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Effects of nanobubble in subsurface drip irrigation on the yield, quality, irrigation water use efficiency and nitrogen partial productivity of watermelon and muskmelon**

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A b s t r a c t. Improving crop yield and quality, as well as water and fertilizer use efficiency in a synergetic manner is a substantial challenge. It involves limits to the sustainable development of protected agriculture. Here, we propose a new irrigation method using nanobubble water through subsurface drip irrigation to improve the agricultural performance of crops. Experiments were conducted to evaluate the effects of nanobubble water on growth, yield, quality, irrigation water use efficiency, and the nitrogen partial productivity of greenhouse watermelon and muskmelon. The results showed that in nanobubble water conditions, reducing the amount of irrigation or fertilization by 20% had no negative impacts on the tested crops, instead there were increases in the yield, quality, irrigation water use efficiency and nitrogen partial productivity of the two crops. When irrigation and fertilization were both decreased by 20%, the irrigation water use efficiency was improved by 82.6 and 70.2%, the nitrogen partial productivity increased by 68.9 and 30.4%, vitamin C increased by 50.1 and 66.7% which was significant. This may be because nanobubble water reduced the redundant growth of crops, and promoted the balance between individual development and production. Moreover, nanobubble water finally achieved increased economic benefits by reducing the input of irrigation and fertilization. Therefore, we suggest that 80% irrigation and 80% fertilization with nanobubble water could be adopted for Cucurbitaceae in greenhouse conditions. This method also has reference significance for reducing agricultural water input.

K e y w o r d s: nanobubble water, reduction of water and fertilization, subsurface drip irrigation, irrigation water use efficiency, nitrogen partial productivity

INTRODUCTION

Through the use of human intervention, protected agriculture can improve crop growth conditions and reduce the adverse effects of natural disasters, thereby achieving efficient, intensive, and sustainable modern agricultural production (Lu *et al.*, 2020; Gao *et al.*, 2019). With a continuous improvement in their living standards, people do not just eat to allay their hunger, they also eat to obtain nutrition, to achieve good health and for longevity. Therefore, crop production needs to guarantee an improvement in yield and quality simultaneously (Su *et al.*, 2018). Blindly pursuing high production, while ignoring the negative results from intensive irrigation and fertilization have triggered a series of adverse effects, including the secondary salinization of the soil, nutrient imbalance, and toxicant accumulation. This approach also has no positive effects on

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the quality and yield of crops and on the sustainable development of protected agriculture (Du *et al.,* 2020). Therefore, reducing the consumption of water and fertilizer, and ensuring crop yield and quality in the greenhouse is crucial to the sustainable development of protected agriculture.

Strengthening the management of water and fertilizer are effective in improving crop yield and quality. For example, Wang *et al.* (2022) and Chen *et al.* (2015) found that increasing the level of irrigation improved the sweet pepper and wheat yield by 26.6 and 7.1%, vitamin C (VC) and lycopene of tomato increased first and then decreased with the increase in water and nitrogen levels. Zhang *et al.* (2017) and Rathore *et al.* (2016) noted that increasing nitrogen fertilizer application improved the yield of rice and wheat, but had both crops had 45-48% smaller agronomic indexes. However, the two aforementioned methods increased agricultural input and failed to achieve synergistic improvements in crop yield, water, and fertilizer use efficiency.

Balancing the relationships between water, fertilization, and oxygen in the crop rhizosphere is an efficient strategy for improving crop growth (Cui *et al.,* 2020; Shen *et al.,* 2017). Aerated irrigation is a new irrigation technology, which simultaneously transports water and oxygen to crop root zones through a subsurface drip irrigation system (Zhou *et al.,* 2020; Zhou *et al.,* 2019). Numerous studies have demonstrated that aerated irrigation has positive effects on crops such as muskmelon, tomato, and cucumber, and the yield, VC, and irrigation water use efficiency (IWUE) were also increased.

