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Optimization of Aeroponic and Ultrasonic Soilless Culture Systems in Terms of Timing and Growth Characteristics of *Lilium* OT Hybrid

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ABSTRACT

This study aimed to optimize an efficient nutrient system to produce cut Lilium flowers while considering the recent severe water crisis and the high cost of chemicals and fertilizers. Lilium bulbs (*Lilium* OT Hybrid cv. ''Zambesi'') were grown in aeroponic (centrifugal) and ultrasonic systems with variable pulse periods. An ultrasonic system (on/off) time in seconds was considered 10/10, 15/5, and 20/0. An aeroponic system was 3/27, 6/24, and 9/21 in seconds. A modified Hoagland nutrient solution was applied, and plants were grown to the flowering stage. The n, plant morpho-physiological responses were evaluated under different systems and operation times. The growth rate in the vegetative stage and plant height were higher in the aeroponic compared to the ultrasonic system, but the effect of pulses was not significant. The highest reproductive growth occurred in 10 and 20% pulses of the aeroponic system. Maximum root length was obtained in 10% of the aeroponic system operation. Maximum but unserious bulb rot was observed in 10% of the aeroponic systems compared to the others. Overall, 10% of the aeroponic system operation was recommendable for Lilium cultivation. Considerably, water consumption was less than half in the ultrasonic system compared to the aeroponic system. Also, the quantum performance of PSII decreased in the time performance by 50%, but it showed better results than the other pulses in the ultrasonic system. The findings reveal that the low water need in the ultrasonic system is a promising achievement. Thus, we recommended performing additional experiments with different pulses and even frequencies to achieve better performances in this system.

Introduction

Lily (*Lilium* spp. (Liliaceae)) comprises more than 100 species and 700 cultivars. It is one of the most important economic ornamental crops (Cao et al., 2018), native to regions such as North America, Europe, and Asia (Kamenetsky and Okubo, 2012). The OT hybrid in this research is triploid. Triploid cultivars occur in a suitable ploidy level with good growth vigor and high adaptability (De Best and Zwart, 2000). The Zambsi variety from OT hybrids has white and fragrant flowers. It was introduced by the Van Den Boss company in the Netherlands.

In the process of lily cut flower production, quantitative and qualitative parameters such as flower color, flower size, vase life, and length or diameter of flowering stem are considered important traits, and the growing conditions of the plant in the pre-harvest could affect the post-harvest quality by 30-70% (Marschner, 2012). According to the position of *Lilium* among other cut flowers in the world (fourth place in sales), as well as the demand for this flower in the global markets and annual sales report of 155 million cut flowers in Dutch flower market (Flora Holland, 2022), it is necessary and inevitable to pay attention to improve the quality and remove post-harvest problems of this crop (De Hertogh et al., 2012; Grassotti and Gimelli, 2011).

Traditional agriculture (Geoponic) has faced

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grave challenges in the agricultural sector with high water consumption, the need for vast lands, high levels of different fertilizer demand, and soil degradation challenges (Killebrew and Wolff, 2014; Walls, 2014) along with global climate change and water scarcity (Li et al., 2016). These challenges have highlighted the need to pay attention to the novel cultivation patterns. Modified hydroponic and aeroponic greenhouse techniques are currently used where production per unit area increases regardless of less water, fertilizer, and space requirements (Lakkireddy et al., 2012). It also carries fewer environmental risks due to its low consumption of chemicals (Alshrouf, 2017). Aeroponics involves a hydroponic system in which water and nutrients are sprayed directly into the roots (Lakhiar et al., 2018). This system has several advantages, including less nutrients and water consumption than soil cultivation and more oxygen available to the roots, which leads to optimal plant growth. This system also allows precise control of the root zone, with no need to disinfect the culture medium, with minimum labor requirement (Lakhiar et al., 2018b). Some researchers report that the aeroponic system can reduce water consumption by 95% (Li et al., 2020), fertilizer consumption by 60%, and toxins by 100% (Alshrouf, 2017). However, energy consumption in aeroponic systems must be considered (Niam and Sucahyo, 2020).

In some aeroponic systems, the nutrient solution is vaporized using ultrasonic transducers that convert wave energy to mechanical vibration (Jamshidi et al., 2019). Some researchers have reported that ultrasonic waves can change the physical and chemical properties of the water-containing nutrient solution, which can ultimately affect the plant yield (Doosti et al., 2012; Naddeo et al., 2014; Gao et al., 2016; Lakhiar et al., 2018). Tunio et al. (2021) used five minimum spraying times and a 30-minute spraying interval for lettuce in an ultrasonic system, stating that the constant contact of roots with oxygen stimulated metabolic processes and had positive effects on the growth of branches, the roots, and nutrient uptake. In the same direction, Liu and Zhang (2013) compared the ultrasonic system with the traditional piezometric atomizer, reporting better and more uniform absorption of nutrient solution by roots, prevention of root washing, and rapid growth of bamboo rhizomes and branches. Also, Chang et al. (2012) stated that aeroponics could be an appropriate system for producing potato mini tubers. They found that interruptions in nutrient supply at the stolon growth stage significantly increase root activity, restrict stolon growth, and finally induce tuber initiation. Therefore, non-tuberous conditions such as hot temperatures and late-season cultivars favor using this nutrient interruption technique.

An ultrasonic mist is a metal device with a relatively small metal coating, which includes a plastic shell, internal adapter, and piezoelectric ultrasonic converter. This converter is the main component that generates high-energy vibrations at a frequency of 0.5 to 3 MHz (MegaHertz). The atomizer is placed in the center of the container under 2.5 to 10 cm of liquid solution and produces dusting of only a few microns (with an approximate size between five and one hundred and fifty microns) in the space around the root (Lakhiar et al., 2018). The use of ultrasonic systems in agriculture and mainly in the horticultural sector can be one of the substantial successes in the optimal use of water, nutrients, and energy for accurate production. An ultrasonic atomizer device can reduce energy consumption by about 90 to 93% (Niam and Sucahyo, 2020), but nowadays, ultrasonic atomizer technology has scantily proved effective on a commercial scale (Nithin et al., 2019; Yang et al., 2019). There are some reasons to explain this condition. First, the difficulty of adjusting some key parameters, such as the characteristics of the sprayer or droplet size and the flow rate of the droplet by plant needs, can impede this system. Secondly, the rational experimental output is nonexistent, relevant to the performance of each type of ultrasonic atomizer technology device and the nutritional demands of plants in such systems. Thirdly, the plant-based response to atomization characteristics resulting from variations in the UA (Ultrasonic Atomizer) device is unclear (Niam and Sucahyo, 2020). Thus, it is necessary to evaluate the performance of this system in comparison with other systems. Therefore, the purpose of this research was to select the right spraying time to achieve the desired growth of Lilium in hydroponic systems such as ultrasonic and centrifugal settings.

Material and Methods

In this experiment, Lilium bulbs (*Lilium* OT Hybrid cv. 'Zambesi') were grown in aeroponic (centrifugal) and ultrasonic systems with variable pulse spraying/fogging periods in aeroponic/ultrasonic, respectively. This experiment was performed in a growth chamber with automatic control of environmental conditions regarding temperature, light, and humidity in the workshop building of the Department of Agricultural Machinery Engineering, Faculty of Agriculture, University of Tehran, Iran. In this study, the solution pipelines were arranged separately, and the boxes were placed perfectly. The automatic solution operation schedule was established. The ultrasonic fogging system was designed based on the piezoelectric phenomenon (electric pressure effect). In this system, piezoelectric ceramics were installed on the lower surface of the boxes, and for each box, four piezoelectric ceramics were considered. As a result of the impact of these ceramics, which have a high frequency and a small amplitude, small water particles (approximately five to one hundred and fifty microns in size) were suspended, either remaining on the root surface of the plant or due to weight, they slowly return to the surface of the water. Accordingly, by increasing the contact surface of the climate and the possibility of surface evaporation, the relative humidity of the plant root environment increases significantly.

