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Eucalyptus Species Selection for Superior Adaptability to Indoor-Outdoor Environments in South Korea

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Abstract

This study was initiated to examine suitable *Eucalyptus* species with high survival and acclimation rates among *E. pulverulenta*, *E. cinerea*, *E. globulus*, *E. websteriana*, *E. parvula*, *E. kruseana*, *E. cordata*, *E. polyanthemos*, *E. gunnii*, and *E. crebra*, in South Korea where have not been conducted under both greenhouse and field conditions during the early tree growth stage. Germination at 70 days after sowing (DAS) was highest in *E. crebra* at 86.1%, followed by *E. cordata* (76.4%), *E. globulus* (68.1%), and *E. pulverulenta* (66.7%). *E. cinerea* and *E. polyanthemos* maintained seedling survival of 100.0% at 70 DAS, with the lowest survival observed for *E. websteriana* and *E. kruseana* (approximately 84–85%). The tallest trees were observed in *E. globulus* at 141.7 cm, followed by *E. polyanthemos* and *E. crebra* at 150 days after transplanting (DAT); the smallest trees were detected in *E. kruseana* (33.7 cm) and *E. parvula* (38.6 cm), with conditions affecting the thickness of their trunks. The number of shoots was significantly higher in *E. globulus* and *E. cordata* at 150 DAT with highest number of leaves in *E. parvula*, followed by *E. globulus*, *E. cordata*, and *E. crebra*. Foliar SPAD was highest for *E. gunnii* at 150 DAT but lower for *E. cinerea*, *E. globulus*, and *E. polyanthemos* with light bluish and whitish green foliage. Leaf browning was negligible for all *Eucalyptus* spp. at 30 DAT but occurred considerably at 150 DAT during early winter, with *E. kruseana* at approximately 45%, *E. polyanthemos* at 21%, and *E. parvula* at 20%. The dry mass of the leaves, shoots, and roots of each species was highest for *E. globulus* at 107.7 g, followd by *E. polyanthemos* and *E. crebra*, and was lowest for *E. cinerea* and *E. websteriana*. A thicker trunk significantly increased the tree height ($r^2 = 0.7779$), total dry weight ($r^2 = 0.7987$), root dry weight ($r^2 = 0.7194$), and number of leaves ($r^2 = 0.1963$).

Additional key words: *E. globulus*, *E. gunnii*, germination, survival, transplanting

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Introduction

More than 800 species have been reported for the genus of *Eucalyptus* (*Eucalyptus* spp.), which are evergreen trees of the family Myrtaceae; more than 500 species *Eucalyptus* spp. occur indigenously in Australia (Coppen et al., 2002; Kellison et al., 2013). *Eucalyptus* spp. are the most common tree species planted along the streets of many countries worldwide, particularly Oceania, owing to their rapid growth and high value as a shelterbelt (Cromer et al., 1981; Pohjonen and Pukkala, 1990; Cotterill and MacRae, 1997; Coppen et al., 2002; Dirr and Warren, 2019). The biomass of *Eucalyptus* spp. also has various industrial applications, mostly for paper pulp, energy wood and timber for coal-fired power as well as medicinal applications, particularly for vaccine adjuvants, aromatic resources, soap, and perfume (Coppen et al., 2002; Sillett et al., 2015; Dirr and Warren, 2019). Potted *Eucalyptus* spp. are very popular for interior decorations, flower arrangements, and air purifiers in South Korea, where they have not been commercially planted as ornamental trees in backyards and are receiving attention in horticultural therapy and healing.

Eucalyptus trees are mostly found between 10°N and 44°S latitude, with 100 to 3,750 mm of precipitation in tropical to warm temperate zones, including of Brazil, India, China, and some countries in the Mediterranean area (Coppen et al., 2002; Teulières et al., 2007; Booth, 2013; Kellison et al., 2013); such conditions could allow the trees to expand to new growing regions worldwide. Global warming has reduced seed germination, tree survival, and suitable areas for planting trees in South America due to heat stress, increased evapotranspiration, and limited water availability (Booth, 2013; Martins et al., 2022). However, climate warming of 2 − 4°C would contribute to strong vegetative growth of temperate and boreal trees of relatively cool origin when compared with warm-origin trees (Feeley et al., 2007; Way and Oren, 2010; Bowman et al., 2014; Drake et al., 2015).

South Korea is located in a temperate area between 33° and 43° north latitude, with an average temperature of 2.7°C and precipitation of 116.6 mm from December to February in the cold winter season of 2022 (KMA, 2022). Some *Eucalyptus* spp., such as *gunnii* and *pauciflora*, can tolerate between −14°C and −18°C although the trees do not undergo endodormancy during winter (Teulières et al., 2007); they could be established in an outside field after hardening from the seedling stage. However, little research has been conducted on the adaptability of *Eucalyptus* trees grown in indoor and outdoor environments in a north temperate zone, with no research performed in S. Korea. *E. pulverulenta*, *E. gunnii*, and *E. parvula* comprise approximately 91% of *Eucalyptus* species sales, and they are mostly used as interior design materials in S. Korea (aT, 2023). The aim of this study was to expand the choice of *Eucalyptus* species by evaluating germination and survival under greenhouse conditions and to select the best species on the basis of their performance after transplantation into a field.

