Comparison of Automated Controller Settings for Irrigation and Fertilizer Needs of Potted Geranium

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Abstract. The future of agricultural water availability is threatened by climate change, population growth, and environmental regulations. Most of the global water is being used for crop irrigation. The objective of this research was to determine optimum timer-based controller settings and controlled-released fertilizer rates for 'American Red' (*Pelargoium ×hortorum*) potted geranium plants. Fertilizer was top-dressed at 3, 6, or 9 g. Plants were irrigated by a timer-based controller set to water at 11:00 AM every other day for 2 minutes, 9:00 AM and 2:00 PM for 1 minute per day, 11:00 AM for 1 minute per day, 11:00 AM for 2 minutes per day, and a control of manual hand watering. Data regarding plant growth, soil and leaf nutrients, and water use were collected. For geranium growth factors, the total flowers per plant was greatest for irrigation at 11:00 AM for 1 minute with 6 g fertilizer. Plant height and shoot dry weight were greatest for 6 and 9 g fertilizer. The number of umbels and soil plant analysis development (SPAD) chlorophyll meter readings were greatest for 9 g fertilizer. For geranium soil nutrient content, the pH was greatest for 3 g fertilizer, whereas the electrical conductivity, potassium, nitrate, sulfate, and boron were greatest for 6 and 9 g fertilizer. Regarding the nutrient content of the leaves, total nitrogen, boron, iron, and copper were greatest for 9 g fertilizer. Water use efficiency was greatest with 6 and 9 g fertilizer and irrigation 1 minute per day at 11:00 AM. The findings indicated that using timer-based controlled irrigation systems programmed to water for 1 minute during the morning with 6 g fertilizer resulted in plants that not only reduced water consumption but also enhanced water use efficiency and overall plant quality.

A report by the US Geological Survey indicated that agriculture is a significant consumer of both ground and surface water in the United States, with irrigation representing 42% of the nation's total freshwater withdrawals in 2015 (Dieter et al. 2018; Environmental Protection Agency 2023; Maupin 2018). Greenhouse and nursery cultivators may use approximately 14,000 to 19,000 gallons of water per acre daily during the peak growing season (Fulcher and Fernandez 2013). The quantity of irrigation required can fluctuate based on factors such as pot size, growing medium, and plant species, with flowering bedding plants typically demanding less water than grasses (Dumroese et al. 2009; San Francisco Public Utilities Commission 2015).

Geranium (*Pelargonium ×hortorum* L.H. Bailey) is one of the most important and widely grown ornamental bedding plants in the world (Valdés et al. 2015). Geranium plants can grow as an annual, biennial, or perennial plant, depending on the species and their climate. Geranium belongs to the Geraniaceae family, and there are approximately 280 species that predominantly originate from South Africa (Fonteno 1992). The most widely cultivated geranium cultivar is the zonal geranium, which is characterized by the unique dark band or zone found on each leaf (Fonteno 1992). Geraniums have remained very popular with consumers for many years, mainly because of their prolific flowering throughout summer and drought tolerance (Lang and Trellinger 2001).

The production of greenhouse container crops, like geranium, is constrained by the limited availability of nutrients and water to the plants, which must be sourced from the relatively small volume of growing medium contained within the containers (Rouphael et al. 2008). In containerized crops, several types of closed soil systems have been developed; of these, drip irrigation and sub-irrigation systems are the most prevalent (Reed 1996). Irrigation frequency has a significant impact on the water regime of the soil, the distribution of roots among the emitters, and the amount of water absorbed by the roots and draining away from the roots (Assouline 2002; Wang et al. 2009). One study suggested that low irrigation frequency induced a long-term decline in stomatal conductance and the transpiration rate, which enabled the rose-scented geranium to maintain greater relative water content and leaf water potential under prolonged water stress (Eiasu et al. 2012). In another study, it was suggested that as the water deficit levels increased, there were concurrent reductions in shoot and flower dry weight and an increase in the root-to-shoot ratio in geranium plants (Sánchez-Blanco et al. 2009).