Then, we examined the function of centrifugal ultrasonic and aeroponic systems. In the first step, for this purpose, a variable pulse spraying (in an aeroponic system) and fogging period (in an ultrasonic system) were applied as in the aeroponic system, three times spraying pulses of 3 to 27, 6 to 24, and 9 to 21 in seconds. The system's operation time was 10, 20, and 30%. In the ultrasonic system (with a frequency of 1.3 MHz), three levels of fogging on/off times occurred in seconds of 10 to 10, 15 to 5, and 20 to zero (always on), with 50, 75, and 100% system time operation, respectively. For growing conditions, day/night temperatures of 23/18±2 °C, relative humidity of 70%, the light intensity of 150-200 µmol m^{-2} s^{-1} (artificial light supplied with LED lamps Red/Blue ratios of 4:1), and 16/8 h of day/night photoperiod were considered. A modified Hoagland nutrient solution (Hogland and Arnon, 1950) was applied for nutrition which contained Ca(NO3)2.4H2O, NH4NO3, KNO3, KH2PO4 and MgSO4.7H2O in mM of 4, 1, 5, 1 and 1, respectively for macro-elements and micro-elements as Fe-DTPA, H3BO3, CuSO4, MnSO4, ZnSO4 and H2MoO4 in mg L^{-1} of 24, 1.3, 0.03, 0.8. 0.1 and 0.01, respectively. The nutrient solution changed based on a recording of the pH and EC of the nutrient solution for the period of the experiment. Accordingly, a pH of 5.7±0.2 remained constant, and EC was adjusted to 1800±100 µS cm^{-1} when dropped below 1100 µS cm^{-1}. Sampling was done, and traits were evaluated by coloring the flower buds at the same time as commercial harvest (Abbasi et al., 2020). Then, plant growth responses such as growth rate, dry weight, stem height, root length, number of root hair, bulb rot, chlorophyll fluorescence parameters, and PSII quantum function were evaluated as affected by different variable operation systems.

Measuring quantitative traits

The growth rate was evaluated by measuring plant height daily from the bulb crown to the tip of the branch based on centimeters per day.

Root length was measured according to Tennant (1975), where the fresh roots were cut into 1 cm segments, and 0.3 g were randomly poured into a mesh tray (dimensions of 2 x 2 cm) containing 0.5 cm depth of water. Then, the number of roots that intersected the horizontal and vertical lines were counted separately. Finally, the root length was calculated from the following equation:

$$X= 11/14 * r (H+U)$$

where X is the root length by 0.3 g, r is the dimensions of the squares of the grid plate (here two cm), H is the number of roots that intersected the horizontal lines, and U is the number of roots that intersected the vertical lines. Then, the number obtained from the formula (X) was multiplied by the fresh weight of the whole root and the length of the whole root was calculated.

For root hair measurements, the roots were collected and cut into 1 cm pieces. Root hairs were counted as described by Dechassa et al. (2003).

To estimate the amount of bulb rot, the number of rotten bulb scales was counted, and the results were classified into five groups and calculated by the Likert method (1932).

Measuring of photosynthetic parameters

Chlorophyll fluorescence imaging in leaves attached to the plant near the harvest stage of each treatment enabled biophysical measurements after placing the plants in darkness for 20 min. The temperature for these measurements was the same as the temperature of the experiment. The leaves were subjected to F_v/F_m assessment using a fluorometer equipped with an imager (Handy FluorCam FC 1000–H, Photon Systems Instruments, Drásov, Czech Republic). The calculation of F_V/F_M occurred on a custom-made protocol (Aliniaeifard and Van Meeteren, 2014).

Statistical analysis

The research was performed using SAS statistical software version 9.4 (SAS Institute, Cary, NC, USA). The experiment was carried out as a factorial arrangement in a completely randomized design with three replications and three observations in each replicate. Comparison of mean values involved least significant differences (LSD, $p<0.05$).

Results

Based on the results of the analysis of variance, the type of system had a significant influence on the growth rate (in vegetative and reproductive stages), plant height, root length, and root hair count, but had no significant effect on the bulb rot and leaf dry weight at the probability level of one percent. Also, the effect of the spraying pulse on the root length and bulb rot was significant at the probability level of one percent, but no significant effect was observed on the growth rate and plant height. The interaction effect of system types and spraying pulses on the growth rate in the reproductive stage, root length, number of root hair, bulb rot, and chlorophyll fluorescence parameters, including F_o, F_m, F_v, and F_v/F_m were significant but had no significant effect on the growth rate in the vegetative stage, leaf dry weight, plant height and Fm/Fo fluorescence parameter at the probability level of one percent. The maximum root length (5928.97 cm) was obtained in the aeroponic system with 10% as the lowest system operation time (Fig. 1). Also, the shortest root length (1768.93 cm) was in 50% of time operation of the ultrasonic system (30% reduction) which had no significant difference with other treatments (Fig. 1). The highest rot of Lilium bulbs (30%), significantly different from other treatments, was observed in the aeroponic system with 10% of system operation time and the lowest rot (2%) was obtained in the ultrasonic system with 50% performance (Fig. 2).

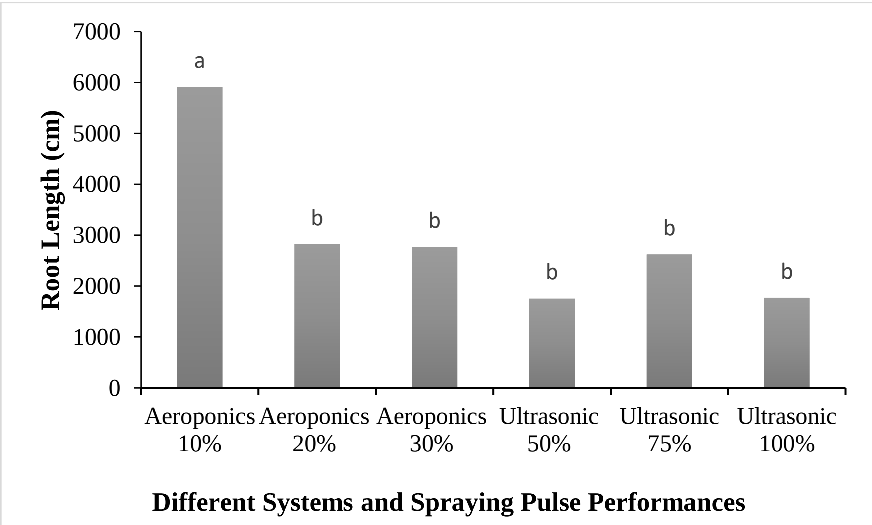

Fig. 1. Effect of spraying time in ultrasonic and aeroponic systems on the root length of Lilium.

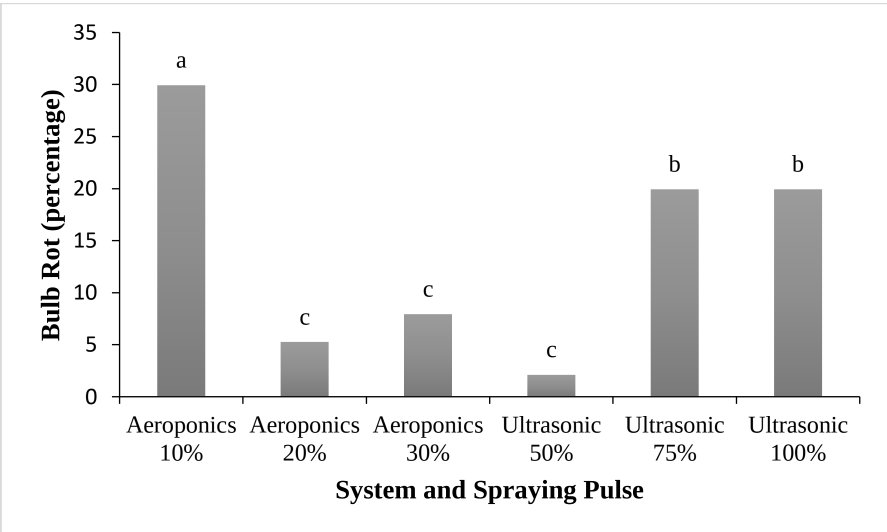

Fig. 2. Effect of spraying time in ultrasonic and aeroponic systems on Lilium bulb rot.