Materials and Methods

Indoor Experiment

The seeds of ten *Eucalyptus* spp., *E. pulverulenta*, *E. cinerea*, *E. globulus*, *E. websteriana*, *E. parvula*, *E. kruseana*, *E. cordata*, *E. polyanthemos*, *E. gunnii*, and *E. crebra*, were collected for germination in an indoor experiment in a small greenhouse (2.4 m × 2.4 m) in Gyeongju-si, South Korea (35°N, 129°E) on April 3, 2022. Hundreds of *Eucalyptus* seeds per species were sown in 72-cell seedling trays with growth medium and drain holes. The growth medium (Olaeolae, Seoul Bio Co., Eumseong-gun, S. Korea) consisted of a mixture of components: 15% peatmoss, 68% coco peat, 7% perlite, 7% zeolite, and 3% vermiculite, which contained 0.65 EC $dS \cdot m^{-1}$, 300 $mg \cdot L^{-1}$ NO_3-N, 250 $mg \cdot L^{-1}$ NH_4-N, 350 $mg \cdot L^{-1}$ P_2O_5, and 13 $cmolc \cdot kg^{-1}$ CEC, with a water content of 55%, bulk density of 0.22 $Mg \cdot m^{-3}$, and pH of 6.2 (1:5, v/v). In the greenhouse, the lowest relative humidity (RH) and air temperature were 13% and 0.3°C, respectively, with the

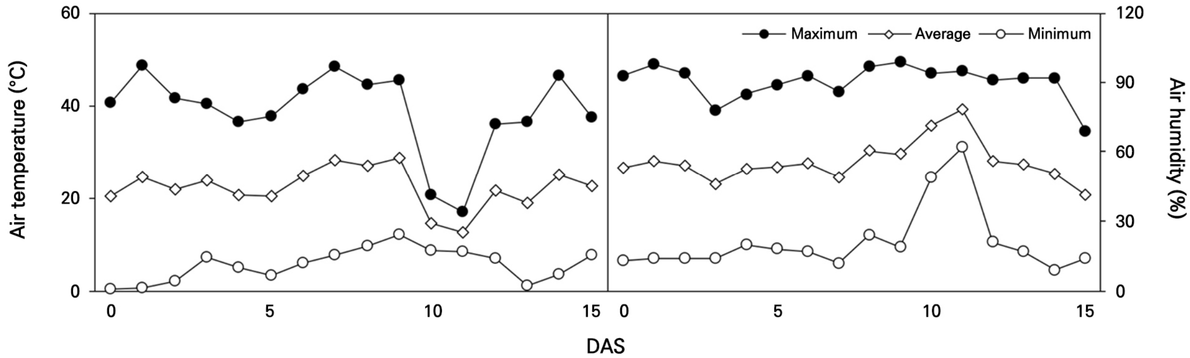

Fig. 1. Air temperature (Panel A) and humidity (Panel B) in a greenhouse at 0 and 15 days after sowing (DAS) in Gyeongju-si in 2022.

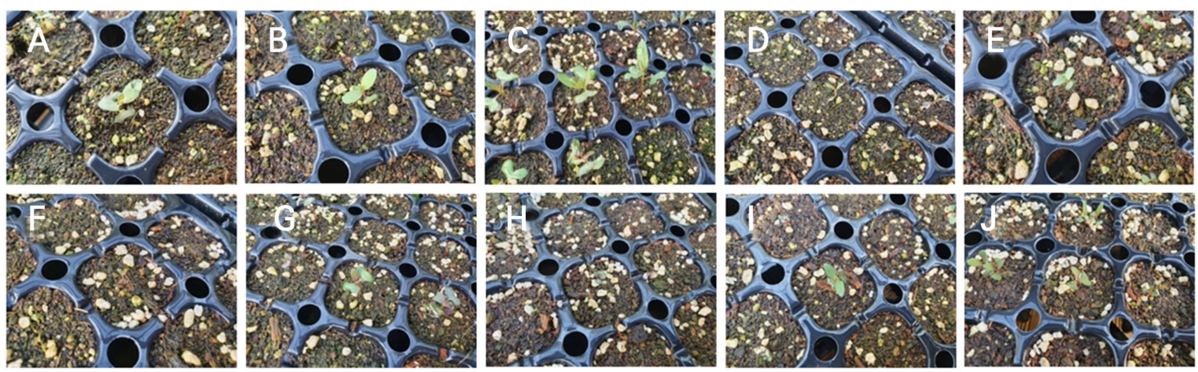

Fig. 2. Seedlings of ten *Eucalyptus* species before transplantation from a glass greenhouse to the field after nine weeks of sowing in Gyeongju-si in 2022. *E. pulverulenta* (A), *E. cinerea* (B), *E. globulus* (C), *E. websteriana* (D), *E. pavula* (E), *E. kruseana* (F), *E. cordata* (G), *E. polyanthemos* (H), *E. gunnii* (I), and *E. crebra* (J).

