JSAT
Journal of Science and Agricultural Technology
Research Article
https://doi.org/10.14456/jsat.2022.9
e-ISSN 2730-1532, ISSN 2730-1524

Effects of electrical conductivity and micro/nanobubbles in nutrient solutions of hydroponics on growth and yield of cherry tomato

Suchada Thichuto[1], Parinyawadee Sritontip[2], Vishnu Thonglek[3] and Chiti Sritontip[1,2*]

[1] Faculty of Science and Agricultural Technology, Rajamangala University of Technology Lanna, Lampang Campus, 52000 Thailand
[2] Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, Lampang, 52000 Thailand
[3] Faculty of Engineering, Rajamangala University of Technology Lanna, Main Campus, Chiang Mai 50300 Thailand

***Corresponding author**: *chiti@rmutl.ac.th*

Received: December 26, 2021. Revised: October 18, 2022. Accepted: November 8, 2022.

ABSTRACT

The objective of this study was to investigate the effects of electrical conductivity and micro/nanobubbles (MNBs) in nutrient solution culture under a hydroponic system on growth and yield of cherry tomatoes. The experiment was assigned using a 3x2 factorial arrangement in a completely randomized design. Factors were factor A, with three levels of electrical conductivity (EC) at 1, 2, and 3 mS/cm in the nutrient solution of the hydroponic system, and factor B, with two levels MNBs, including with or without the application of MNBs, respectively. The cherry tomato seedling was grown in a deep-flow technique (DFT) hydroponic system. The experiment was conducted in a greenhouse environment from July to October 2021 at the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, Lampang, Thailand. The results showed that the EC levels and MNBs did not increase plant height, inflorescence, leaf number per shoot, and leaf size. However, increasing EC from 1 to 2 mS/cm enhanced leaf greenness and chlorophyll fluorescence. On the other hand, the EC at 2 mS/cm with MNBs was the most effective, in particular on fruit size, fruit weight, and yield. Additionally, EC at 3 mS/cm with MNBs improved the total soluble solids of cherry tomato fruits. Results from this experiment suggest that levels of electrical conductivity and micro/nanobubbles have the potential to enhance growth, yields, and fruit quality of cherry tomatoes.

Keywords: tomato, electrical conductivity, micro/nanobubbles

INTRODUCTION

Tomato is a vegetable that is important to the economy of the world and Thailand. In 2020, Thailand had 37,420 rai of tomato harvested area with a total yield of 132,650 tons (OAE, 2020). Tomato is also important to health due to consumers are paying more attention to health concerns. The cherry tomato (*Lycopersicon esculentum* var. cerasiforme) is small-fruited; when fruits are ripe, the fruit color turns red, yellow, or orange according to the species. Ripen fruits are preferably eaten fresh, with firm flesh, sweet and sour tastes (Thepnarong, 2013). Tomato ripens fruits are a good source of carotenoids, naturally occurring pigments commonly found in plants (Ketsakul, 2015). In addition, lycopene is an important compound in the carotene family, found predominantly in red tomatoes (Stahl and Sies, 1996). The demand for healthy tomato markets has increased for consumers. However, the tomato production side still faces technical problems, especially under conventional field conditions. For example, climate changes or high temperatures during the rainy season can cause lower fruit set and fruiting. Moreover, high moisture in the soil and air humidity are suitable for promoting some root diseases and severe outbreaks resulting in low tomato production and insufficient yield to be sold in the market.

The hydroponic system is a plant cultivation technique using only water with nutrient solutions or non-soil materials. This technique is an efficient system that can produce safe and stable yields; it is able to produce vegetables even during the period when planting condition in regular soil is quite difficult (Sritontip et al., 2017). In general, plant growth depends on several factors, one of which is plant nutrients. Moreover, the nutrient solution is the most important factor for plant growth, development, yield, and quality. The electrical conductivity (EC) in the nutrient solution concentration is an index of salt concentration that defines the total amount of salts in a nutrient solution. EC level in the nutrient solution is a good indicator of the number of available ions to the corp in the root zone that the higher and lower EC may severely affect plant growth, development, and yield (Trejo-Téllez and Gómez-Merino, 2012; Nemali and van Iersel, 2004) Nantakit (1995) reported that EC values were relatively influential in the growth and yield of plants, and appropriate EC values are required for individual plant needs. Crop yields will be decreased if the EC value is too low or too high.