In this research, the highest vegetative growth rate (2.2 cm day^{-1}) was observed in the aeroponic system with an operation time of 10% (1.25 cm day^{-1}), and the highest reproductive growth rate (1.36 cm day^{-1}) was observed with 20% of system operation time (Fig. 3 and 4). The growth rate in the ultrasonic system was slower, and plants in the aeroponic system showed better vegetative growth than in the ultrasonic system. However, with 50% ultrasonic system operation time, the reproductive stage (1.21 cm day^{-1}) functioned similar to the aeroponic system. The lowest reproductive growth rate (0.66 cm day^{-1}) was obtained in the ultrasonic system with 75% performance. The reproductive growth rate decreased by 30% in this treatment.

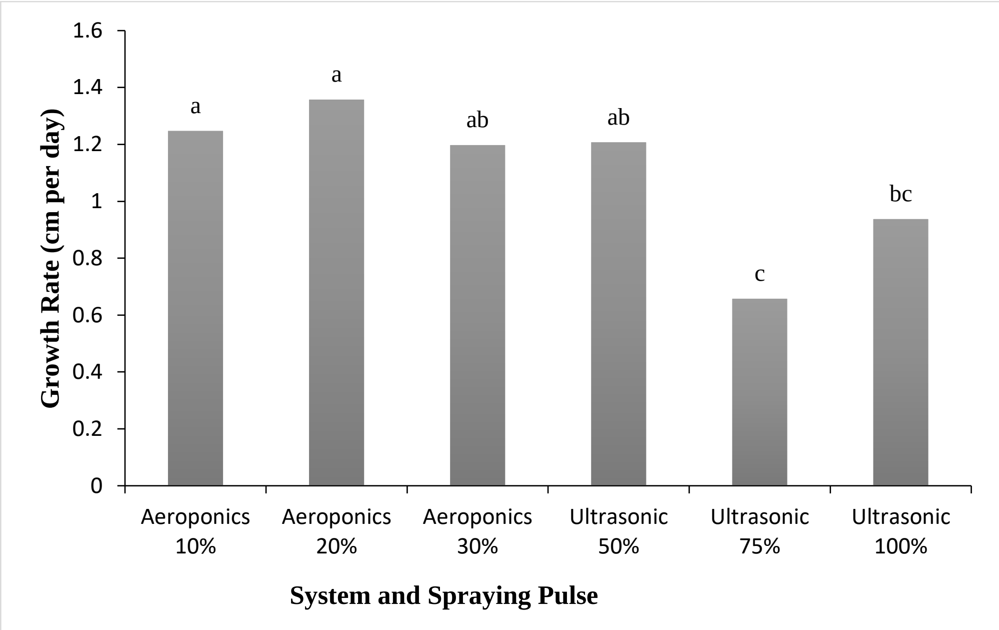

Fig. 3. Effect of spraying time in ultrasonic and aeroponic systems on the growth rate of reproductive stage of Lilium.

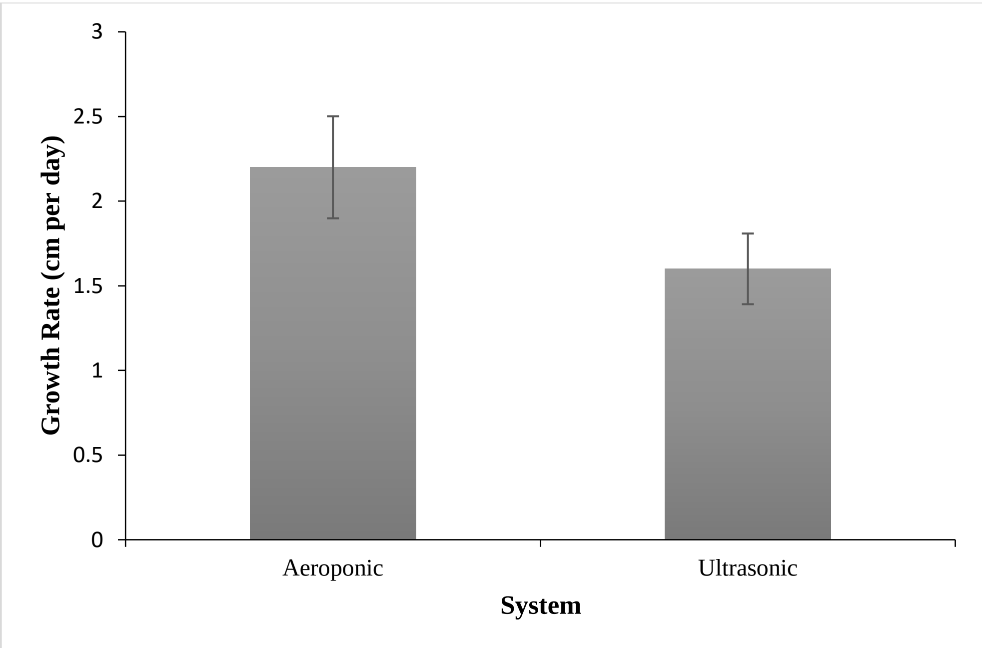

Fig. 4. Effect of ultrasonic and aeroponic systems on the growth rate of Lilium vegetative stage.

Regarding root hair count, more root hairs were observed with the 75% ultrasonic system operation time (25 # mm^{-1} root) and 100% (24 # mm^{-1} root) and there were no significant differences among other treatments. The lowest count (7 mm^{-1} root) was obtained with the 20% aeroponic system operation time (Fig. 5).

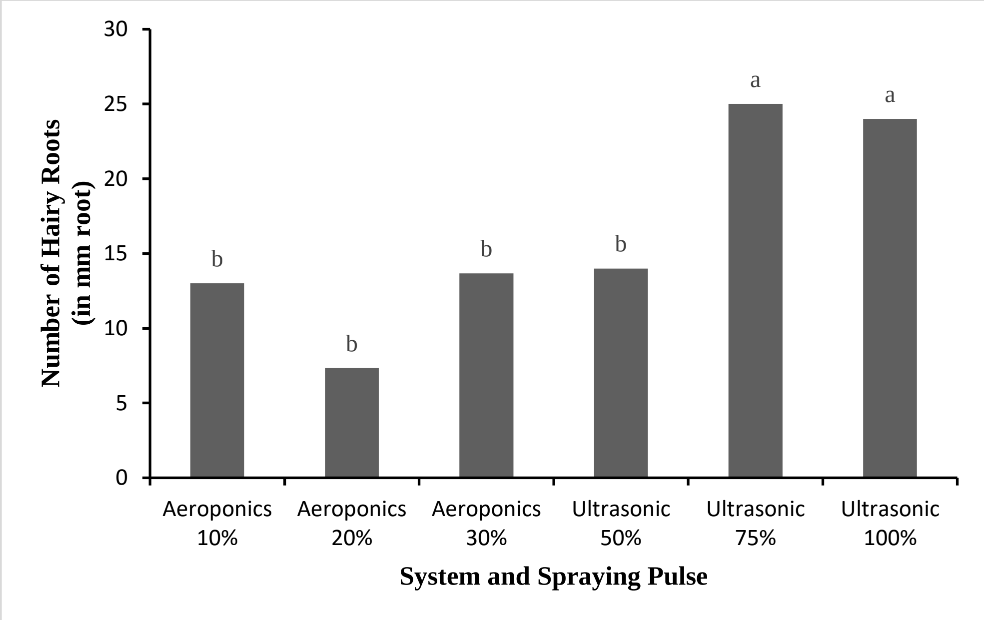

Fig. 5. Effect of ultrasonic and aeroponic systems on the root hair count in Lilium plants.

Based on the results, the maximum cut flower height (103.39 cm) was obtained in the aeroponic than in the ultrasonic system (80.03 cm). However, the effect of spraying pulses was not significant on this trait in both systems (Fig. 6).