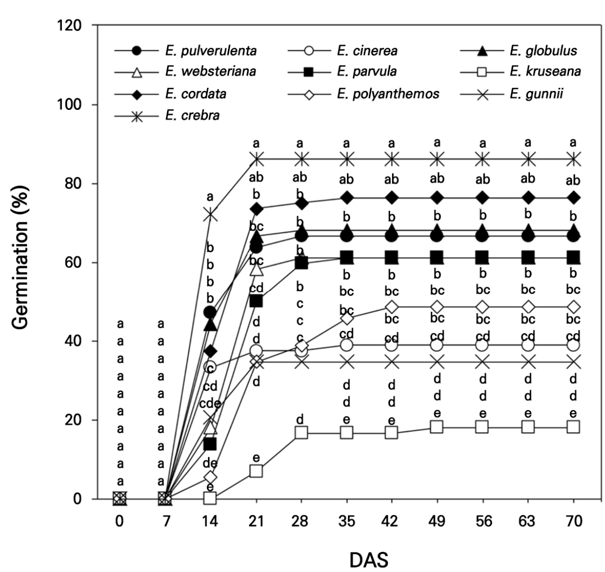

Fig. 3. Germination rates of ten *Eucalyptus* species in a glass greenhouse at one-week intervals from 0 to 70 days after sowing (DAS) in Gyeongju-si in 2022. Different lowercase letters on each phase indicate significant differences determined using Duncan's multiple-range test at $p < 0.05$.

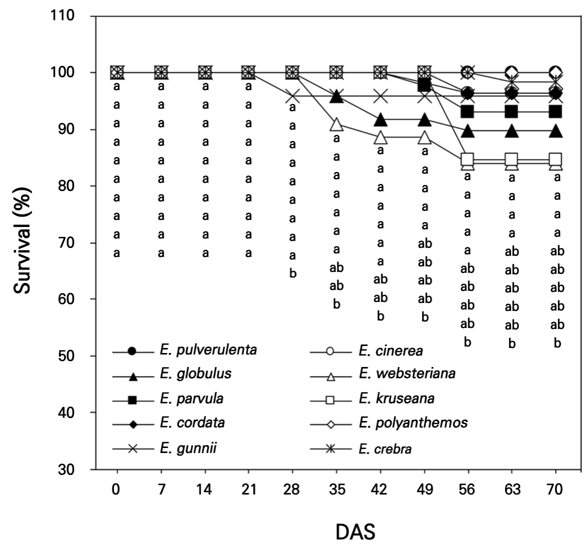

Fig. 4. Survival rates of ten *Eucalyptus* species in a glass greenhouse at one-week intervals from 0 to 70 days after sowing (DAS) in Gyeongju-si in 2022. Different lowercase letters on each phase indicate significant differences determined using Duncan's multiple-range test at $p < 0.05$.

corresponding highest RH and air temperature being 99% and 48.6°C recorded in April (KMA, 2022, Fig. 1); an open-roof greenhouse system was used to decrease the temperature during the rest of the experimental period (May and June). The seed germination and survival rates were visually observed 14 days after sowing (DAS, Fig. 2) and were measured once a week from 0 to 70 DAS in April – June 2022 (Figs. 3 and 4).

Outdoor Experiment

An outdoor study was conducted in an experimental field of a university farm in Gyeongsan-si, S. Korea (35°N, 127°E) on June 10, 2022, with 167 g of manure compost (poultry 30%, cow 30%, pig 5%, saw dust 30%, and zeolite 5%; Taesan Farming Corp., Gyeongju-si, S. Korea) per tree to improve soil fertility. The field soil nutrition before transplanting of *Eucalyptus* seedlings was 0.04 $dS \cdot m^{-1}$ EC, 12.7 $g \cdot kg^{-1}$ organic matter, 3.5 $mg \cdot kg^{-1}$ NO_3, 658.3 P_2O_5, 0.18 $cmolc \cdot kg^{-1}$ K_2O, 6.6 cmolc/kg CaO, and 1.4 $cmolc \cdot kg^{-1}$ MgO at pH 6.8. Two hundred *Eucalyptus* seedlings (20 per *Eucalyptus* species) were transplanted with 2.0 m between rows and 0.5 m between the trees from a small greenhouse for the outdoor experiment (Fig. 5). None of the *Eucalyptus* species were trained, and they were naturally grown with plastic tree support. The trees in the soil, a mixture of silt loam, were irrigated using a hand-held hose whenever the dry period exceeded five days in the field.

Tree height, trunk thickness 10 cm above the soil surface, and number of shoots and leaves were measured 30 and 150 days after transplanting (DAT). Leaf chlorophyll concentrations were estimated for fully expanded leaves of the mid-positioned shoots of each tree by means of SPAD-502 measurements (Minolta Co., Tokyo, Japan) at 30 and 150 DAT.

Leaf browning in each tree was recorded on the basis of any browning symptoms visually detected at 30 and 150 DAT.

The trees, including the roots, were destructively harvested at 150 DAT and separated into roots, leaves, and shoots. Each organ was dried in an oven at 65°C for seven days and the dry weight was then measured. The dry mass was partitioned into that of a whole tree considering its top-to-root ratio.