Micro/nanobubbles (MNBs) technology has been developed in Japan with wide applications for agriculture and fishery due to their tendency to decrease in size; subsequently, collapse under water, and generate free hydroxyl radicals resulting in a significant increase in ion concentration that stable in water for a long period of time (Takahachi et al, 2007; Marui, 2013). The application of MNBs can be employed for a variety of purposes such as wastewater quality improvement, disinfection, stimulating seed germination, promoting the physiological activities of other organisms, etc. (Oshita and Liu, 2013). Phaengkieo et al. (2019) reported that MNBs with a hydroponics system promoted plant growth, canopy width, and root length and reduced planting time by about a week in lettuce. Ebina et al. (2013) experimented to compare the growth of lettuce grown in a hydroponic solution with or without using MNBs. Their data indicated that MNBs stimulated plant height, leaf length, and fresh weight. However, data is limited in referring to the effect of EC levels and MNBs on the cherry tomato. Therefore, this research aimed to evaluate the effect of EC levels and MNBs on the growth, yield, and leaf nutrient contents of cherry tomato under a hydroponic system.

MATERIALS AND METHODS

This study was carried out in a greenhouse environment from July to October 2021 at the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, Lampang province, Thailand. The experiment was assigned using a 3x2 factorial arrangement in a completely randomized design. Factors were factor A, with three levels of electrical conductivity (EC) at 1, 2, and 3 mS/cm in the nutrient solution of the hydroponic system, and factor B, with two levels MNBs, including with or without the application of MNBs, respectively. There were 10 replications of each method with one plant each. Cherry tomato seeds were germinated in 104-cell nursery seedling trays. When seedlings were 28 days of age, they were transplanted into a hydroponics system. All seedlings were grown in deep-flow technique (DFT) hydroponic. The U-shaped PVC containers were sized 34 cm in width, 3 m in length, and 12 cm in height (5 cm nutrient solution level height) and 100 liters for nutrient solution containers (Figure 1). The nutrient solution formula modified from Huett (2003) and Sritontip et al. (2017), the 1 liter of stock solution fertilizers consisted of stock fertilizers A and B. The stock fertilizer A contained 128 g $Ca(No_3)_2{\bullet}4H_2O$ and 56 g Fe-EDTA and the stock B fertilizer contained 8.7 g $NH_4{\bullet}H_2PO_4$, 13.60 g KH_2PO_4, 133 g KNO_3, 51.80 g $MgSO_4$, 0.30 g $MnSO_4$, 0.20 g $ZnSO_4$, 0.035 g $CuSO_4$, 0.55 g HBO_3, and 0.0175 g $(NH_4)_2MoO_4$ and nutrient solution pH was adjusted to be 6.5 by addition of sulfuric acid (H_2SO_4). Then, stock nutrient solutions A and B were diluted in 100 liters of water and mixed to obtain designated levels of electrical conductivity in a nutrient solution container every week. For the application of MNBs, the MNBs generator model KVM-25 (developed by the Faculty of Engineering, RMUTL, Thailand) was used and applied for 10 minutes at 10.00 A.M. every two days. This could support a water flow rate of 25 L/min, an airflow rate of 2 L/min, an operating pressure of 0.25-0.4 MPa, and a 0.75KW pump; having air nanobubbles, the total bubble distribution was 2.3141E+11/ml, median size 87 nm, mode size 209 nm and average size 199 nm that measured by Horiba-960A laser scattering particle size distribution analyzer® (Figure 2). The EC was controlled with an EC meter model EC 59 (Martini Instrument, Romania).

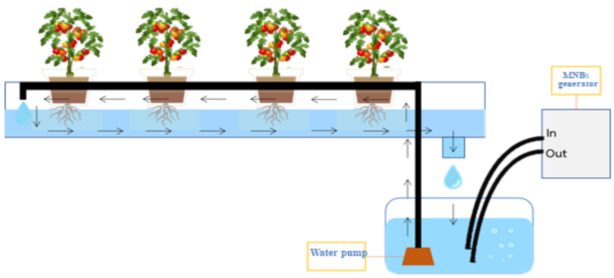

Figure 1. Hydroponic system model for growing the cherry tomato.

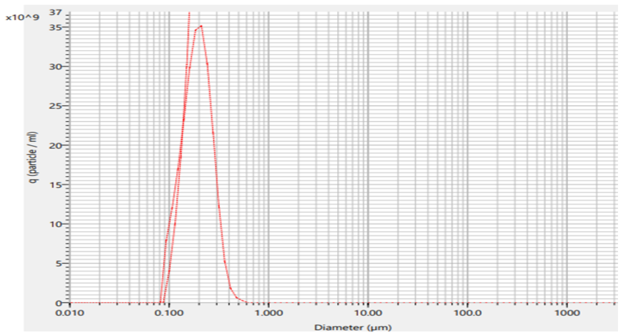

Figure 2. Diameter of micro/nanobubbles produced by KVM-25 detected by Horiba-960A.