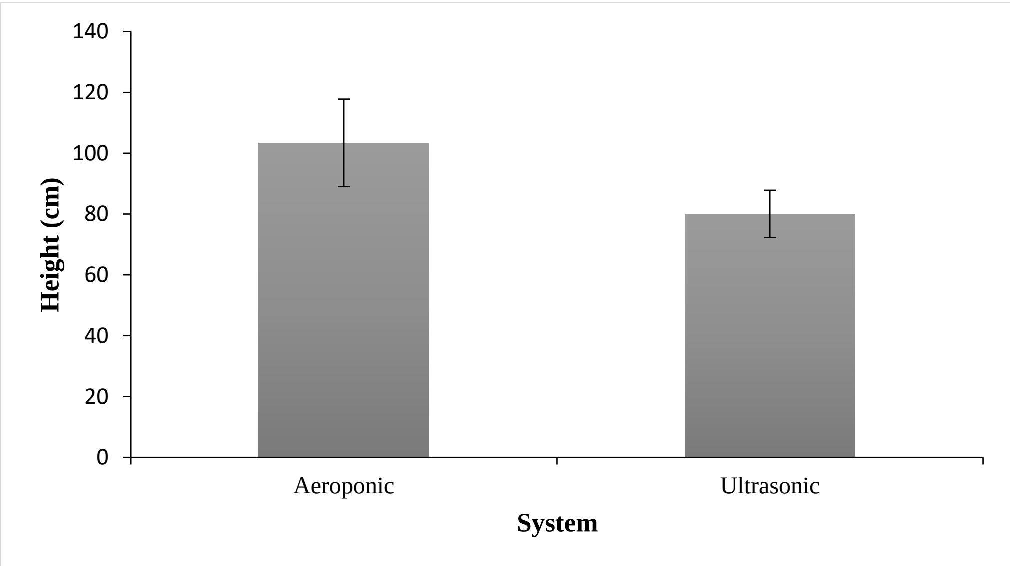

Fig. 6. Effect of ultrasonic and aeroponic systems on the height of Lilium plants.

Although leaf dry weight was not significantly different among the systems and pulses, leaf dry weight increased by 0.12 g per 10 leaves in the aeroponic system with an operation time of 30% (Fig. 7).

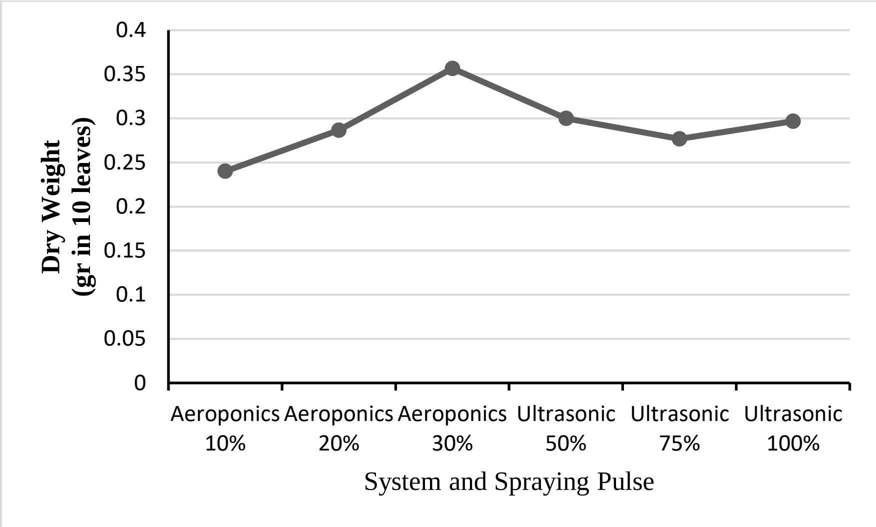

Fig. 7. Effect of ultrasonic and aeroponic systems on the leaf dry weight in Lilium plants.

The shortest pulse produced the tallest plants, causing the fastest growth affected by spraying pulse and the system type in aeroponic and ultrasonic systems (Fig. 8 and 9). Though due to the issue of energy efficiency, the shortest pulse was considered the best pulse for Lilium growth in hydroponic conditions.

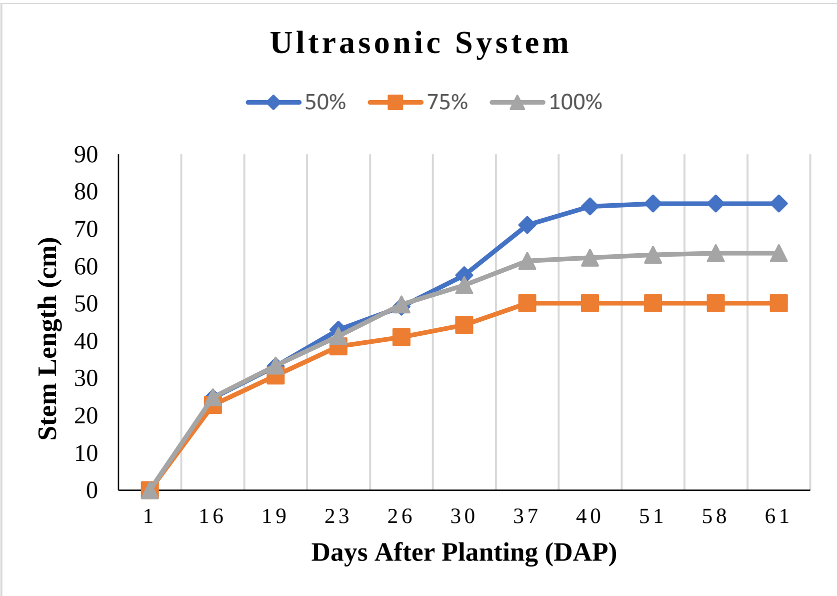

Fig. 8. Effect of operating performance (%) of the ultrasonic system on the stem length of Lilium at different times after planting (DAP).

The vegetative growth rate was higher than the reproductive growth rate in both systems. An increase in leaf area was also observed when growth halted. The growth stages for lilium in the aeroponic and ultrasonic systems can be named as the stage of rapid vegetative growth (up to day 16 after planting), the reproductive stage with a slower growth rate (up to day 44 after planting), and the cessation of stem growth rate when the leaf area develops and bud sizes increase, and then the harvest stage. Accordingly, both applied systems were not significantly different at the beginning of each period.

The lowest F_o, F_m and F_v were obtained in response to 10% aeroponic system operation time and then with 50% system operation time of the ultrasonic system. The highest value of these traits was obtained in response to 30% aeroponic, 75% and 100% ultrasonic operation time, respectively (Fig. 10, 11 and 12). Also, the F_v/F_m

ratio decreased (0.66) in response to 50% ultrasonic system operation time (Fig. 13).

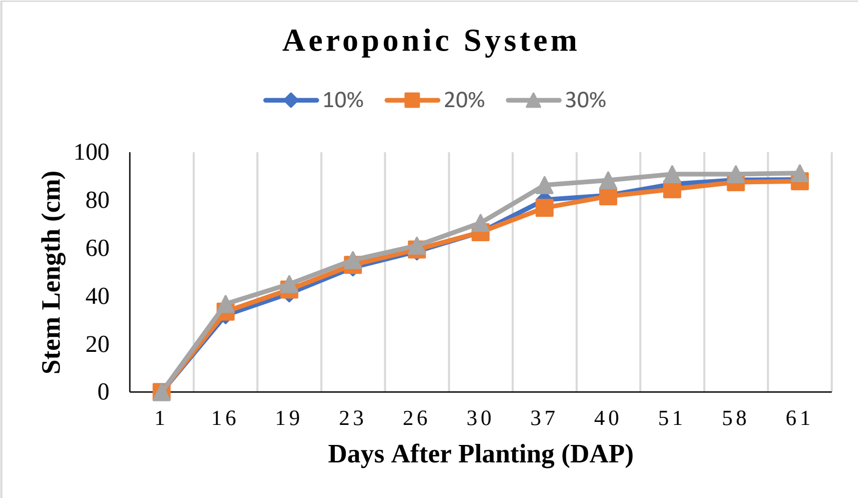

Fig. 9. Effect of operating performance (%) of the aeroponic system on the stem length of Lilium at different times after planting (DAP).

