.3 a	5.1 a	3.9 a	9.7 a	5.2 b	— ^y	42.1 ab	42.5 a	36.1 b	45.8 a	29.5 b	—
Kasia	5.3 ab	6.2 a	3.8 b	10.6 a	9.3 a	4.8 b	17.1 a	20.6 a	18.2 a	26.1 a	18.2 b	14.6 b
Maria	10.8 a	8.4 b	5.3 c	21.3 a	10.6 b	—	16.3 a	13.1 b	8.8 c	22.8 a	12.3 b	—
Mini	7.6 a	7.2 a	4.6 b	14.0 a	11.9 a	—	47.5 a	43.7 a	32.6 b	51.7 a	31.8 b	—
Rose Glow	6.5 a	5.2 ab	3.6 b	11.5 a	6.7 b	—	32.4 a	30.6 a	25.6 b	40.3 a	35.9 a	—
Talago	3.8 a	3.5 a	3.4 a	6.0 a	7.2 a	3.2 b	20.9 a	20.6 a	11.9 b	32.9 a	22.3 a	—

^zMeans with same letters within a row and harvest are not significantly different among treatments by Tukey's honestly significant difference multiple comparison or between treatments by Student's *t* test at *P* < 0.05.

^yData not collected because of dead plants.

Fig. 2. Cluster analysis of the salt tolerance of eight barberry cultivars. The relative leaf area, relative shoot dry weight, relative soil plant analysis development (SPAD) reading, and visual score of barberry plants irrigated with saline solution at an electrical conductivity (EC) of 5.0 dS·m⁻¹ (EC 5) and 10.0 dS·m⁻¹ (EC 10) were used as salt tolerance indices for hierarchical cluster analysis. The dendrogram was obtained based on the Ward's linkage method and squared Euclidean distance on the means of the salt tolerance indices for the aforementioned four multivariate parameters at both harvests. The relative leaf area and SPAD data in EC 10 were excluded in the cluster analysis because of incomplete data set resulting from dead plants.

confirmed using a hierarchical cluster analysis with multivariate parameters including visual score, relative leaf area, relative shoot DW, and relative SPAD in both EC 5 and EC 10 treatments. The dendrogram shows two distinguishable clusters (Fig. 2). The first cluster of 'Concorde', 'Kasia', and 'Talago' was considered salt-tolerant cultivars, whereas the second cluster of 'Celeste', 'Helmond Pillar', 'Maria', 'Mini', and 'Rose Glow' was salt-sensitive cultivars.

Performance index. Performance index was affected by elevated salinity with variations among cultivars (Table 3). At the first harvest, a reduced PI was observed on all barberry cultivars in EC 5 and EC 10 in the morning except for 'Helmond Pillar', 'Kasia', and 'Talago' in EC 5, and 'Talago' in EC 10. In the afternoon, the PI of 'Concorde', 'Maria', and 'Talago' in EC 5 was reduced, but this was not the case for other cultivars. In addition, all barberry cultivars in

EC 10 had reduced PI. At the second harvest, EC 5 decreased the PI of 'Celeste', 'Helmond Pillar', 'Maria', 'Mini', and 'Rose Glow' measured both in the morning and afternoon. No significant difference of PI was observed between morning and afternoon (*P* > 0.05).

Performance index reflects the functionality of both photosystems I and II and is a sensitive indicator of plant vitality (Strasser et al., 2000, 2004). Our results agreed with a previous report that PI was shown to express only small diurnal changes (Živčák et al., 2014). Performance index has been reported to be sensitive to water stress reflecting different drought tolerance (Lepeduš et al., 2012; Živčák et al., 2008) and N deficiency (Živčák et al., 2014). In our study, PI was also responsive to salinity stress and could be a reliable and useful parameter to evaluate the salt damage of barberry cultivars.