The physiological character attributes of cherry tomatoes in a hydroponic system were measured, including stem height, inflorescence growth, leaf greenness, leaf chlorophyll fluorescence, yield, and fruit quality. Stem height (cm) was measured every week. The growth rates were calculated according to the formula of Shabana et al. (1981) as follows:

$$\text{Growth rate} = \frac{(X_1 - X_0) \times 100}{X_0}$$

where: X_0 = the first measurement, X_1 = the next measurement.

For inflorescence growth, plants were measured in the length of inflorescence (cm), the diameter of inflorescence (mm), the number of leaves per inflorescence, leaf width (cm), and leaf length (cm). Changes in the greenness of the leaves were detected using the Konica Minolta model SPAD-502 plus® at 14, 21, and 49 days after transplant. Changes in the chlorophyll fluorescence of tomato leaves were measured by using Handy PEA^{+}® (Hansatech instruments, England) at 14, 21, and 49 days after transplant. Yield and fruit quality were recorded, including fruit width (mm), fruit length (mm), fruit weight (g), and yield weight per plant (g). Total soluble solids (TSS) were measured by extracting juice from cherry tomato fruit, dropped on a hand refractometer, and then reading the number of dissolved solids in degrees Brix (°Brix). The mature fully leaves at the 3rd leaf position of the floral shoot during the fruiting stage were collected to analyze for nutrient concentrations. The leaf samples were washed and dried at 70 ◦C for 48 hours and milled. The nitrogen (N) was determined using a micro-Kjeldahl digestion solution. The digested solution was diluted prior to colorimetric analysis using the indophenol reaction (Novozamsky et al., 1974). Phosphorus (P) was determined by dry digestion followed by the vanadomolybdate method (Walinga, 1995). The potassium (K), Calcium (Ca), and magnesium (Mg) were analyzed by dry digestion and atomic absorption spectroscopy (PinAAcle 900T, Atomic absorption spectrophotometer, PerkinElmer, Massachusetts, United States) (Kalra, 1998; Walinga, 1995).

Data were analyzed using the two-way Analysis of Variance. Mean comparisons were compared using Duncan's new multiple range tests, and significance was set at P-value less than 0.05.

RESULTS AND DISCUSSION

Stem height

The result showed that the EC factor (Figure 3a) did not affect tomato plant height between 14 to 21 and 42 to 49 days after transplanting (P>0.05). However, the EC of 3 mS/cm had shown the highest stem height of growth rate at 35 days after transplanting. Factor B (Figure 3b) found that there was no statistical difference between with or without MNBs between 14 to 49 days after transplanting (P>0.05). There was no interaction detected (P>0.05) between the two factors (Figure 3c). EC values tended to have a linear relation to the plant growth rates and imply plant needs in response to appropriate EC values. Crop yields will fluctuate if the EC value is inappropriate (Nantakit, 1995). The decrease of EC in nutrient solution reduces the plant height and diameter of the stem in tomatoes (Lu et al., 2022).