Fertilization is a crucial factor in the potted production of greenhouse geranium plants that exerts a significant influence on both plant growth and visual aesthetics (Marschner 1995). In greenhouse cultivation, two primary types of fertilizers are typically used: constant liquid fertilizer and controlled-release fertilizer (CRF). Traditional constant liquid fertilization of containerized plant materials growing in porous media can lead to the generation of excessive runoff (Rathier and Frink 1989). Controlled-release fertilizers frequently lead to enhancements in foliar color and plant size, simultaneously curbing nutrient loss and mitigating runoff, as supported by prior research (Altland et al. 2003; Cox 1985). Geraniums that were provided with 100% CRF exhibited increased total dry weights and released lower levels of nitrate, ammonium, and phosphorus in runoff compared with those of plants that received 100% continuous liquid fertilizer (Morvant et al. 2001).

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Growers are increasingly seeking environmentally sustainable approaches to enhance their production practices, particularly in the realms of irrigation and fertilization. Current research of geranium plants has been focused on the effects of water and nutrient stress. A prior investigation involving 'Maverick Red' geranium revealed that the application of 8 g 16N–9P–12K CRF resulted in the greatest quality in terms of plant height, width, and flower count (Dunn et al. 2015). However, another study of geranium cultivated with 15N–3.9P–9.9K CRF observed that using 6 or 9 g fertilizer resulted in a significant increase in the number of umbels produced per plant and earlier flowering, ultimately leading to enhanced water use efficiency (Singh et al. 2020). The objective of this study was to determine optimum CRF rates with different timer-based controlled irrigation for 'American Red' geranium in a greenhouse.

Materials and methods

Location and greenhouse conditions. The research was conducted at the research greenhouse facility at Oklahoma State University, Stillwater campus (36°08′09″N, 97°05′12″W). Illuminance, temperature, and humidity were recorded with an Illuminance ultraviolet recorder TR-74Ui (T & D, Matsumoto, Japan). No supplemental light was used in the greenhouse, and the average daily light integral was 12.4 ± 2.3 $mol \cdot m^{-2} \cdot d^{-1}$. The environmental control was set to 24/18 °C in the greenhouse, resulting in a daily average temperature of 21.9 ± 4.1 °C.

Plant material. 'Americana Red' rooted plugs in 36 cells (size, 54.5 × 2 7.8 × 7.6 cm) were obtained from Raker-Roberta's Young Plants (Litchfield, MI, USA) on 5 Jan 2023. Rooted plugs were transplanted into 15.2-cm azalea pots filled with soilless media (Berger BM7 35% bark; Berger, Saint-Modeste, QC, Canada) on 6 Jan 2023 and hand-watered for 3 d.

Treatment. Treatments consisted of four timer-based controllers (Hunter X-Core; Hunter, San Marcos, CA, USA) and were performed for 1 min per day at 11:00 AM, 2 min per day at 11:00 AM, 1 min per day at 9:00 AM and 2:00 PM, and 2 min every other day at 11:00 AM; a manual control was assigned to separate benches, with irrigation supplied by pressure-compensated drip emitters at a rate of 2 gph. All treatments were automated using solenoids, except for the manual control. For the manual control, plants were checked daily at 1:00 PM and watered based on visual soil moisture. A 15N–3.9P–10K CRF (Osmocote Plus 3-4 month; ICL Specialty Fertilizers, Summerville, SC, USA) was applied as a top-dress at the time of transplant at rates of 3, 6, and 9 g.

Data collection. The amount of water per irrigation was recorded daily. At the end of the study on 13 Mar 2023 (9 weeks from transplanting), a leaf foliar analysis and soil analysis were conducted for one pot per treatment (a total of 48 plants from both replications for both leaf foliar and soil analysis) by sending samples to the Soil, Water, and Forage Analytical laboratory (Stillwater, OK, USA); the plants were analyzed as outlined by Zhang and Henderson (2018). Relative greenness was measured using a chlorophyll meter (SPAD-502; Konica Minolta, Tokyo, Japan), with one reading per plant using a leaf from the middle of the plant on the upper part of the leaf. The number of umbels and the number of flowers in an umbel on the day of harvest were collected from the geraniums. The