Mineral analysis. Salt solution prepared with NaCl and CaCl₂ increased the concentration of Na and Ca in barberry leaves (Table 4). Treatment EC 5 increased the Na concentration of all barberry cultivars. The averaged Na concentration of all barberry cultivars in EC 5 was 34 times higher than those in control. Treatment EC 10 further increased the Na concentration of all barberry cultivars up to 87 times higher than those in control. The highest Na concentration (17.4 mg·g⁻¹ DW) was found in 'Maria' in EC 10. Compared with control, leaf Ca concentration of 'Celeste', 'Concorde', and 'Maria' in EC 5 increased by 47%, 34%, and 78%,

Table 3. Performance index of eight barberry cultivars irrigated with nutrient solution [electrical conductivity (EC) = 1.2 dS·m⁻¹; control] or saline solution [EC = 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10)] in the greenhouse. Data were collected after the fourth treatment (first harvest) and the eighth treatment (second harvest).

Cultivars	First harvest						Second harvest					
	AM			PM			AM			PM		
	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10	Control	EC 5	EC 10
Celeste	11.3 a ^z	7.4 b	3.6 c	9.8 a	6.6 ab	3.6 b	11.3 a	4.6 b	4.4 b	11.9 a	3.3 b	—
Concorde	10.8 a	7.5 ab	4.8 b	13.6 a	7.5 b	4.2 b	15.4 a	14.9 a	— ^y	9.4 a	8.9 a	—
Helmond Pillar	7.9 a	5.3 ab	3.5 b	6.2 a	6.0 a	2.2 b	8.3 a	2.6 b	—	9.9 a	4.5 b	—
Kasia	9.1 a	9.3 a	2.9 b	11.3 a	8.9 ab	4.0 b	7.5 a	4.7 a	6.7 a	4.6 a	6.3 a	3.0 b
Maria	9.8 a	6.0 b	1.7 c	9.0 a	6.4 b	1.2 c	8.3 a	5.1 b	—	6.8 a	3.2 b	—
Mini	8.1 a	4.8 b	0.9 c	6.9 a	4.5 ab	2.3 b	7.5 a	4.4 b	—	6.9 a	2.4 b	—
Rose Glow	8.0 a	3.1 b	1.4 b	4.7 a	3.2 ab	1.4 b	6.3 a	2.3 b	—	6.2 a	2.5 b	—
Talago	8.5 a	6.5 a	4.2 a	9.8 a	5.2 b	2.4 b	8.5 a	4.4 a	4.2 a	12.4 a	1.2 b	—

^zMeans with same lowercase letters within a row and time are not significantly different among treatments by Tukey's honestly significant difference multiple comparison at $P < 0.05$.

^yData not collected because of dead plants.

Table 4. Foliar Na, Cl, K, and Ca concentrations of barberry cultivars irrigated with nutrient solution [electrical conductivity (EC) = 1.2 dS·m⁻¹; control] or saline solution [EC = 5.0 dS·m⁻¹ (EC 5) or 10.0 dS·m⁻¹ (EC 10)] in the greenhouse. Plants at the first harvest were used for mineral analysis.

Cultivars	Treatment	Mineral concn. (mg·g ⁻¹ dry weight)			
		Na	Cl	Ca	K
Celeste	Control	0.1 c ^z	0.8 c	7.9 c	15.6 b
	EC 5	4.3 b	22.2 b	11.6 b	18.0 ab
	EC 10	11.8 a	50.4 a	16.8 a	20.8 a
Concorde	Control	0.1 c	0.6 c	7.5 c	17.9 a
	EC 5	2.6 b	9.6 b	10.0 b	15.8 b
	EC 10	6.7 a	22.2 a	12.6 a	16.5 b
Helmond Pillar	Control	0.3 c	0.5 c	8.3 b	16.3 ab
	EC 5	6.6 b	18.3 b	11.0 ab	14.2 b
	EC 10	14.1 a	40.0 a	15.0 a	17.1 a
Kasia	Control	0.2 c	0.8 c	7.4 b	19.6 a
	EC 5	4.8 b	15.4 b	10.9 b	14.9 b
	EC 10	15.3 a	54.8 a	16.6 a	20.1 a
Maria	Control	0.1 c	0.7 c	10.2 c	19.8 b
	EC 5	6.6 b	44.8 b	18.1 b	26.6 a
	EC 10	17.4 a	68.1 a	23.4 a	26.4 a
Mini	Control	0.2 c	0.3 c	9.2 b	17.4 ab
	EC 5	4.4 b	14.3 b	12.1 b	15.7 b
	EC 10	10.3 a	34.9 a	17.8 a	19.1 a
Rose Glow	Control	0.1 c	0.5 c	10.9 b	18.7 b
	EC 5	4.5 b	28.3 b	13.3 b	21.1 ab
	EC 10	10.7 a	46.4 a	18.1 a	21.9 a
Talago	Control	0.2 c	1.0 c	9.0 b	16.2 a
	EC 5	4.8 b	18.0 b	10.9 b	14.2 a
	EC 10	10.3 a	34.2 a	15.2 a	17.2 a