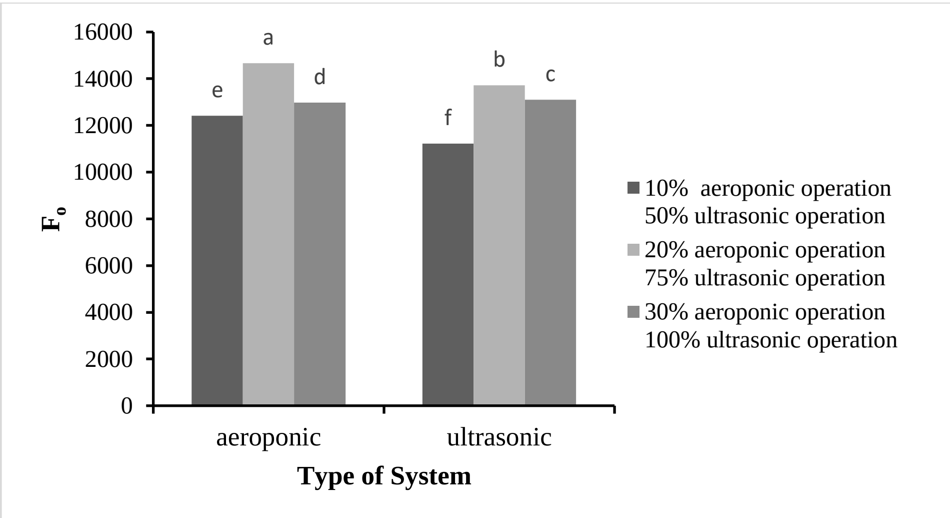

Fig. 10. Effect of ultrasonic and aeroponic systems and different pulses on Fo (minimum fluorescence) in Lilium plants.

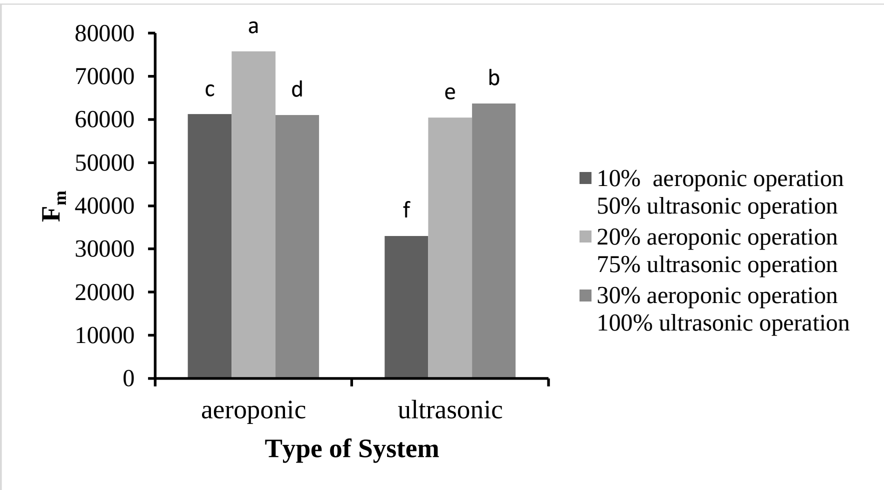

Fig. 11. Effect of ultrasonic and aeroponic systems and different pulses on F_m (maximum fluorescence) in Lilium plants.

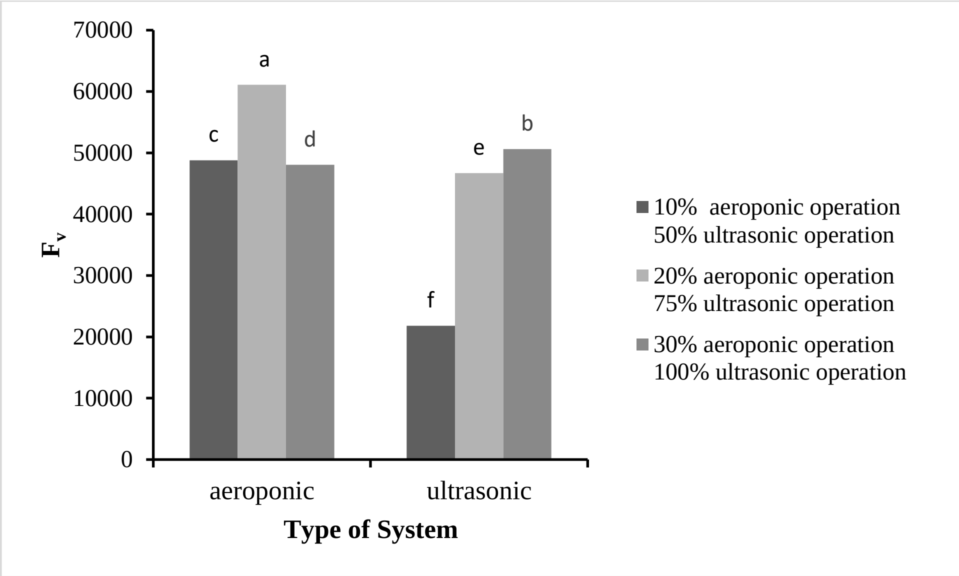

Fig. 12. Effect of ultrasonic and aeroponic systems and different pulses on Fv (variable fluorescence) in Lilium plants.

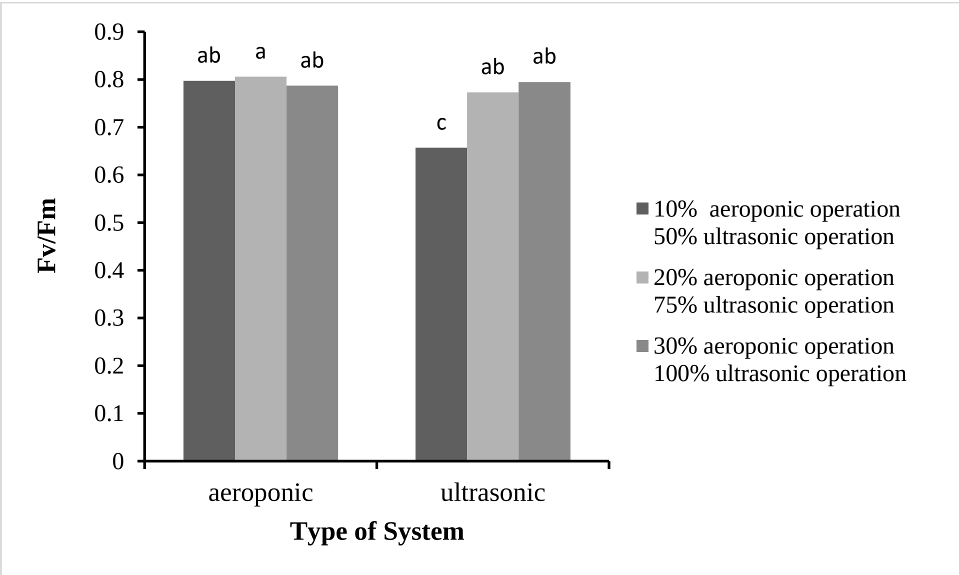

Fig. 13. Effect of ultrasonic and aeroponic systems and different pulses on F_v/F_m (maximum photochemical quantum yield of photosystem II) in Lilium plants.

Discussion

An increase in root length in the aeroponic system operation time of 10% could be due to the increase in plant growth rate based on the availability of abundant oxygen to the roots (Hayden et al., 2004; Niam and Sucahyo, 2020), an increase in root metabolism (Chiipanthenga et al., 2012), and an increase in water-use efficiency and nutrient uptake in the aeroponic system (Eldridge et al., 2020). Similarly, in the shortest system operation time, less deposition of water droplets on the roots and unsaturation of the root surface may have increased gas and nutrient solution exchange, leading to greater root access to nutrients and increased root growth (Eldridge et al., 2020). In a relevant study, lettuce cultivation in the aeroponic system improved root growth by increasing root area, volume, and length (Li et al., 2018), which is consistent with our findings in the current study.

Sumarni et al. (2013) stated that the advantage of aeroponic cultivation is free-to-root propagation due to direct, rapid, and sufficient uptake of water and oxygen. In this case, a high root volume can encourage water retention on the surface of the bulb and increase bulb rot (as observed in 30%

aeroponic system operation time). In the aeroponic system, humidity is the main component for vibrant plant growth and development. However, plant growth is significantly affected by the increase and decrease in relative humidity. It affects plant physiological functions and creates pathogenic problems. Therefore, it is crucial to regularly maintain and control the required humidity of the growth chamber based on plant-driven demands (Lakhiar et al., 2018).

Numerous articles have stated that in aeroponic culture, research should determine droplet size and spray distance to improve continuous access to water and nutrients for optimal growth of plant aerial parts as vegetative and reproductive organs (Li et al., 2018; Tunio et al., 2021). This need has been addressed to some extent in the reproductive development stage of Lilium in the current study. The growth rate in the ultrasonic system was slower, and plants in the aeroponic system showed better vegetative growth than the ultrasonic one.