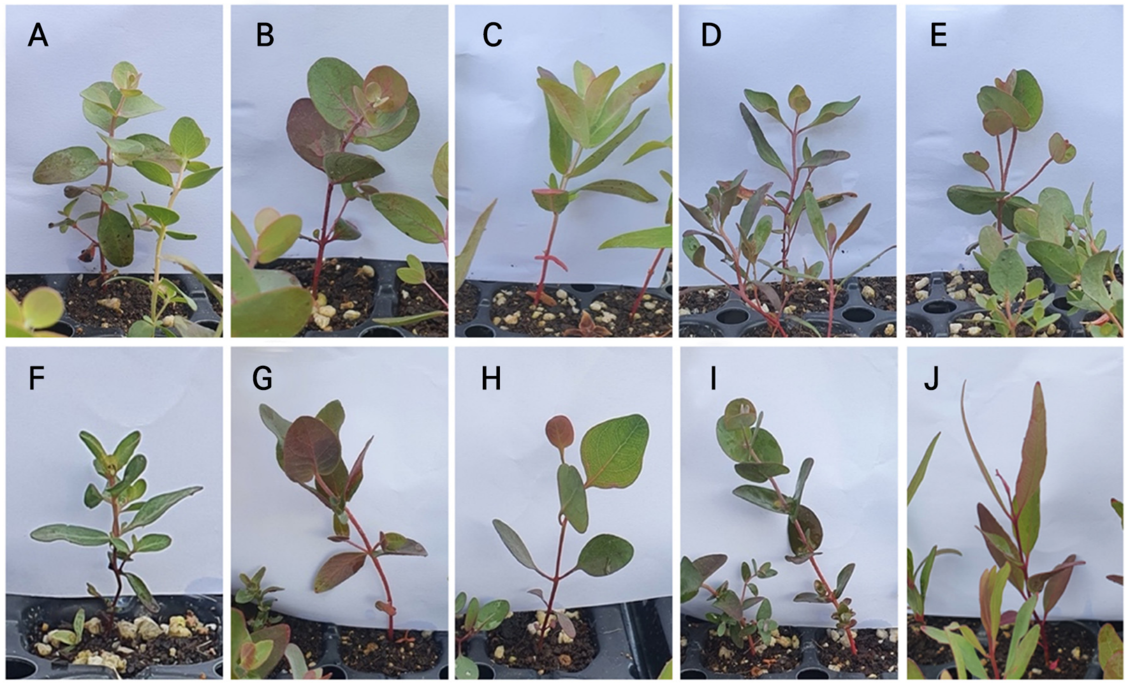

Fig. 5. Photographs of ten *Eucalyptus* species harvested at 200 days after transplanting in Gyeongsan-si in January, 2023. *E. pulverulenta* (A), *E. cinerea* (B), *E. globulus* (C), *E. websteriana* (D), *E. parvula* (E), *E. kruseana* (F), *E. cordata* (G), *E. polyanthemos* (H), *E. gunnii* (I), and *E. crebra* (J).

Data Analysis

One hundred replicates (seeds) per Eucalyptus species were used for the indoor experiment, with ten replicates per species for the outdoor experiment. All data were analyzed with ANOVA in SAS Version 14.1 (SAS Inc., Cary, NC, USA). The significance of the means was determined using Duncan's multiple range test (DMRT) at $p < 0.05$ level of probability.

Results and Discussion

Indoor Experiment

Seed germination of ten *Eucalyptus* spp. increased sharply from 7 DAS and mostly peaked between 21 and 28 DAS, except for the seed germination of *E. polyanthemos*, which peaked by 42 DAS (Fig. 3). The maximum germination studied in Irish and British climates was rapidly reached by 3 to 10 DAS for 15 *Eucalyptus* species collected from alpine forests in Australia, mostly due to the suitable growing conditions at these locations although this metric varied significantly for each species (Afroze et al., 2021). Germination at 0–7 DAS was not significantly different among the species at $p < 0.05$. Germination was significantly higher for *E. crebra* at 14–70 DAS, at approximately 86.1% at 70 DAS, followed by *E. cordata* (76.4%), *E. globulus* (68.1%), and *E. pulverulenta* (66.7%). *E. crebra* seedlings in a pot showed increased photosynthetic efficiency and stomatal conductance under water-limited conditions when compared with other *Eucalyptus* species (Silva et al., 2016). In contrast, the germination rates of *E. cinerea* and *E. gunnii* were less than 40.0%, with the lowest germination rate (18.1%) obtained for *E. kruseana* mostly from 14 DAS to 70 DAS.

Seed survival was recorded as 100.0% for all the *Eucalyptus* species at 0−21 DAS but it decreased slightly to approximately 90.1% for *E. websteriana* and 96.0% for *E. gunnii* and *E. globulus* at 35 DAS (Fig. 4). *E. cinerea* and *E. polyanthemos* maintained 100.0% seedling survival at 70 DAS, which differed from seed germination. The lowest survival rate was observed for *E. websteriana* at approximately 84.1% at 70 DAS and a considerable decline in the survival of *E. kruseana* occurred at 49−56 DAS. *E. websteriana* is more sensitive to heat stress than other ornamental shrubs during hot summers (Suleiman et al., 2007), which may have led to a decrease in species survival in the horticultural growth medium during the warm and humid season in this study (Fig. 1). In addition, the seeds contain lower carbohydrate and nutrient levels, implying that the viability and vigor of *E. cinerea* and *E. kruseana* seeds were less enhanced (Harrison et al., 2014).

Outdoor Experiment

The minimum temperature after 120 DAS in 2022 and 2023 was lower than those of the 30-year average with occurred in heavy rainfall (Fig. 6).