Table 1. Test of the effects of timer-based controlled irrigation treatments set to water 1 min once per day at 11:00 AM, 2 min once per day at 11:00 AM, 1 min twice per day at 9:00 AM and 2:00 PM, 2 min every other day at 11:00 AM, and a manual treatment checked daily with 3, 6, or 9 g 15N–3.9P–10K controlled-release fertilizer on the growth of 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Source	Irrigation	Fertilizer (g)	Irrigation × fertilizer
Plant height	*[i]	**	NS
Plant width	NS	***	NS
Total flowers	NS	**	*
Number of umbels	NS	***	NS
Umbel height	NS	NS	NS
Shoot dry wt	NS	**	NS
Root dry wt	NS	NS	NS
SPAD	NS	**	NS

[i] Significant at *$P \leq 0.05$, **$P \leq 0.01$, and ***$P \leq 0.001$, or nonsignificant (NS).

Table 2. Total flower number least square means for irrigation treatments with 3, 6, and 9 g controlled-release fertilizer combinations for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Irrigation	Fertilizer (g)	Total flower no.
1 min during the morning	3	4.2 ab[i]
	6	4.7 a
	9	4.3 ab
1 min during the morning, 1 min during the afternoon	3	4.4 ab
	6	4.5 ab
	9	4.6 ab
2 min during the morning	3	4.2 ab
	6	4.5 ab
	9	4.6 ab
2 min during the morning every other day	3	3.9 b
	6	4.3 ab
	9	4.3 ab
Manual	3	4.3 ab
	6	4.2 ab
	9	4.2 ab

[i] Means within a column followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Table 3. Height, width, number of umbels, shoot dry weight, and soil plant analysis development (SPAD) chlorophyll meter least square means for 3, 6, and 9 g controlled-release fertilizer rates on growth factors for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA, using timer-based controlled irrigation.

Fertilizer (g)	Plant ht (cm)	Plant width (cm)	No. of umbels	Shoot dry wt (g)	SPAD (unitless)
3	27.3 b[i]	31.9 b	4.3 c	26.1 b	52.5 b
6	28.4 a	35.8 a	4.9 b	29.0 a	53.8 a
9	29.0 a	35.7 a	5.4 a	29.7 a	54.0 a

[i] Means within a column followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

heights (from the top of the pot to the highest point) and the widths (average of two perpendicular measurements) of each plant were measured and recorded. Shoots were collected by cutting the stem at the media level and dried in an oven at 53 °C for 5 d. The root dry weight was recorded by washing the roots and letting them dry at 53 °C for 4 d.

Statistical analysis. This 3 × 5 factorial experiment was arranged in a randomized complete block design with 10 replicates per treatment combination. The experimental units were single pots per fertilizer treatment consisting of 10 pots per irrigation and fertilizer level per plant species. The experiment was replicated. Weekly irrigation amounts were measured and analyzed using linear mixed model methods for repeated measures. Irrigation, fertilizer, week, all two-way interactions, and the three-way interaction were included as fixed effects in the model, and replication or block was a random effect. The cumulative irrigation amount and nutrient responses were analyzed using linear mixed model methods by evaluating only the fixed effects of the main effects of irrigation and fertilizer and the irrigation × fertilizer interaction effect. Unequal variances models were necessary for some of the response variables. Tukey's pairwise comparison was performed to determine significant effects. All tests were performed at the nominal 0.05 level. The data analysis for this experiment was performed using SAS/STAT software (version 9.4 for Windows; SAS Institute Inc., Cary, NC, USA).