^zFor each cultivar, means with same lowercase letters within a column are not significantly different among treatments by Tukey's honestly significant difference multiple comparison at $P < 0.05$.

respectively, whereas those in EC 10 increased by 112%, 68%, and 130%, respectively (Table 4). Treatment EC 5 did not increase the leaf Ca concentration of 'Helmond Pillar', 'Kasia', 'Mini', 'Rose Glow', and 'Talago', but EC 10 increased the leaf Ca concentration by 81%, 124%, 94%, 66%, and 68%, respectively. Salt treatment also increased leaf Cl concentrations (Table 4). The leaf Cl concentration of all barberry cultivars in EC 5 was 14–60 times higher than that of their respective control, whereas those in EC 10 had 34–106 times more in leaf Cl concentrations. The highest Cl concentration (68.1 mg·g⁻¹ DW) was found in 'Maria' barberry in EC 10.

Marosz (2012) reported that leaf Na content of *B. thunbergii* 'Atropurpurea' seedlings irrigated with tap water containing 3.3 g·L⁻¹ (56.4 mM) NaCl for eight times at 7-day intervals increased 15 times compared with that containing 0 mM NaCl, but the leaf Ca

concentration did not change; however, when the plants were irrigated with tap water containing 10.5 g·L⁻¹ Na₂CO₃ (100 mM), the leaf Na increased 17.5 times and Ca concentration decreased by 24%. Both studies consistently showed that barberry plants preferentially uptake Na instead of Ca when they were grown at elevated salinity conditions. High concentrations of Na, Cl, or both accumulated in leaf tissue may damage the chloroplasts and thus inhibit photosynthesis (Taiz and Zeiger, 2015). Excessive Na and Cl uptake also competes with the uptake of other nutrient ions such as K or nitrogen (N), resulting in nutritional disorders and reduced plant quality (Grattan and Grieve, 1999).

Potassium plays an important role in regulation of the ψ_s of plant cells and also activates many enzymes involved in respiration and photosynthesis (Taiz and Zeiger, 2015). High accumulation of Na might cause the reduction of K uptake (Hasegawa et al.,

2000). In our study, treatment EC 5 reduced the leaf K concentration of 'Concorde' and 'Kasia' barberry, and EC 10 further decreased the leaf K concentration of 'Concorde' barberry (Table 4). However, compared with control, no significant difference of leaf K content was observed in 'Helmond Pillar', 'Mini', and 'Talago' in both EC 5 and EC 10, 'Celeste' and 'Rose Glow' in EC 5, and 'Kasia' in EC 10. Similar results have been documented by Marosz (2012) showing that the leaf K content of *B. thunbergii* 'Atropurpurea' seedlings did not change when irrigated with tap water containing 3.3 g·L⁻¹ (56.4 mM) NaCl or 6.0 g·L⁻¹ CaCl₂ (54.1 mM). In addition, leaf K content of 'Maria' in both EC 5 and EC 10 and 'Celeste' and 'Rose Glow' in EC 10 increased with saline solution applied.

Conclusions

Among the eight barberry cultivars used in this study, Helmond Pillar, Maria, Mini, and Rose Glow barberry were relatively salt sensitive as evidenced by higher mortality, greater reduction in shoot DW, and more severe foliar salt damage. 'Concorde', 'Kasia', and 'Talago' barberry were more salt tolerant with less foliar salt damage and smaller reduction in shoot DW at elevated salinity. Salt tolerance of 'Celeste' barberry was slightly better than that of the clustered sensitive group. These results are valuable for growers and landscape professionals in plant selection for sites where low-quality water may be used for irrigation.

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