E. globulus and *E. crebra* were significantly taller (Fig. 7A) and thicker (Fig. 7B) at 30 DAT. The tallest trees were *E. globulus* (141.7 cm), followed by *E. polyanthemos* (80.4 cm) and *E. crebra* at 150 DAT; the slowest growth was observed in *E. kruseana* at 33.7 cm and *E. parvula* at 38.6 cm. *E. globulus* had a thicker trunk (13.4 mm), followed by *E. polyanthemos* (9.2 mm) and *E. crebra* (6.5 mm) as compared to *E. pulverulenta* (4.9 mm), *E. cinerea* (4.9 mm), *E. websteriana* (4.4 mm), and *E. kruseana* (4.0 mm). *E. globulus* has high amounts of fiber compounds from byproducts in the stem wood, resulting in a fast growth rate; it is the most widely planted species in forests in the Mediterranean area and in subtropical areas worldwide (Cromer et al., 1981; Pohjonen and Pukkala, 1990; Cotterill and MacRae, 1997). *E. globulus*, *E. crebra*, and *E. pulverulenta* can be cultivated in an open field and adapted to a temperate climate with an arid spring, warm and humid summer, and cold winter, such as in S. Korea by adjusting the osmotic potential and maintaining high turgor pressure (Merchant et al., 2007).

There wer fewer than ten shoots per tree for all *Eucalyptus* spp. recorded at 30 DAT, and not many shoots per tree were produced by *E. pulverulenta* and *E. polyanthemos* at 150 DAT. Other amounts were produced by *E. globulus* (31) and *E. cordata* (27), but these decreased (Fig. 8A). The number of leaves ranged from 40 to 60 per tree at 30 DAT, and the

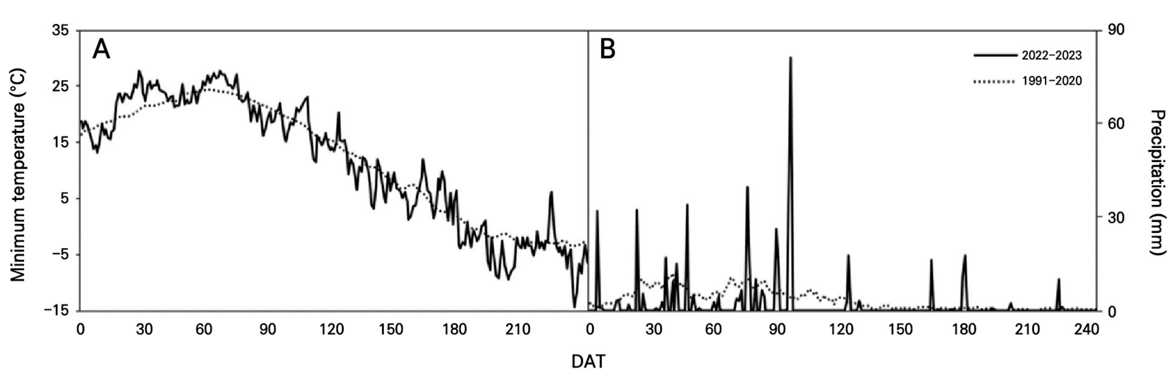

Fig. 6. Minimum temperature (Panel A) and precipitation (Panel B) at 0 and 240 days after transplanting (DAT) in Gyeongsan-si in 2022.

highest number was found in *E. parvula* (596), followed by *E. globulus* (460), *E. cordata* (402), *E. crebra* (388), and *E. gunnii* (336) at 150 DAT (Fig. 8B). *E. parvula* grows round with low-branched and multiple stems and a compact trunk size, generating a high number of leaves and providing high value as an ornamental shrub (Dirr and Warren, 2019). In contrast, the vigorous *E. polyanthemos* produces a low number of shoots and leaves. *E. crebra* and *E. polyanthemos* were similar in terms of the vigorous tree structure and volume but were in terms of the tree arrangements based on their shoots and leaves, which can provide different performance levles of ornamental shrubs. Foliar SPAD units, indicating chlorophyll contents and nitrogen concentration (Ribeiro et al., 2009; Ferreira et al., 2015), for all *Eucalyptus* spp. were between 40 and 60 at 30 DAT. This metric was highest for *E. gunnii* and relatively low for *E. cinerea*, *E. globulus*, and *E. polyanthemos*, with light bluish and whitish-green foliage (Fig. 8C). The SPAD units for all *Eucalyptus* spp. increased at 150 DAT, except for *E. globulus*, most likely due to the indirect dilution effect as a contributor to the stimulation of vegetative growth (Dirr and Warren, 2019; Wujeska-Klause et al., 2019). However, SPAD between 35 and 45 in the *E. globulus* case could be an optimum range for young evergreen trees as these levels would indicate an adequate nitrogen status to satisfy their growth (Ribeiro et al., 2009). *E. gunnii* showed the highest SPAD values at 150 DAT, maintaining dark green foliage during the summer and fall seasons and indicating a high foliar nitrogen content available for annual tree growth.