Table 4. Height least square means for irrigation treatments for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Irrigation	Height (cm)
1 min during the morning	27.8 ab[i]
1 min during the morning, 1 min during the afternoon	29.3 a
2 min during the morning	29.2 a
2 min during the morning every other day	26.4 b
Manual	28.5 ab

[i] Means followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Table 5. Test of the effects on the nutrient content of the soil for timer-based controlled irrigation treatments set to water 1 min once per day at 11:00 AM, 2 min once per day at 11:00 AM, 1 min twice per day at 9:00 AM and 2:00 PM, 2 min every other day at 11:00 AM, and a manual treatment checked daily with 3, 6, or 9 g 15N–3.9P–10K controlled-release fertilizer on the growth of geranium 'Americana Red' grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Source	Irrigation	Fertilizer (g)	Irrigation × fertilizer
pH	NS[i]	*	NS
EC	NS	**	NS
Sodium	NS	*	NS
Potassium	NS	*	NS
Magnesium	NS	NS	NS
Chlorine	NS	NS	NS
Nitrate	NS	**	NS
Sulfate	NS	**	NS
Boron	NS	**	NS
Ammonium	NS	*	NS

[i] Indicates significant at *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, or nonsignificant (NS).
EC = electrical conductivity.

Results and discussion

Regarding geranium growth factors, there was an irrigation × fertilizer interaction for the total flowers per plant ($P < 0.0348$) (Table 1). The total flowers per plant was greatest with the treatment comprising 1 min in the morning with 6 g fertilizer; however, this value was only different from that resulting from the treatment comprising 2 min during the morning every other day with 3 g fertilizer (Table 2). Both fertilization and irrigation practices are vital to altering flowering patterns, influencing flower quantity, and blooming enhancement. Research of herbaceous perennial species has demonstrated a species-specific response to decreased irrigation, resulting in increased blooming in some species while decreasing flowering in others (Bayer 2022). Jin et al. (2023) observed an increase in the number of flowers as both irrigation and fertilizer amounts increased for Rose of Shanon (*Hibiscus syriacus* L.). Dunn et al. (2015) found significant differences in 'Maverick Red' geranium flower numbers of plants that received 10 g compared with those of plants that received 0 or 4 g CRF. Scagel et al. (2008) highlighted the influence of the nitrogen (N) content on plant growth and flowering and noted that greater N fertilization rates resulted in increased N content within 'H-1 P.J.M.' (*Rhododendron* L.) rhododendron and 'Cannon's Double' azalea, leading to enhanced flower quantity and size. However, excessive N fertilization may have adverse effects, potentially delaying and decreasing the overall flowering rate (Berding and Skinner 1980; Brunkhorst 2003). Similar to our study, a study of geranium revealed that moderate-deficit irrigation decreased water consumption while preserving plant quality, but that severe-deficit irrigation led to a decrease in the number of flowers per plant (Sánchez-Blanco et al. 2009).

There was a significant fertilizer main effect for plant height ($P < 0.0029$), width ($P < 0.0001$), number

Table 6. The pH, electrical conductivity (EC), sodium (Na), potassium (K), nitrate (NO_3N), sulfate (S), boron (B), and ammonium (NH_4) least square means for 3, 6, and 9 g controlled-release fertilizer rates for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA, with timer-based controlled irrigation.

Fertilizer (g)	pH	EC (mS/cm)	Na ($mg \cdot L^{-1}$)	K ($mg \cdot L^{-1}$)	NO_3N ($mg \cdot L^{-1}$)	SO_4 ($mg \cdot L^{-1}$)	B ($mg \cdot L^{-1}$)	NH_4 ($mg \cdot L^{-1}$)
3	6.9 a[i]	7.3 b	140.6 b	3.1 b	3.7 b	5.6 b	0.2 b	8.1 b
6	6.5 b	7.9 a	187.8 ab	4.5 a	4.9 a	6.1 a	0.3 a	62.7 a
9	6.4 b	7.9 a	189.3 a	4.4 a	4.7 a	6.2 a	0.3 a	59.2 ab