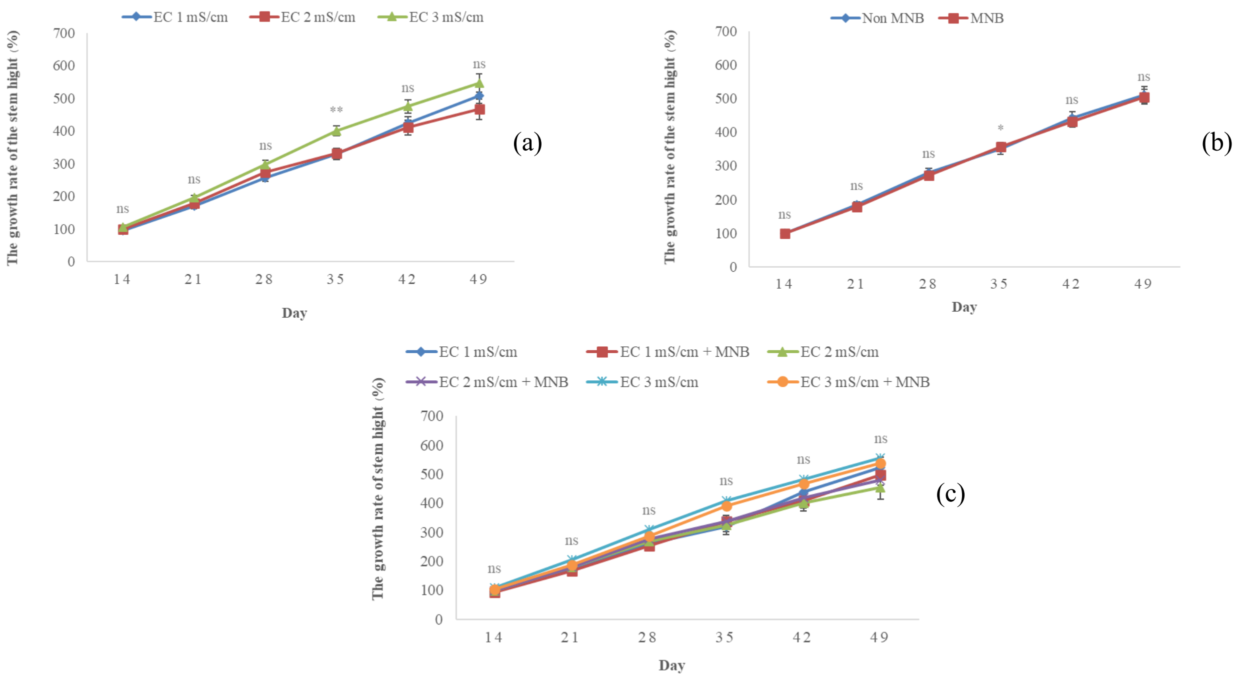

Figure 3. Stem height of cherry tomato from 14 to 49 days after transplanting under different EC levels (a), with or without MNBs (b), and interaction between EC and MNBs (c).

Inflorescence growth

Effects of EC and MNBs on the growth of the inflorescence, leaf number, and leaf size are shown in Table 1. In the flowering stage, the results indicated that EC and MNBs did not affect inflorescence length, inflorescence diameter, leaf number, and leaf width, except with MNBs showed higher leaf length than non-MNBs (P<0.05). However, there was no interaction between EC and MNBs factors or treatment combinations. This study suggested that EC levels and MNBs application did not affect inflorescence size and leaf number, and width of cherry tomatoes.

Table 1. Effect of EC and MNBs on the growth of the inflorescence, leaf number, and leaf size.

Items	Inflorescence length (cm)	Inflorescence diameter (mm)	Leaf number (leaves)	Leaf width (cm)	Leaf length (cm)
Factor A					
EC 1 mS/cm	153.85	8.13	16.95	3.55	7.65
EC 2 mS/cm	165.30	8.24	18.25	3.81	8.25
EC 3 mS/cm	164.65	8.24	15.60	3.64	7.84
F-test	ns	ns	ns	ns	ns
Factor B					
Non MNBs	156.67	8.12	17.33	3.61	7.59[b]
MNBs	165.87	8.29	16.53	3.72	8.23[a]
F-test	ns	ns	ns	ns	*
Interaction between factor A and factor B					
EC 1 mS/cm+ non- MNBs	149.90	8.11	17.80	3.61	7.22
EC 1 mS/cm + MNBs	157.80	8.15	16.10	3.49	8.07
EC 2 mS/cm+ non – MNBs	160.00	8.04	17.40	3.64	7.97
EC 2 mS/cm + MNBs	170.60	8.43	19.10	3.98	8.52
EC 3 mS/cm+ non – MNBs	160.10	8.20	16.80	3.58	7.57
EC 3 mS/cm + MNBs	169.20	8.28	14.40	3.70	8.11
F-test	ns	ns	ns	ns	ns
C.V. (%)	20.55	7.76	22.93	10.98	12.77

The values with the same letter within a column are statistically non-significant by Duncan's test at P > 0.05. The asterisk indicates significantly different means (*for ≤ 0.05, **for ≤ 0.01), otherwise not significant (ns).