Leaf browning was negligible for all *Eucalyptus* spp. at 30 DAT but occurred considerably at 150 DAT during early winter for *E. kruseana* at approximately 45%, with *E. polyanthemos* showing a rate of 21% and *E. parvula* leaves showing

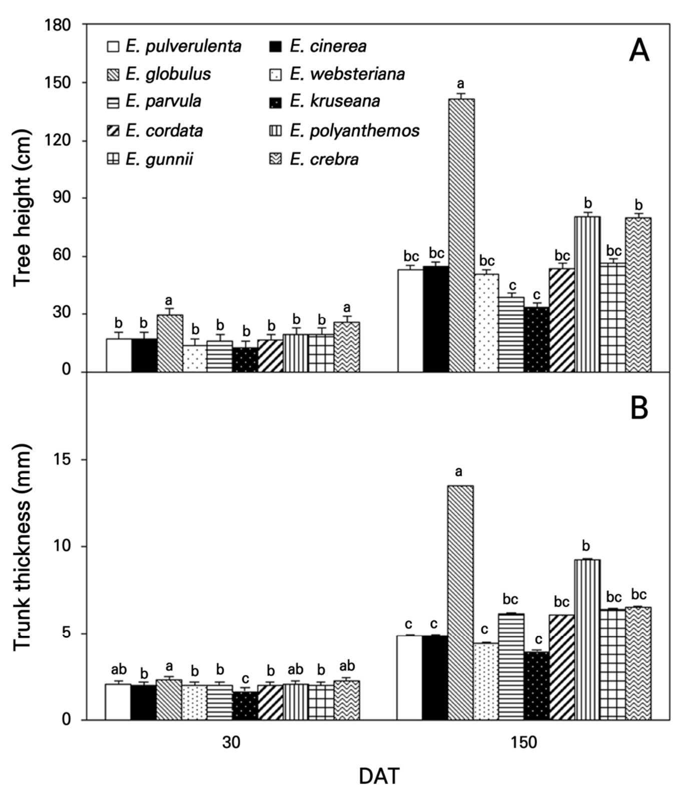

Fig. 7. Tree height (Panel A) and trunk thickness (Panel B) of ten *Eucalyptus* species at 30 and 150 days after transplanting (DAT) in Gyeongsan-si in 2022. Different lowercase letters on each phase indicate significant differences determined using Duncan's multiple-range test at $p < 0.05$. Bar represents error of the means.

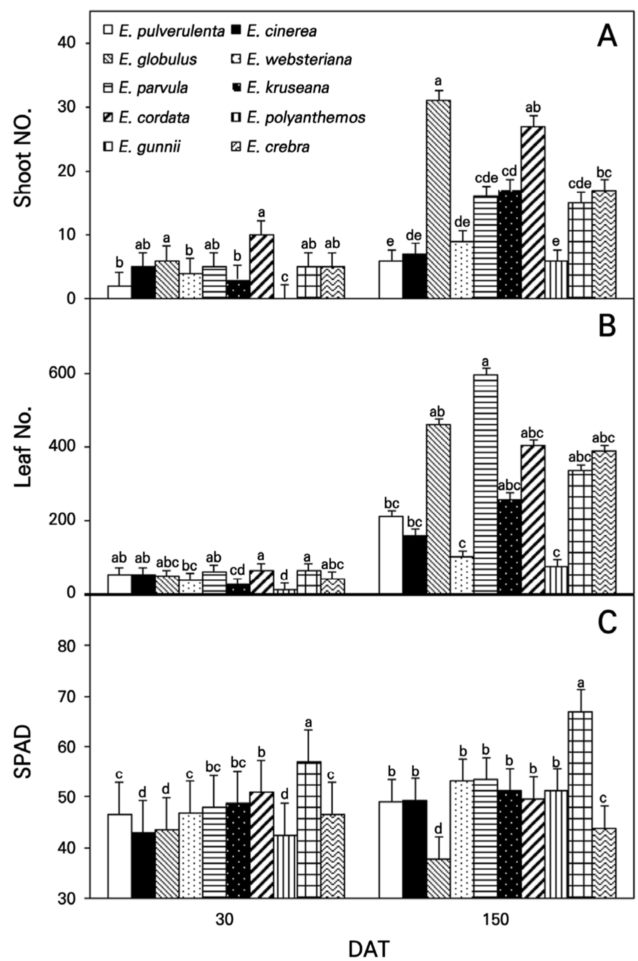

Fig. 8. Number of shoots (Panel A), number of leaves (Panel B), and SPAD (Panel C) of ten *Eucalyptus* species at 30 and 150 days after transplanting (DAT) in Gyeongsan-si in 2022. Different lowercase letters on each phase indicate significant differences determined using Duncan's multiple-range test at $p < 0.05$. Bar represents error of the means.