[i] Means within a column followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

of umbels ($P < 0.0001$), shoot dry weight ($P < 0.0029$), and soil plant analysis development (SPAD) ($P < 0.0147$) (Table 1). Plant height values were greatest with 6 and 9 g fertilizer (Table 3). Plant width values were greatest with 6 g and 9 g fertilizer (Table 3). A trend of increased plant height and leaf area with the addition of N was seen for guanandi (*Calophyllum brasiliense* Cambèss) plants (Ciriello et al. 2014). The highest number of umbels was observed with the 9 g fertilizer treatment (Table 3). In a study of 'Maverick Red' geranium, there was no notable difference in the number of umbels among CRF fertilizer treatments of 0, 4, 8, 10, or 12 g 16N–9P–12K (Dunn et al. 2015). The shoot dry weight values were greatest for both 6 and 9 g fertilizer (Table 3). Singh et al. (2020) observed that dry weight production at 3, 6, and 9 g fertilizer rates were not different; however, they noted that an increase in ambient carbon dioxide resulted in greater values for dry weight, flower count, and stomatal conductance of 'Pinto Premium Rose Bicolor' geranium among various fertilizer rates. However, for 'Dreams White' petunia (*Petunia ×hybrida* Vilm.), the shoot dry weight increased as the CRF rate increased from 0 to 1.67 g per plant (equivalent to 0–6.25 $kg \cdot m^{-3}$ substrate), but it decreased again at even greater CRF rates (Alem et al. 2015). The SPAD values were greatest for 6 and 9 g fertilizer (Table 3). Previous studies indicated that increasing N rates correlated with greater leaf SPAD readings, indicating an increase in the chlorophyll content per leaf area and an extended period of elevated SPAD readings (Hou et al. 2021; Li et al. 2022; Xiong et al. 2015). Applications of a high N fertilizer significantly increased 'Amelie' geranium plant growth and flowering attributes as well as increased the percentages of N, phosphorus (P), and potassium (K) and the chlorophyll content (Gaber 2019).

There was a significant irrigation main effect for plant height ($P < 0.035$) (Table 1). Plant height values were greatest for the 1 min during the morning, 1 min per day at 9:00 AM and 2:00 PM, and 2 min per day at 11:00 AM treatments, but they were only different from those resulting from 2 min every other day at 11:00 AM (Table 4). In a 2012 study that examined geraniums, water deficit yielded the lowest plant height values when deficit irrigation was applied with variations, depending on the timing of deficit irrigation for zonal geranium (Álvarez et al. 2012). Additionally, the height and shoot dry weight of carnation

Table 7. Test of effects on the nutrient content of the leaves with timer-based controlled irrigation treatments set to water 1 min once per day at 11:00 AM, 2 min once per day at 11:00 AM, 1 min twice per day at 9:00 AM and 2:00 PM, 2 min every other day at 11:00 AM, and a manual treatment checked daily with 3, 6, or 9 g 15N–3.9P–10K controlled-release fertilizer on leaf chemical properties of 'Americana Red' geranium grown for 67 d at the research greenhouse in Stillwater, OK, USA.

Leaf chemical properties	Irrigation	Fertilizer	Irrigation × fertilizer
Total nitrogen	NS[i]	**	NS
Phosphorus	NS	NS	NS
Calcium	NS	NS	NS
Potassium	NS	NS	NS
Magnesium	NS	NS	NS
Sulfur	NS	NS	NS
Boron	*	*	NS
Iron	NS	**	NS
Zinc	NS	NS	NS
Copper	NS	*	NS

[i] Indicates significant at *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, or nonsignificant (NS).

Table 8. Total nitrogen (TN), boron (B), iron (Fe), and copper (Cu) least square means for the nutrient content of the leaves with 3, 6, and 9 g fertilizer for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Fertilizer (g)	TN ($mg \cdot L^{-1}$)	B ($mg \cdot L^{-1}$)	Fe ($mg \cdot L^{-1}$)	Cu ($mg \cdot L^{-1}$)
3	3.2 b[i]	54.3 b	4.7 b	4.3 b
6	3.4 a	55.2 ab	4.8 b	5.5 ab
9	3.5 a	59.7 a	5.2 a	6.7 a

[i] Means within a column followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Table 9. Boron (B) least square means for the nutrient content of the leaves with irrigation treatments for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Irrigation (g)	B ($mg \cdot L^{-1}$)
1 min during the morning	59.6 a[i]
1 min during the morning, 1 min during the afternoon	53.0 b
2 min during the morning	59.1 ab
2 min during the morning every other day	56.5 ab
Manual	53.8 ab

[i] Means followed by same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Table 10. Test of the effects of weekly irrigation treatments set to water 1 min once per day at 11:00 AM, 2 min once per day at 11:00 AM, 1 min twice per day at 9:00 AM and 2:00 PM, 2 min every other day at 11:00 AM, and a manual treatment checked daily with 3, 6, or 9 g 15N–3.9P–10K controlled-release fertilizer on the water use efficiency (WUE) of 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA.