Leaf greenness and chlorophyll fluorescence

Effects of EC and MNBs on leaf green color and chlorophyll fluorescence in different growth stages are presented in Table 2. During the vegetative stage, the interaction between EC and MNBs was observed in leaf green color and chlorophyll fluorescence (P<0.05). However, the interaction between EC and MNBs was observed only in the leaf green color (P<0.05), but not chlorophyll fluorescence (P>0.05). In the fruiting stage, no interaction was observed for leaf green color and chlorophyll fluorescence (P>0.05). In the vegetative stage, treatment combinations of EC at 2 to 3 mS/cm plus with or without MNBs showed the highest leaf green colors (P<0.05), while chlorophyll fluorescence was also affected by both EC and MNBs (P<0.05); ranged from 0.725 to 0.765 Fv/Fm (P<0.05). In the flowering stage, leaf green colors were the highest for treatment combinations of EC at 3 mS/cm plus with or without MNBs (P<0.05), but not chlorophyll fluorescence (P>0.05). In the fruiting stage, only EC at 2 to 3 mS/cm had significant effects on the leaf green color (P<0.05). No effects of MNBs were observed for chlorophyll fluorescence in the flowering stage, leaf green color, and chlorophyll fluorescence in the fruiting stage (P>0.05). Li and Stanghellini (2001) found that tomato trees received appropriate EC is beneficial for leaf chlorophyll content. However, the lower EC in the nutrient solution resulted in a decrease in the net photosynthetic rates and chlorophyll content of tomatoes (Lu et al., 2022).

Table 2. Effects of EC and MNBs on leaf green color (LGC) and chlorophyll fluorescence (CF).

Items	Vegetative stage		Flowering stage		Fruiting stage	
	LGC (SPAD)	CF (Fv/Fm)	LGC (SPAD)	CF (Fv/Fm)	LGC (SPAD)	CF (Fv/Fm)
Factor A						
EC 1 mS/cm	53.11^{b}	0.735^{b}	59.58^{b}	0.783^{b}	58.13^{b}	0.808
EC 2 mS/cm	59.95^{a}	0.747^{b}	61.22^{b}	0.806^{a}	61.17^{ab}	0.809
EC 3 mS/cm	60.91^{a}	0.770^{a}	67.19^{a}	0.800^{a}	63.22^{a}	0.811
F-test	**	**	**	*	**	ns
Factor B						
Non MNBs	57.68	0.746	62.36	0.796	61.02	0.809
MNBs	58.30	0.756	62.96	0.797	60.66	0.809
F-test	ns	ns	ns	ns	ns	ns
Interaction between factor A and factor B						
EC 1 mS/cm+ non - MNBs	53.26^{b}	0.725^{b}	59.71^{b}	0.784	58.39	0.808
EC 1 mS/cm + MNBs	52.96^{b}	0.745^{ab}	59.44^{b}	0.782	57.87	0.808
EC 2 mS/cm+ non - MNBs	58.83^{a}	0.746^{ab}	61.30^{b}	0.804	60.94	0.809
EC 2 mS/cm + MNBs	61.06^{a}	0.747^{ab}	61.14^{b}	0.808	61.39	0.808
EC 3 mS/cm+ non - MNBs	60.94^{a}	0.765^{a}	66.07^{a}	0.800	63.72	0.810
EC 3 mS/cm + MNBs	60.88^{a}	0.774^{a}	68.30^{a}	0.800	62.71	0.812
F-test	**	*	**	ns	ns	ns
C.V. (%)	7.25	4.21	7.25	3.10	8.78	1.05

LGC = leaf green color. CF = chlorophyll fluorescence. The values with the same letter within a column are statistically non-significant by Duncan's test at P > 0.05. The asterisk indicates significantly different means (*for ≤ 0.05, **for ≤ 0.01), otherwise not significant (ns).

Yield and fruit quality

The effects of EC levels and MNBs on yield and fruit quality are shown in Table 3. There were interactions between the two factors in all parameters of yield and fruit quality (P<0.05). The combination indicated that using EC at 1 to 2 mS/cm + MNBs tended to have higher means for fruit width, fruit length, and fruit weight (P<0.01) while EC 1 mS/cm without MNBs was the lowest (P<0.01). Using EC at 1 mS/cm + MNBs, and EC 2 to 3 mS/cm with or without MNBs tended to produce higher yields per plant of the cherry potato (P<0.05) while EC at 3 mS/cm with or without MNBs tended to obtain more amount of total soluble solids (P<0.01). Akrawong (2011) reported that the use of EC at 2.4 mS/cm in the pre-flowering stage and then increased to 3.6 mS/cm after the flowering stage increased fresh weight and plant dry weight of fresh edible tomato cultivar CLN 3125 after growing for 94 days. However, using EC at 1.2 mS/cm in the pre-flowering stage and increased to 2.4 mS/cm after the flowering stage resulted in higher fruit weight and total soluble solids. Tsutsumi et al. (2020) reported that aeration of the nutrient solution had been tried to enhance the growth of leafy vegetables such as lettuce, rape, and spinach in hydroponic cultivation. Ebina et al. (2013) found that the application of MNBs in lettuce grown in hydroponic systems increased vegetative growth when compared to no use of micro-nanobubbles. The application of MNBs can improve plant growth, yield, and fruit quality due to dissolved oxygen (DO) in nutrient solution increased when compared non-MNBs (Zhou, et al., 2019). Nevertheless, using EC at 3 mS/cm with and without MNBs did not affect yield and fruit quality except for total soluble solids because the higher nutrient concentration may cause irregular ion absorption of a root system. These results agree with Park et al. (2010) who reported that lower EC at 0.5 and 1.0 mS/cm produced higher leaf weight than those EC at 2 mS/cm, but in lettuce, while Zhou et al. (2019) reported that MNBs water oxygenation is an effective way to increase both yield and quality of tomatoes.