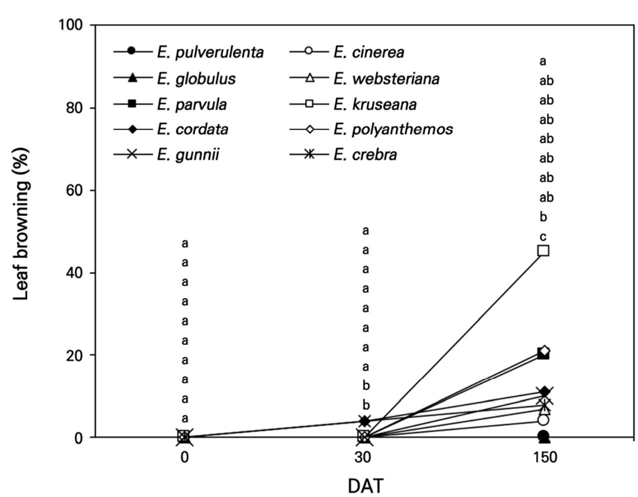

Fig. 9. Leaf browning of ten *Eucalyptus* species at 30 and 150 days after transplanting (DAT) in Gyeongsan-si in 2022. Different lowercase letters on each phase indicate significant differences determined using Duncan's multiple-range test at $p < 0.05$.

a similar rate of 20% (Fig. 9). The brown leaves were caused by the synthesis of anthocyanins related to the photoinhibition of *E. nitens* and *E. globulus* seedlings transplanted from the greenhouse to the field at a low temperature (Close et al., 2000; Close and Beadle, 2003). The minimum temperature between 140 DAS and 150 DAS was recorded as 4.48°C (Fig. 6) and may have affected the photoinhibition of *E. kruseana* trees, resulting in the discoloration of leaves. However, the SPAD values were not reduced among the species during those periods.

The dry mass of leaves, shoots, and roots of each species was highest for *E. globulus* (107.7 g), and 64.3% of the dry mass was shoot dry mass. This was followed by *E. polyanthemos* (58.7 g) and *E. crebra* (46.7 g), with the lowest dry mass for *E. cinerea* (13.5 g) and *E. websteriana* (13.9 g) (Table 1) after all the trees, including roots, were harvested (Fig. 10).

Table 1. Dry mass of leaf, stem, root, and top:root ratio of ten *Eucalyptus* tree species at 200 days after transplanting in Gyeongsan-si in January 2023

Species	Tree partitioning (g, %)				Top : Root
	Leaf	Stem	Root	Total	
E. pulverulenta	6.1 b (31.1)	7.6 b (38.8)	5.9 c (30.1)	19.7 bc	2.3 b
E. cinerea	5.3 b (39.9)	4.2 b (31.5)	3.8 c (28.6)	13.5 c	2.5 b
E. globulus	60.2 a (55.9)	69.3 a (64.3)	23.7 a (22.1)	107.7 a	5.4 ab
E. websteriana	8.0 b (57.8)	4.0 b (28.9)	1.8 c (13.2)	13.9 bc	6.5 a
E. parvula	8.4 b (40.3)	5.9 b (28.5)	6.5 c (31.2)	20.9 bc	2.2 b
E. kruseana	8.7 b (49.4)	6.6 b (37.5)	2.3 c (13.2)	17.7 bc	6.6 a
E. cordata	14.2 b (50.4)	10.1 b (35.9)	3.8 c (13.7)	28.2 bc	6.3 a
E. polyanthemos	21.4 b (36.5)	19.9 b (33.9)	17.3 ab (29.6)	58.7 b	2.3 b
E. gunnii	9.7 b (43.8)	7.4 b (33.3)	5.0 c (22.9)	22.2 bc	3.3 ab
E. crebra	19.0 b (40.8)	13.3 b (28.5)	14.3 b (30.8)	46.7 bc	2.2 b

Mean values ($n = 5$) in each column followed by the same lower-case letters were not significantly different according to Duncan's multiple range test at $p < 0.05$.

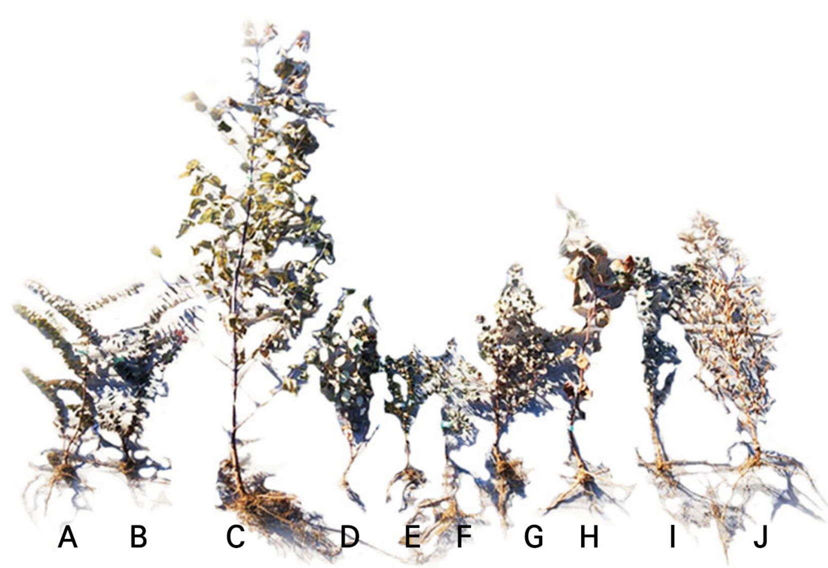

Fig. 10. Photographs of ten *Eucalyptus* species harvested at 200 days after transplanting in Gyeongsan-si in January of 2023. *E. pulverulenta* (A), *E. cinerea* (B), *E. globulus* (C), *E. websteriana* (D), *E. pavula* (E), *E. kruseana* (F), *E. cordata* (G), *E. polyanthemos* (H), *E. gunnii* (I), and *E. crebra* (J).