Source	Irrigation	Fertilizer	Irrigation − Fertilizer
WUE	***[i]	*	NS

[i] Indicates significant at *$P \leq 0.05$, **$P \leq 0.01$, ***$P \leq 0.001$, or nonsignificant (NS).

(*Dianthus* ×*caryophyllus* L.), cheddar pinks (*Dianthus* ×*gratianopolitanus* L.), and rosemary (*Rosmarinus officinalis* L.) decreased with heightened water stress levels (Álvarez et al. 2009; Zhen et al. 2014).

Regarding the geranium soil nutrient content, there was no irrigation ×fertilizer interaction. There was a significant fertilizer main effect for pH ($P < 0.0191$), electrical conductivity (EC) ($P < 0.0044$), sodium (Na) ($P < 0.0243$), K ($P < 0.0162$), nitrate (NO_3N) ($P < 0.0035$), sulfate (SO_4) ($P < 0.0031$), boron (B) ($P < 0.003$), and ammonium (NH_4) ($P < 0.0284$) (Table 5). The pH values were greatest with 3 g fertilizer and were different from those with both 6 and 9 g fertilizer. Different N forms have varying impacts on the medium pH, with nitrate N affecting pH solely through plant uptake, whereas ammoniacal N influences the medium pH through both plant uptake and nitrification (Argo 2003). Controlled-release fertilizers lower soil pH in alkaline soils to enhance nutrient availability (Liu et al. 2014). The EC, Na, K, NO_3N, SO_4, B, and NH_4 values were greatest with both 6 and 9 g fertilizer (Table 6). Fertilization affects soil nutrient content and crop yield by influencing the ability of crops to absorb and distribute elements such as N and P (Yang et al. 2019).

Table 11. Water use efficiency (WUE) and fertilizer rates for 'Americana Red' geranium grown for 67 d at the research greenhouse in Stillwater, OK, USA, using timer-based controlled irrigation.

Fertilizer (g)	WUE ($mL \cdot g^{-1}$)
3	3.6 b[i]
6	3.8 ab
9	4.0 a

[i] Means followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Regarding the geranium nutrient content of the leaves, there was no irrigation × fertilizer interaction. There was a significant fertilizer main effect for total N ($P < 0.0091$), B ($P < 0.0155$), iron (Fe) ($P < 0.0014$), and copper (Cu) ($P < 0.0285$) (Table 7). The total N, B, and Cu values were greatest with 9 g fertilizer, but they were only different from those with 3 g fertilizer (Table 8). Transpiration significantly influenced B accumulation, as observed by an increase in B accumulation and its concentration in leaf tips under conditions of elevated water use (Nable et al. 1990). The Fe values were greatest with 9 g fertilizer and were different from those with 3 and 6 g fertilizer (Table 8). Soil organic fertilizers not only contain a high Fe content and exhibit stable performance with primarily water-soluble properties but also possess the ability to increase soil organic matter content, promote the release and maintenance of soil nutrients, bolster plant Fe transfer capacity, and enhance plant Fe uptake (Souri et al. 2018). The leaf Cu concentration increased with a low Fe supply, whereas high Cu levels decreased the leaf Fe concentration (Waters and Armbrust, 2013). There was a significant irrigation main effect for B ($P < 0.0302$) (Table 7). The B values were greatest with 1 min per day during the morning, but they were only different from those with 1 min during the morning and 1 min during the evening (Table 9).