Bucksetha et al. (2016), Margaret (2012), and Stoner and Clawson (1998) have stated that the main problem with the number of root hairs in the aeroponic system is related to water nutrient droplet size. Larger droplets permit less supply of oxygen availability in the root zone. The smaller droplets produce too much root hair without developing a lateral root system for sustainable growth. This means that roots may not form a lateral root system and thus cannot continue to grow (Lakhiar et al., 2019). According to the findings of the present research, the growth rate in the ultrasonic system was lower than in the aeroponic system. In this case, plants were forced to compensate by increasing root surface area and weight (Salachas, 2015). Photosynthetic materials are mostly allocated to the roots. However, ultrasonic could be an alternative production system for other high-value root production purposes.

Also, researchers have shown that continuous contact of roots with oxygen in the aeroponic system stimulates metabolic processes, which in turn may positively affect branch growth and nutrient uptake (Tunio et al., 2021) and accordingly can lead to an increase in plant height. Lettuce growth parameters in the aeroponic system reportedly responded positively to nozzles that used air in the spray composition (Tunio et al., 2021). These results are consistent with the findings of the present study.

Leaf dry weight improved in response to 30% aeroponic system operation time. Probably, the roots uniformly absorbed nutrients and moisture. Root morphology and architecture reportedly affected aerosol capture and thin film formation (Kratsch et al., 2006). Research into the formation, thickness, composition, and residency times of aeroponically-produced root surface thin films allowed aeroponic cultivation systems to be modified for the optimal performance of specific crops. It would be informative to assess the interplay between these parameters during root surface thin-film formation and retention for different crops. This might inform aerosol delivery regimes and characteristics for specific crops at defined developmental stages to ensure water, nutrient, and oxygen uptake to support optimal plant performance. It is anticipated that root surface thin-film formation is likely governed by aerosol composition, plant root architecture, and environmental properties (Eldridge et al., 2020).

Wider distances between misting sprayers and roots restricted root access to the water microdroplets, decreasing nutrient availability and absorbance. In this case, plants were forced to compensate by increasing root surface area and weight (Salachas, 2015). Thus, the droplet size and the misting interval will have a significant effect on the growth response of plants in the aeroponic and ultrasonic cultures. However, additional research is needed to prove this opinion.

In line with Lakhiar et al. (2018), plant root structures responded to the root zone environment through enhanced growth and branching systems. Also, some researchers stated that roots encounter heterogeneous conditions along their growth axis and dynamically regulate root system architecture and root hair morphogenesis (Morris et al., 2017; Shahzad and Amtmann, 2017; Vissenberg et al., 2020). Regarding the results and our observations, especially in the early stages of growth in the aeroponic (centrifugal) system, the roots appeared more vertically than horizontally spread on the surface in the ultrasonic system due to the adaptation of the plant to absorb more food-rich fogs. In the aeroponic system, due to larger droplets, excess moisture can fall more easily with the vertical architecture of the roots.

Water consumption in both aeroponic and ultrasonic systems was measured based on the amount of water entering and leaving the system. The results showed that water consumption in the ultrasonic system was about half of the aeroponic system (45%).

The photosynthetic traits revealed whether the supply of water and nutrient solution to the plants by these systems and pulses followed plant-driven demands. Characteristics of chlorophyll fluorescence are a critical consideration for measuring the quantum yield of photosystem II (PSII) and photoinactivation by determining the possible quantum yield under water-limiting conditions (Batra et al., 2014). Photosynthesis is significantly affected by drought because the latter blocks the transport of energy from PSII to PSI (Siddique et al., 2016). By analyzing photosynthesis, one can determine the degree of resistance to adverse environmental conditions, e.g., excessive congestion (Prasad et al., 2015; Olechowicz et al., 2018) and drought (Kalaji et al., 2018; Iqbal et al., 2019).

Parameters derived from the rapid fluorescence induction kinetics test (OJIP transient) provided more information on the chlorophyll fluorescence and the quantum yield of PSII (Table 1). Chlorophyll fluorescence is an easily applicable method for assessing the adverse effects of environmental stresses on plants (Moosavi-Nezhad et al., 2021; Moradi et al., 2021; Seif et al., 2021; Shomali et al., 2021). This may suggest that chlorophyll fluorescence, which reflects energy excitation in PSII, can be used as an index for studying plant stress tolerance. The merits of this index are its stability under changing climates and its fast and easy application (Roden et al., 1999; Roháˇcek, 2002). Furthermore, the parameters reflected by chlorophyll fluorescence indicate the overall photochemical leaf status but not their short-term status (Roden et al., 1999). Rapid fluorescence induction kinetics (OJIP transient) is a quick and non-destructive method applicable in many studies to assess photosynthetic functionality under different stress conditions (Bayat et al., 2018; Estaji et al., 2019). OJIP transient reflects details about energy flow through the thylakoid membrane, specifically in PSII components (Kalaji et al., 2017), and provides information about the physiological state of PSII (Antal and Rubin, 2008).

Table 1. Abbreviations and definitions of the photosynthetic parameters assessed in the current study.

Abbreviation	Definition	
F_o	Minimum fluorescence, when all PSII reaction centers (RCs) are open (O-step of OJIP transient)	$F_{50\mu s}$
F_v	Variable fluorescence of the dark-adapted leaf	F_m - F_o
F_m	Maximum fluorescence, when all PSII RCs are closed (P-step of OJIP transient)	F1s = Fp
F_v/F_m	Maximal quantum yield of PSII photochemistry	$1-(F_0/F_m) = (F_m-F_0)/F_m$
F_m/F_o	Structural damage to PSII	

When an electron acceptor of quinone (QA) is in a reduction state, chlorophyll fluorescence is high, and accordingly, the amount of Fv increases likewise. When quinone is in its oxidation mode, chlorophyll fluorescence and Fv decrease (Paknejad et al., 2007). Environmental tensions decrease Fv due to the prevention of PSII photooxidation. Since the Fv indicates a complete reduction of quinone, drought stress disturbs the transfer of electrons to PSI (Ali-Dib et al., 1994; Ommen and Donnelly, 1999; Paknejad et al., 2007). An increase in F0 indicates damage to the photosystem II electron collection chain, reducing the capacity of quinone A (QA) and its lack of complete oxidation due to the slow flow of electrons in photosystem II. In general, PSII becomes inactivated (Zlatev and Yordanov, 2004). The F0 increases due to drought stress, as reported by other researchers (Mamnoei and Seyed Sharifi, 2010; Javadipour et al., 2012). Also, when molecular quinone (as a primary electron acceptor in PSII) is in oxidized mode, it creates a situation where reaction center PSII is active, electron acceptors, and energy are transferred to PSI for producing ATP and NADPH. In such conditions, the system has the lowest fluorescence (F0). As the reduction escalates gradually, the fluorescence increases and continues until full-reduction, where reduction centers of PSII become closed gradually, and electron transfer to PSI no longer occurs. Then, the fluorescence of chlorophyll increases, and the centers of the photosystem have the highest fluorescence (Fm). Drought stress impedes electron acceptance and transfer capacity, causing the system to speed up F_m (Paknejad et al., 2007; Amirjan et al., 2009).

In the current study, the reduced F_v/F_m and a higher chance of photoinhibition occurred because of a reduction in F_v/F_m value when the PSII function and structure were damaged by stress, causing most of the absorbed light energy to dissipate from the PSII reaction center (Moosavi-Nezhad et al., 2021). A decrease in

F_v/F_m occurred only in response to 50% ultrasonic system operation time. This decrease probably indicates that PSII operated while dependent on different efficiencies in different pulses of irrigation and that the intensity of the tension was significant enough that it destroyed the centers of the PSII. This event means that an increase in the first fluorescence can indicate degradation of the PSII reaction center, the transformation of the structure, and changes in PSII pigments in tension conditions such as drought (Havaux and Niyogi, 1999). However, with 50% ultrasonic system operation pulsing time, we observed a better final performance than the other two pulses.