Table 3. Effect of EC levels and MNBs on yield and fruit quality.

Items	Fruit width (mm)	Fruit length (mm)	Fruit weight (g)	Yield per plant (g)	Total soluble solids (°Brix)
Factor A					
EC 1 mS/cm	22.03^{b}	34.32^{b}	9.23^{b}	2,357.85^{b}	5.21^{c}
EC 2 mS/cm	22.94^{a}	35.40^{a}	10.18^{a}	2,599.62^{a}	5.37^{b}
EC 3 mS/cm	22.01^{b}	33.97^{b}	8.98^{b}	2,526.25^{a}	5.62^{a}
F-test	**	**	**	**	**
Factor B					
Non-MNB	22.01^{b}	33.89^{b}	9.02^{b}	2,426.17^{b}	5.34^{b}
MNB	22.64^{a}	35.24^{a}	9.91^{a}	2,562.97^{a}	5.45^{a}
F-test	**	**	**	*	*
Interaction between factor A and factor B					
EC 1 mS/cm+ non - MNBs	21.52^{c}	33.14^{d}	8.52^{c}	2,262.54^{b}	5.14^{d}
EC 1 mS/cm + MNBs	22.54^{ab}	35.51^{ab}	9.94^{ab}	2,453.17^{ab}	5.27^{c}
EC 2 mS/cm+ non - MNBs	22.60^{ab}	34.56^{bc}	9.66^{ab}	2,499.49^{ab}	5.31^{c}
EC 2 mS/cm + MNBs	23.28^{a}	36.24^{a}	10.70^{a}	2,699.74^{a}	5.43^{bc}
EC 3 mS/cm+ non - MNBs	21.91^{bc}	33.97^{cd}	8.87^{bc}	2,516.49^{a}	5.58^{ab}
EC 3 mS/cm + MNBs	22.10^{bc}	33.97^{cd}	9.09^{bc}	2,536.00^{a}	5.65^{a}
F-test	**	**	**	*	**
C.V. (%)	3.87	4.06	12.10	10.36	4.91

The values with the same letter within a column are statistically non-significant by Duncan's test at P > 0.05.
The asterisk indicates significantly different means (*for ≤ 0.05, **for ≤ 0.01), otherwise not significant (ns).

Leaf nutrient concentration

There were interactions between EC and MNBs on concentrations of N, P, K, and Ca, except Mg in leaves (Table 4). The increase of EC at 3 mS/cm and with MNBs had significantly increased N, P, K, and Ca in leaves (P<0.05). However, EC 1 mS/cm+ non – MNBs was the lowest in N concentration (P<0.05). The experiment in the "Rinka409" tomato that was grown hydroponically showed that a high EC nutrient solution treatment led to an increase in the nutrient content in leaves (Suzuki et al., 2015). Maboko et al. (2017) reported that high EC in the cucumber experiment could enhance plant growth, leaf chlorophyll content, dry matter, and the increase in nutrient uptake of N, P, and K concentration in leaves. Data indicated that stimulation using MNBs in nutrient solution improved N, K, and Ca contents in tomato leaves because MNBs benefit from enriching dissolved oxygen (DO) in a nutrient solution, and nutrients are transported up by the root system (Park and Kurata, 2009; Park et al., 2010). However, Mg concentration in leaves was unaffected by EC plus MNBs (P>0.05).