Water use efficiency (WUE) had no irrigation × fertilizer interaction. There was a significant fertilizer main effect ($P < 0.0138$) (Table 10) for WUE. The greatest values were observed with 9 g fertilizer, but they were only different from those with 3 g fertilizer (Table 11). Fertilization not only promotes crop root growth and expands its water-foraging space but also fosters crop canopy development, increases transpiration, reduces evaporation, and enhances the transpiration-to-evaporation ratio, thus greatly improving the crop WUE (Jákli et al. 2017; Trachsel et al. 2013). Enhancing yield through fertilization significantly increases WUE, thus emphasizing the crucial role of adequate crop nutrition in conserving and efficiently using water resources (Viets 1962). There was a significant irrigation main effect ($P < 0.0005$) for WUE (Table 10). The greatest values were observed with 1 min per day at 11:00 AM, and they were different from those with all other treatments (Table 12). THE WUE increases during water deficit stress

Table 12. Water use efficiency (WUE) least square means with irrigation treatments for 'Americana Red' geranium grown for 67 d at the research greenhouse in Stillwater, OK, USA.

Irrigation	WUE ($mL \cdot g^{-1}$)
1 min during the morning	5.2 a[i]
1 min during the morning, 1 min during the afternoon	3.1 bc
2 min during the morning	2.9 c
2 min during the morning every other day	3.9 b
Manual	3.9 b

[i] Means followed by the same lowercase letter are not significantly different according to the pairwise comparison in the mixed model ($P \leq 0.05$).

Table 13. **Test of effects of irrigation on irrigation totals and irrigation leaching for 'Americana Red' geranium grown for 67 d in the research greenhouse in Stillwater, OK, USA, using timer-based controlled irrigation treatments.**

Source	Treatment	Week	Treatment × week
Weekly irrigation totals	***	***	***
Weekly leachate totals	***	***	***

[i] Indicates significant at $*P \leq 0.05$, $**P \leq 0.01$, $***P \leq 0.001$, or nonsignificant (NS).

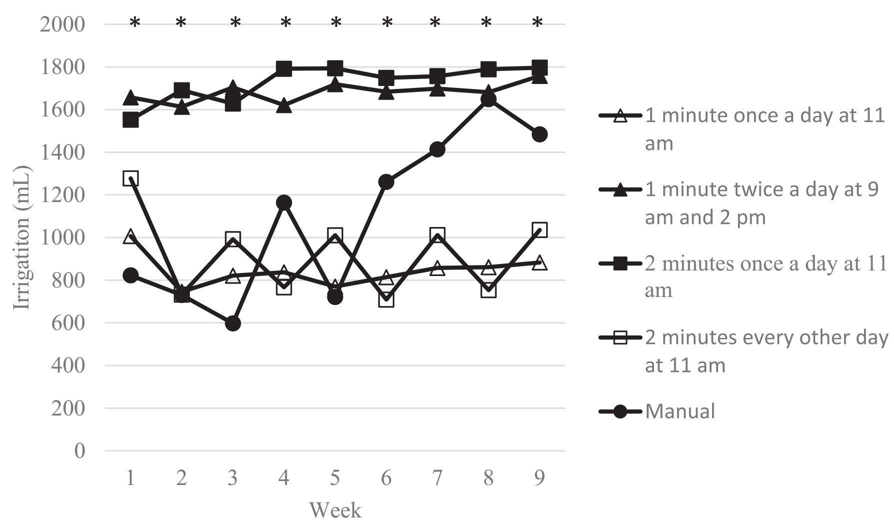

Fig. 1. Interaction between irrigation and weeks for geraniums grown for 67 d in the greenhouse in Stillwater, OK, USA, with timer-based controlled irrigation treatments. *Significant difference among treatments for that week.

conditions when the decrease in the photosynthetic rate is less than the reduction in the transpiration rate or stomatal conductance (Earl 2002). The irrigation water loss attributable to deep percolation and poor distribution of water of 'Grand Naine' (*Musa acuminata* L.) banana crop root zone caused low WUE under excess and faulty irrigation practices with drip systems (Panigrahi et al. 2019).