Conclusion

As we know, aeroponics is a modern, innovative technology for plant cultivation without involving soils. This system is the best plant-growing technology in many aspects compared with different cultivation systems. According to the results, bulb rot was less prominent in ultrasonic systems. Primary traits, such as growth rate in vegetative and reproductive stages, plant height, and root length, showed higher values in the aeroponic system. Thus, the 10% aeroponic system is recommendable for Lilium cultivation if energy consumption is a concern. In the ultrasonic, the system operation time of 50% showed better results than other pulses. Water consumption in the ultrasonic was less than half of that in the aeroponic system. Regarding the water crisis, we can recommend additional experiments with different pulses and even frequencies to achieve better performance in this system.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

References

Abbasi F, Khaleghi A, Khadivi A, Solgi M. 2020. Effect of benzyladenine and salicylic acid on morphological and biochemical traits of Asiatic hybrid *Lilium* 'Navona'. Gesunde Pflanzen 72 3, 219-225 https://doi.org/10.1007/s10343-020-00504-8

Ali-Dib T, Monneveux P.H, Acevedo J, Nachil MM. 1994. Evaluation of praline analysis and chlorophyll fluorescence quenching measurements as drought tolerance indicators in durum wheat (*Triticum turgidum* L. Var. durum). Euphytica 79, 65-73.

Aliniaeifard S, Van Meeteren U. 2014. Natural variation in stomatal response to closing stimuli among *Arabidopsis thaliana* accessions after exposure to low VPD as a tool to recognize the mechanism of disturbed stomatal functioning. Journal of Experimental Botany 65, 6529–6542.

Alshrouf A. 2017. Hydroponics, aeroponic and aquaponic as compared with conventional farming. American Scientific Research Journal for Engineering Technology and Sciences (ASRJETS) 27, 247-255

Amirjan M.R, Iranbakhsh A, Abnosi M.H. 2009. Molecular mechanism of photosynthesis. Arak University.

Antal T, Rubin A. 2008. In vivo analysis of chlorophyll a fluorescence induction. Photosynthesis Research 96, 217–226.

Batra N.G, Sharma V, Kumari N. 2014. Drought-induced changes in chlorophyll fluorescence, photosynthetic pigments, and thylakoid membrane proteins of *Vigna radiata*. Journal of Plant Interactions 9, 712–721. doi: 10.1080/17429145.2014.905801

Bayat L, Arab M, Aliniaeifard S, Seif M, Lastochkin, O, Li T. 2018. Effects of growth under different light spectra on the subsequent high light tolerance in rose plants. AoB Plants 10, ply052

Buckseth T, Sharma A.K, Pande K.K, Singh B.P, Muthuraj R. 2016. Methods of pre-basic seed potato production with special reference to aeroponic––a review. Scientia Horticulturae 204, 79–87. http://dx.doi.org/10.1016/j.scienta.2016.03.041

Cao Q, Zhang X, Gao X, Wang L, Jia G. 2018. Effects of ploidy level on the cellular, photochemical and photosynthetic characteristics in Lilium FO hybrids. Plant Physiology and Biochemistry 133, 50–56

Chiipanthenga M, Maliro M, Demo P Njoloma J. 2012. Potential of aeroponics system in the production of quality potato (*Solanum tuberosum* L.) seed in developing countries. African Journal of Biotechnology 11, 3993–3999.

Dechassa, N, Schenk, M K, Claassen, N, Steingrobe, B. 2003. Phosphorus efficiency of cabbage (*Brassica oleraceae* L. var. capitata), carrot (*Daucus carota* L.), and potato (*Solanum tuberosum* L.). Plant and Soil 250, 215–224.

De Hertogh A, Schepeen J.M, Kamenetsky R, Le Nard M Okubo H. 2012. The globalization of flower bulb industry. Ornamental geophytes: from basic science to sustainable production 1, 1-15.

Doosti M.R, Kargar R, Sayadi M.H. 2012. Water treatment using ultrasonic assistance: a review. Environment and Civil Engineering Department, University of Birjand, Birjand, Iran. Proceedings of the International Academy of Ecology and Environmental Sciences 2, 96-110.

Eldridge B.M, Manzoni L.R, Graham C.A, Rodgers B, Farmer J.R, Dod A.N. 2020. Getting to the roots of aeroponic indoor farming. New Phytologist 228, 1183–

1192. www.newphytologist.com

Estaji A, Kalaji H.M, Karimi H.R, Roosta H.R, Moosavi-Nezhad S.M. 2019. How glycine betaine induces tolerance of cucumber plants to salinity stress? Photosynthetica 57, 753–761.

Flora Holland. 2022. Annual report. www.royalfloraholland.com

Gao J, Zhang J, Lu D. 2016. Design and atomization experiments of an ultrasonic atomizer with a levitation mechanism. Applied Engineering in Agriculture 32, 353-360.

Grassotti A, Gimelli F. 2011. Bulb and cut flower production in the genus Lilium: current status and the future. Acta Horticulturae 900, 21-35.

Havaux M, Niyogi KK. 1999. The violaxanthin cycle protects plants from photooxidative damage by more than one mechanism. Proceedings of the National Academy of Sciences 96, 8762- 8767.

Hayden A.L, Brigham L.A, Giacomelli GA. 2004. Aeroponic cultivation of ginger (*Zingiber officinalis*) rhizomes. Acta Horticulturae 659, 397-402.

Hogland D.R, Arnon D.I. 1950. The water culture method for growing plants without soil. Circular. California Agricultural Experiment Station 347, 1-32.

Iqbal N, Hussain S, Raza A, Yang CQ, Safdar M.E, Brestic M, Aziz A, Hayyat M.S, Asghar M.A, Wang X.C, Zhang J, Yang W, Liu J. 2019. Drought tolerance of soybean (*Glycine max* L. Merr.) by improved photosynthetic characteristics and an efficient antioxidant enzyme activities under a split-root system. Frontiers in Physiology 10, 786. doi: 10.3389/fphys.2019.00786

Jamshidi A.R, Ghazanfari M.A, Ommani AR. 2019. Effect of ultrasonic atomizer on the yield and yield components of tomato grown in a vertical aeroponic planting system. International Journal of Horticultural Science and Technology 2, 237-246.

Javadipour Z, Movahhedi Dehnavi M, Balouchi H.R. 2012. Evaluation of photosynthesis parameters, chlorophyll content and fluorescence of safflower cultivars under saline condition. Electronic Journal of Crop Production 6, 35-56 (in Persian with English abstract).

Kalaji H, Rastogi A, Živčák M, Brestic M, Daszkowska-Golec A, Sitko K. 2018. Prompt chlorophyll fluorescence as a tool for crop phenotyping: an example of barley landraces exposed to various abiotic stress factors. Photosynthetica 56, 953–961. doi: 10.1007/s11099-018-0766-z

Kalaji M.H, Goltsev V.N, Zuk-Golaszewska K, Zivcak M, Brestic M. 2017. Chlorophyll fluorescence: understanding crop performance basics and applications. Boca Raton, CRC Press.

Kamenetsky R, Okubo H. 2012. Ornamental geophytes: from basic science to sustainable production. CRC Press 598.

Killebrew K, Wolff H. 2014. Environmental impacts of agricultural technologies. Evans School of Public Affairs University of Washington. http://econ.washington.edu/files/2014/06/2010

Kratsch H.A, Graves W.R, Gladon R.J. 2006. Aeroponic system for control of root-zone atmosphere. Environmental and Experimental Botany 55, 70–76.

Lakhiar I.A, Gao J, Naz Syed T, Chandio F.A, Buttar N.A. 2018. Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. Plant Interactions 13, 338-352 DOI: 10.1080/17429145.1472308

Lakhiar I.A, Gao, J, Xu X, Syed T.N, Chandio F.A, Jing Z, Buttar N.A. 2019. Effects of various aeroponic atomizers (droplet sizes) on the growth, total polyphenol content and antioxidant activity of leafy lettuce (*Lactuca sativa* L.). Transactions of the ASABE 62, 1475–1487.

Lakhiar I.A, Liu X, Wang G, Gao J. 2018a. Experimental study of ultrasonic atomizer effects on values of EC and pH of nutrient solution. International Journal of Agricultural and Biological Engineering 11, 59-64.

Lakhiar I.A, Gao J, Naz Syed T, Chandio F.A, Buttar N.A. 2018b. Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. Plant Interactions, 13, 338-352 DOI: 10.1080/17429145.1472308

Lakkireddy K.K, Kasturi R, Sambasiva K, Rao K.R.S. 2012. Role of hydroponics and aeroponics in soilless culture in commercial food production. Research and Reviews: Agricultural Science and Technology 1, 26-35.