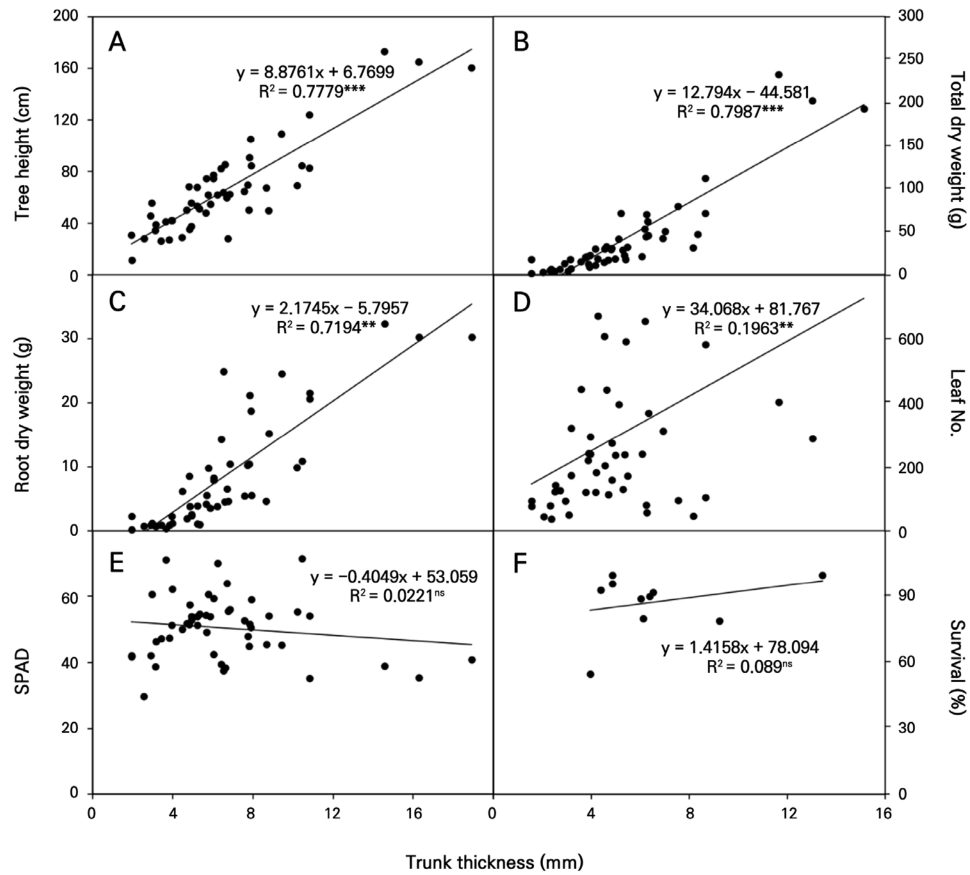

Fig. 11. Linear regression analysis between trunk thickness and tree height (Panel A), and total dry weight. (Panel B), root dry weight (Panel C), number of leaves (Panel D), SPAD (Panel E), and survival (Panel F) of ten *Eucalyptus* tree species in January of 2023. ** and *** adjacent to each dot point for trunk thickness indicate significant differences as determined by Duncan's multiple-range test at $p < 0.01$ and 0.001, respectively. ns denotes not significantly different.

The highest top:root values were observed for *E. kruseana* (6.6), *E. websteriana* (6.5), and *E. cordata* (6.3), indicating shallow root systems and a reduced fixing capacity of the soil. However, the top-to-root values were relatively evenly distributed for *E. pulverulenta* (2.3), *E. cinerea* (2.5), *E. parvula* (2.2), *E. polyanthemos* (2.2), and *E. crebra* (2.2).

A thick trunk significantly increased tree height ($r^2 = 0.778$), total dry weight ($r^2 = 0.799$), root dry weight ($r^2 = 0.719$), and number of leaves ($r^2 = 0.196$), with little effect on SPAD ($r^2 = 0.022$) and tree survival ($r^2 = 0.089$) (Fig. 11). The trunk thickness of *Eucalyptus* spp. was strongly correlated with the above-ground biomass and canopy volume of the trees, which has been used as a common estimator of tree biomass, particularly for young-growth trees (Harrington, 1975; Sillett et al., 2015). Only one *E. polyanthemos* did not appear to show an increased number of leaves, with fewer shoots produced from the bark despite the increase in trunk thickness (Figs. 7 and 8).

Conclusion

In summary, *E. globulus*, *E. crebra*, and *E. polyanthemos* are suitable *Eucalyptus* species for comprehensive cultivation in S. Korea given the country's hot summers, broadening the selection of *Eucalyptus* species from *E. pulverulenta*, *E.*

gunnii, and *E. parvula* in S. Korea (aT, 2023). *E. kruseana* is not recommended for transitioning indoor seedlings to outdoor environments, as previously shown in a cold stress study of *Eucalyptus* species (Teulières et al., 2007). *Eucalyptus* species should be continuously studied for acclimation through a cold winter (decreasing by −15°C to −20°C) with subsequent growth in the following season in S. Korea to investigate low-temperature stress tolerance. A long-term field study is also required to evaluate the physiological responses of various *Eucalyptus* species to a wide range of climate conditions during global warming and provide information on indoor and outdoor suitability in the early tree growth stage.

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