Total weekly irrigation had a significant treatment × week interaction ($P < 0.0001$) (Table 13). Irrigation during week 1 was greatest with 2 min per day at 11:00 AM and 1 min twice per day at 9:00 AM and 2:00 PM, but it was different from that with 1 min per day at 11:00 AM and the manual treatment (Fig. 1). Irrigation during weeks 2 and 3 was greatest with 2 min per day at 11:00 AM and 1 min twice per day at 9:00 AM and 2:00 PM, but it was different from that of all other treatments. Irrigation during weeks 4, 5, and 6 was greatest with 2 min per day at 11:00 AM, but it was different from that of all other treatments except 1 min twice per day at 9:00 AM and 2:00 PM (Fig. 1). Irrigation during weeks 7, 8, and 9 was greatest with 2 min per day at 11:00 AM, but it was different from that with 1 min per day at 11:00 AM and 2 min every other day at 11:00 AM (Fig. 1). Irrigation leachate had a significant treatment × week interaction ($P < 0.0001$) (Table 13). Week 3 irrigation leachate was greatest with 2 min per day at 11:00 AM and 1 min twice per day at 9:00 AM and 2:00 PM, but it was only different from that with manual treatment (Fig. 2). Week 6 irrigation leachate was greatest with 2 min per day at 11:00 AM, but it was only different from that with 1 min per day at 11:00 AM. Week 7 irrigation leachate was greatest with the manual treatment, but it was only different from that were 1 min per day at 11:00 AM (Fig. 2). The leachate volume differs during various collection periods because of plant transpiration and soil evaporation (Quiñones et al. 2007). The leaching fraction increases with both increased total irrigation and longer intervals between irrigation, thus offering valuable insights regarding optimizing irrigation strategies. The findings highlighted the potential for substantial water conservation through adjustments in the irrigation dosage and frequency (Mondaca-Duarte et al. 2023).

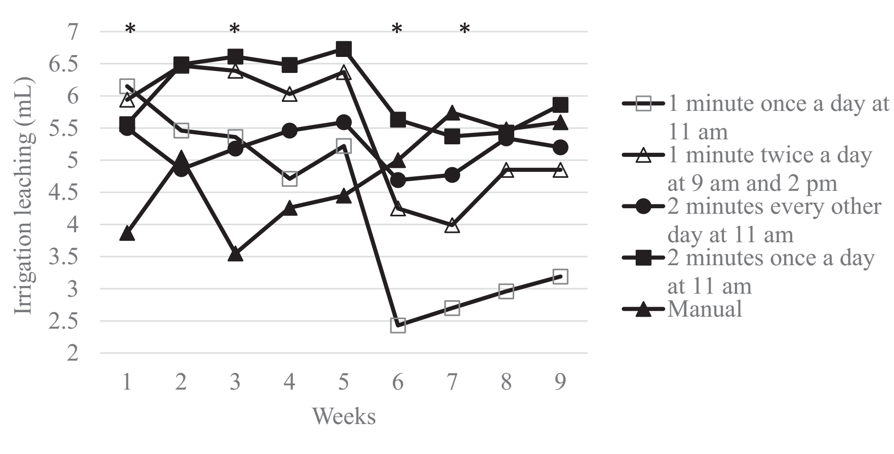

Fig. 2. Interaction between irrigation leachate and weeks for geraniums grown for 67 d in the greenhouse in Stillwater, OK, USA, with timer-based controlled irrigation treatments. *Significant difference among treatments for that week.

Conclusions

The results of this study demonstrate the complex interaction between irrigation practices, fertilizer applications, and their combined effects on plant growth, flowering, and nutrient uptake. In general, timer-based irrigation performed as well as the manual control, allowing for automated irrigation. Greater fertilizer rates with 6 or 9 g generally resulted in increased plant growth, nutrient uptake, and flower production, with 6 g being more cost-effective. Conversely, irrigation frequency and timing affected plant height and WUE, with an optimal irrigation regime of 1 min daily at 11:00 AM promoting more growth and efficient water utilization. Further research should explore additional factors that influence plant responses and refine management practices that maximize crop performance and minimize environmental impacts across multiple species, locations, and watering times and amounts.

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