Table 4. Effect of EC levels and MNBs on leaf nutrient concentration

Items	N (%)	P (%)	K (%)	Ca (%)	Mg (%)
Factor A					
EC 1 mS/cm	1.53^{c}	0.14^{b}	1.59^{b}	2.07^{b}	1.00^{b}
EC 2 mS/cm	1.85^{b}	0.14^{b}	1.66^{b}	2.29^{b}	1.07^{ab}
EC 3 mS/cm	2.24^{a}	0.16^{a}	1.83^{a}	2.74^{a}	1.11^{a}
F-test	**	*	**	**	*
Factor B					
Non-MNB	1.72^{b}	0.14	1.65^{b}	2.22^{b}	1.04
MNB	2.03^{a}	0.15	1.73^{a}	2.51^{a}	1.08
F-test	**	ns	*	**	ns
Interaction between factor A and factor B					
EC 1 mS/cm+ non – MNBs	1.38^{c}	0.13^{c}	1.58^{c}	1.90^{c}	0.97
EC 1 mS/cm + MNBs	1.69^{b}	0.14^{bc}	1.60^{bc}	2.23^{bc}	1.04
EC 2 mS/cm+ non – MNBs	1.76^{b}	0.13^{c}	1.63^{bc}	2.26^{bc}	1.06
EC 2 mS/cm + MNBs	1.93^{b}	0.14^{bc}	1.68^{bc}	2.32^{b}	1.08
EC 3 mS/cm+ non – MNBs	2.02^{b}	0.16^{ab}	1.73^{b}	2.51^{b}	1.10
EC 3 mS/cm + MNBs	2.46^{a}	0.16^{a}	1.92^{a}	2.97^{a}	1.12
F-test	**	**	**	**	ns
C.V. (%)	18.26	14.13	8.33	16.75	11.15

The values with the same letter within a column are statistically non-significant by Duncan's test at P > 0.05. The asterisk indicates significantly different means (*for ≤ 0.05, **for ≤ 0.01), otherwise not significant (ns).

CONCLUSIONS

The application of EC at 1 to 3 mS/cm did not affect the growth of the inflorescence, leaf number, and leaf size for cherry potatoes, but MNBs increased leaf length. However, the interaction between EC and MNBs occurred for leaf green color and chlorophyll fluorescence in the vegetative stage, leaf green color in the flowering stage, yield, and fruit quality. In the vegetative stage, treatment combinations of EC at 2 to 3 mS/cm plus with or without MNBs showed the highest leaf green colors, while chlorophyll fluorescence was also affected by both EC and MNBs. High EC plus MNBs increased N, P, K, and Ca in tomato leaves. Results from this experiment suggest that levels of electrical conductivity and micro/nanobubbles have the potential to improve some growth parameters, yields, and fruit quality of cherry tomatoes.

ACKNOWLEDGMENT

Thanks to the Center of Academic Excellence in Plasma and Micro/Nano Bubbles Applications for Advanced Agriculture and Fishery, Rajamangala University of Technology Lanna, for technical support, and extend thanks to the Agricultural Technology Research Institute, Rajamangala University of Technology Lanna, for providing convenience in using of various equipment and tools for conducting this research.

REFERENCES

Akrawong, F. 2011. The effect of nutrient solution concentrations on growth, yield and fruit quality of table tomato cv. 'CLN 3125' grown in coconut substrate. B.S. Dissertation. Kasetsart University, Bangkok, Thailand.

Ebina, K., Shi K., Hirao M., Hashimoto J., Kawato Y., Kaneshiro S., Morimoto T., Koizumi K., and Yoshikawa H. 2013. Oxygen and air nanobubble water solution promote the growth of plants, fishes and mice. PLOS ONE. 8(6): 1-7 (e65339). https://doi.org/10.1371/journal.pone.0065339.

Huett, D. O. 1993. Managing nutrient solutions in hydroponics. NSW Agriculture and Horticultural Research & Development Corporation. Wollongbar, New South Wales, Australia.

Kalra, Y.P. 1998. Handbook of reference methods for plant analysis. CRC Press, Boca Raton. Ketsakul, S. 2015. Tomato production technology. Research Project Report. Department of Agriculture, Ministry of Agriculture and Cooperatives, Bangkok. (in Thai)

Li, Y., and Stanghellini, C. 2001. Analysis of the effect of EC and potential transpiration on vegetative growth of tomato. Scientia Horticulturae. 89(1): 9–21. https://doi.org/10.1016/S0304-4238(00)00219-3.

Lu, T., Yu H., Wang T., Zhang T., Shi C. and Jiang W. 2022. Influence of the electrical conductivity of the nutrient solution in different phenological stages on the growth and yield of cherry tomato. Horticulturae. 8(378): 1-14. https://doi.org/10.3390/horticulturae8050378.

Marui, T. 2013. An introduction to micro/nano-bubbles and their applications**.** Systemics, Cybernetics and Informatics. 11(4): 68-73.