Li Q, Li X, Tang B, Gu M. 2018. Growth responses and root characteristics of lettuce grown in aeroponics, hydroponics, and substrate culture. Horticulturae 4, 35. doi:10.3390/horticulturae4040035 www.mdpi.com/journal/horticulturae

Li T, Zhang Y.Q, Zhang Y, Cheng R.F, Yang Q.C. 2016. Light distribution in Chinese solar greenhouse and its effect on plant growth. International Journal of Horticultural Science and Technology 3, 99-111.

Li W, Wang Y, Wei H, Zhang Y, Guo Z, Qiu Y, Wen L, Xie Z. 2020. Structural characterization of Lanzhou lily (*Lilium davidii* var. unicolor) polysaccharides and determination of their associated antioxidant activity. Science of Food and Agriculture 15, 5603-5616.

Li Y, Shi R, Jiang H, Wu L, Zhang Y, Song S, Su W, Liu H. 2020. End-of-day LED lightings influence the leaf color, growth and phytochemicals in two cultivars of lettuce. Agronomy 10, 1475.

Likert R. 1932. A technique for the measurement of attitudes. Archives of Psychology, 140.

Liu J, Zhang Y. 2013. An automatic aeroponics growth system for bamboo seedling and root. Applied Mechanics and Materials 307, 97-102.

Mamnoei E, Seyed Sharifi R. 2010. Study the effects of water deficit on chlorophyll fluorescence indices and the amount of proline in six barley genotypes and its relation with canopy temperature and yield. Iranian

Journal of Plant Biology 5, 51-62. (in Persian with English abstract).

Margaret C. 2012. Potential of aeroponics system in the production of quality potato (*Solanum tuberosum* L.) seed in developing countries. African Journal of Biotechnology 11, 3993–3999.

Marschner H. 2012. Mineral Nutrition of Higher Plants (3rd edition). Academic Press. Elsevier Ltd.

Moosavi-Nezhad M, Salehi R, Aliniaeifard S, Tsaniklidis G, Woltering EJ, Fanourakis D.Z, uk-Gołaszewska K, Kalaji H.M. 2021. Blue light improves photosynthetic performance during healing and acclimatization of grafted watermelon seedlings. Molecular Sciences 22, 8043, 1-24. https://doi.org/10.3390/ijms22158043.

Moradi S, Kafi M, Aliniaeifard S, Salami S.A, Shokrpour M, Pedersen C, Moosavi-Nezhad M, Wróbel J, Kalaji H.M. 2021. Blue light improves photosynthetic performance and biomass partitioning toward harvestable organs in saffron (*Crocus sativus* L.). Cells 10, 1994, 1-23. https://doi.org/10.3390/cells10081994.

Morris E.C, Griffiths M, Golebiowska A. 2017. Shaping 3D root architecture. Current Biology 27, 919–930.

Naddeo N, Cesaro A, Mantezavinos A, Fatta-kassinos D.D, Bekgirono V. 2014. Water and wastewater disinfection by ultrasound irradiation––a critical review. Global Nest 16, 561-577.

Niam A.G, Sucahyo L. 2020. Ultrasonic atomizer application for low cost aeroponic chambers (LCAC): a review. IOP Conference. Series: Earth and Environmental Science 542, 012034, 1-8. DOI 10.1088/1755-1315/542/1/012034

Nithin J.T, Lokesh M, Balasubramanian N, Anand T.N.C. 2019. Atomization characteristics of a compact disc-type ultrasonic atomizer unit ILASS–Europe. 29th Conference. Institute for Liquid Atomization and Spray Systems 2-4.

Olechowicz J, Chomontowski C, Olechowicz P, Pietkiewicz S, Jajoo A, Kalaji M. 2018. Impact of intraspecific competition on photosynthetic apparatus efficiency in potato (*Solanum tuberosum*) plants. Photosynthetica 56, 971–975. DOI: 10.1007/s11099-017-0728-x

Ommen O.E, Donnelly A. 1999. Chlorophyll content of spring wheat flag leaves grown under elevated CO2 concentrations and other environmental stresses within the 'ESPACE-wheat' project. European Journal of Agronomy 10, 197-203.

Paknejad F, Nasri M, Tohidi Moghadam H.R, Zahedi H, Jami Alahmad M. 2007. Effects of drought stress on chlorophyll fluorescence parameters, chlorophyll content and grain yield of wheat cultivars. Journal of Biological Sciences 7, 841-847.

Prasad A, Kumar A, Suzuki M, Kikuchi H, Sugai T, Kobayashi M. 2015. Detection of hydrogen peroxide in photosystem II (PSII) using catalytic amperometric biosensor. Frontiers in Plant Science 6, 862, 1-10. DOI: 10.3389/ fpls.2015.00862

Roden J.S, Egerton J.J.G, Ball M.C. 1999. Effect of elevated [CO2] on photosynthesis and growth of snow gum (*Eucalyptus pauciflora*) seedlings during winter and spring. Functional Plant Biology 26, 37–46.

Rohá˘cek K. 2002. Chlorophyll fluorescence parameters: the definitions, photosynthetic meaning, and mutual relationships. Photosynthetica 40, 13–29.

Salachas G, Savvas D, Argyropoulou K, Tarantillis P, Kapotis G. 2015. Yield and nutritional quality of aeroponically cultivated basil as affected by the available root-zone volume. Emirates Journal of Food and Agriculture 27, 911–918.

Seif M, Aliniaeifard S, Arab M, Mehrjerdi M.Z, Shomali A, Fanourakis D, Li T, Woltering E. 2021. Monochromatic red light during plant growth decreases the size and improves the functionality of stomata in chrysanthemum. Functional Plant Biology 48, 515–528.

Shahzad Z, Amtmann A. 2017. Food for thought: how nutrients regulate root system architecture. Current Opinion in Plant Biology 39, 80–87.

Shomali A, Aliniaeifard S, Didaran F, Lotfi M, Mohammadian M, Seif M, Strobel W.R, Sierka E, Kalaji H.M. 2021. Synergistic effects of melatonin and gamma-aminobutyric acid on protection of photosynthesis system in response to multiple abiotic stressors. Cells 10, 1631.

Siddique Z, Jan S, Imadi S.R, Gul A, Ahmad P. 2016. Drought stress and photosynthesis in plants in water stress and crop plants: a sustainable approach. (1st edition). Pakistan. Parvaiz Ahmad 1–11. DOI: 10.1002/9781119054450.ch1

Stoner R.J, Clawson J.M. 1998. A high performance, gravity insensitive, enclosed aeroponic system for food production in space. Principal Investigator, NASA SBIR NAS10-98030.

Sumarni E, Suhardiyanto H, Seminar K.B, Saptomo S.K. 2013. Temperature distribution in aeroponics system with root zone cooling for the production of potato seed in tropical lowland. International Journal of Scientific and Engineering Research 4, 799–804.

Tennant D. 1975. A test of a modified line intersect method of estimating root length. The Journal of Ecology 63, 995-1001.

Tunio M.H, Gao J, Lakhiar LA, Solangi K.A, Qureshi W.A, Shaikh S.A. 2021. Influence of atomization nozzles and spraying intervals on growth, biomass yield, and nutrient uptake of butter-head lettuce under aeroponics system. Agronomy 11, 97, 1-17. https://doi.org/10.3390/agronomy11010097

Vissenberg K, Claeij N, Balcerowicz D, Schoenaers S. 2020. Hormonal regulation of root hair growth and responses to the environment in Arabidopsis. Journal of Experimental Botany 71, 2412–2427. DOI:10.1093/jxb/eraa048

Walls M. 2014. Agriculture and Environment. M.T.T Agrifood Research Finland.

http://ec.europa.eu/research/agriculture/scar/pdf/scar_foresight_environment_en.pdf

Yang Z, Tao R, Ni H, Zhong K, Lian Z. 2019. Performance study of the internally-cooled ultrasonic atomization liquid desiccant dehumidification system. Energy 175, 745–757.

Zlatev Z.S, Yordanov I.T. 2004. Effects of soil drought on photosynthesis and chlorophyll fluorescence in bean plants. Bulgarian Journal of Plant Physiology 30, 3-18.