Maboko, M.M. Du Plooy, C. P., and Chiloane, S. 2017. Yield and mineral content of hydroponically grown mini-cucumber (*Cucumis sativus* L.) as Affected by reduced nutrient concentration and foliar fertilizer application. HortScience 52(12):1728–1733.

Nantakit, A. 1995. Hydroponics. King Mongkut's Institute of Technology Ladkrabang, Bangkok.

Nemali, K. S., and Van Iersel, M. W. 2004. Light intensity and fertilizer concentration: I. Estimating optimal fertilizer concentration from water-use efficiency of *Wax Begonia*. HortScience. 39(6): 1287-1292.

Novozamsky, I., Van Eck, R., Van Schouwenburg, J.C., and Walinga, I. 1974. Total nitrogen determination in plant material by means of the indophenol blue method. Netherlands Journal of Agricultural Science. 22: 3-5.

OAE. 2020. Agricultural statistics of Thailand 2020. Office of Agricultural Economics, Ministry of Agriculture and Cooperatives, Bangkok.

Oshita, S. and Liu, S. 2013. Nanobubble characteristics and its application to agriculture and foods. In: Proceedings of AFHW 2013, International Symposium on Agri-Foods for Health and Wealth August 5-8, 2013. Golden Tulip Sovereign Hotel, Bangkok, p. 23-32.

Park, J.S., and Kurata., K. 2009. Application of microbubbles to hydroponics solution promotes lettuce growth. Hort. Technology. 19(1): 212-215.

Park, J.S., Ohashi, K., Kurata, K., and Lee, J.W. 2010. Promotion of lettuce growth by application of microbubbles in nutrient solution using different rates of electrical conductivity and under periodic intermittent generation in a deep flow technique culture system. Europ. J. Hort. Sci. 75(5): 198-203.

Phaengkieo, D., Chaoumead, A., Wangngon, B. and Chumnumwat, S. 2019. The application of nanobubble technology for DRFT hydroponics. Journal of Innovative Technology Research. 3(2): 33-41.

Shabana, H.R., Benjamin, N.D. and Mohammed, S. 1981. Pattern of growth and development in date palm plant fruit. Date Plant Journal. 1: 31-42.

Sritontip, C., Changjeraja, C., Khaosumain, Y., Panthachod, S., Sritontip, P. and Lasak, S. 2017. Low-cost soilless cultivation (1st ed). Community Technology Transfer Center,Rajamangala University of Technology Lanna, Chiang Mai.

Stahl, W. and Sies, H. 1996. Lycopene: a biologically important carotenoid for humans. Archives of Biochemistry and Biophysics. 336(1): 1-9. https://doi.org/10.1006/abbi.1996.0525.

Suzuki, M., Umeda, H., Matsuo, S., Kawasakia, Y., Ahn, D., Hamamoto, H., and Iwasakia, Y. 2015. Effects of relative humidity and nutrient supply on growth and nutrient uptake in greenhouse tomato production. Scientia Horticulturae 187: 44-49.

Trejo-Téllez, L.I. and Gómez-Merino, F. C. 2012. Nutrient solutions for hydroponic systems. In: Asao, T. (ed) Hydroponics–A standard methodology for plant biological researches. InTech. Croatia. p. 1-22.

Tsutsumi, H., Higashi R. and Kinugasa, T. 2020. A new technique to realize a drastic acceleration of crop growth in the DFT hydroponic cultivation with hyper-oxygenated nutrient solution. Journal of Horticulture. 7(4): 1-7.

Takahashi, M., Chiba, K. and Li, P. 2007. Free-radical generation from collapsing microbubbles in the absence of a dynamic stimulus. Physical Chemistry B. 111: 1343-1347. https://doi.org/10.1021/jp0669254.

Thepnarong, P. 2013. Effects of temperature and storage life on chilling injury of cherry tomato (*Lycopersicon esculentum* cv. CH154) and the application of calcium for chilling reduction. M.S. Dissertation. Suranaree University of Technology, Nakhon Ratchasima, Thailand.

Walinga, I., van der Lee, J.J., Houba, V.J.G., van Vark, W., and Novozamsky, I. 1995. Plant analysis manual. Springer, Dordrecht.

Zhou Y.P., Zhou B., Xu F., Muhammad T., and Li Y.K., 2019. Appropriate dissolved oxygen concentration and application stage of micro-nano bubble water oxygenation in greenhouse crop plantation. Agricultural Water Management. 223(36): 105713. https://doi.org/10.1016/j.agwat.2019.105713