With oxygenation of irrigation, the yield of muskmelon (Xie *et al.,* 2017), tomato and cucumber (Zhou *et al.,* 2019), increased within the range of 3.4-66.4%. Also, the VC content for tomato, cucumber, and muskmelon increased by 6.6-61.4, 6.7-58.9 and 18.4-42.9% as compared to the control group. In addition, deficit irrigation is a well-recognized water-saving strategy. Deficit irrigation improves the efficiency of water use by modifying the physiological processes of plants, but it does not have a positive effect on growth and crop yield (Khapte *et al.,* 2019). Nevertheless, there are a limited number of reports concerning the technology of nanobubble water combined with lower volumes of irrigation water and fertilization. Indeed, there is a lack of research concerning the cost-effective control of multiple factors.

Traditional aeration methods, such as Venturi tube and air compressor, can easily trigger the chimney effect, leading to low aeration efficiency. Alternatively, nanobubbles are characterized by a high specific area, long persistence time, highly efficient gas solubility, and rapid mass transfer rates (Agarwal *et al.*, 2011; Temesgen *et al.*, 2017), therefore it was used as the aeration method in the study. Experiments were conducted over two seasons on greenhouse watermelon and muskmelon. Specifically, the study aimed to i) reveal the effects of NBW combined with reduced water and fertilizer application on the growth, yield, quality as well as the water and nitrogen use efficiency of watermelon and muskmelon in greenhouses, ii) assess the economic applicability of NBW and explore the potential of NBW to increase the income of farmers.

MATERIALS AND METHODS

The experiments were conducted in a greenhouse at the experimental station of China Agricultural University, Tongzhou, Beijing, China (39°42′7 “N, 116°40′59 “E). The experimental site was characterized by a temperate continental monsoon climate, and the annual average temperature was 11.3°C. The soil was sampled within a depth of 0-30 cm before the experiments, and both the physical and chemical properties of the soil are shown in Table 1. The varieties of watermelon and muskmelon tested were “Jinghang No. 6” and “Yang Jiao Cui”, respectively. The trials were conducted in the spring and autumn, 2019. The spring watermelon and muskmelon were both transplanted on March the 30th and harvested on June the 29th and July the 13th, respectively. The fall crops were transplanted on July the 25th and harvested on October the 2nd and October the 17th, respectively.

The experiments were arranged in a randomized block design and consisted of four treatments, including: (i) nanobubble water irrigation with oxygen(O) + 100% irrigation amount (W_{100}) + 80% topdressing amount (F_{80}), $OW_{100}F_{80}$, (ii) O + 80% irrigation amount (W_{80}) + 100% topdressing amount (F_{100}), $OW_{80}F_{100}$, (iii) O + 80% irrigation amount (W_{80}) + 80% fertilizer amount (F_{80}), $OW_{80}F_{80}$, and (iv) groundwater with no-oxygen(N) + 100% irrigation amount + 100% topdressing amount, $NW_{100}F_{100}$ (Table 2). Four replications were set up for each treatment. The experimental treatments began after transplantation. The irrigation of watermelon was halted 15 days before harvest.

The nanobubble water (NBW) used in the experiment was generated by a nanobubble generator developed by China Agricultural University. The power and flow rate of the machine were 3.7 kW and 3-4 $m^3 h^{-1}$, respectively. The average bubble particle size was 136.2 ± 12.1 nm and the bubble concentration was 6.2e+08 ± 0.5 particles ml^{-1} as

Table 1. Soil physicochemical properties within the depth of 0-30 cm

Soil density (g cm^{-3})	Field capacity (%)	pH	Total (g cm^{-3})			Organic matter (g kg^{-1})	Available (mg kg^{-1})		
			N	P	K		N	P	K
1.77	23.0	7.8	1.26	0.76	22.0	18.1	85.5	41.1	203.0

Table 2. Irrigation and nitrogen fertilizer amount of watermelon and muskmelon in the experiments

Crops	Irrigation amount (m^3 ha^{-1})	Nitrogen fertilizer amount (kg ha^{-1})	Treatments
Watermelon	100% (709.6)	100% (223.5)	$NW_{100}F_{100}$
	80% (584.0)	100% (223.5)	$OW_{80}F_{100}$
	100% (701.3)	80% (178.8)	$OW_{100}F_{80}$
	80% (576.0)	80% (178.8)	$OW_{80}F_{80}$
Muskmelon	100% (608.2)	100% (188.0)	$NW_{100}F_{100}$
	80% (500.6)	100% (188.0)	$OW_{80}F_{100}$
	100% (601.1)	80% (150.4)	$OW_{100}F_{80}$
	80% (493.8)	80% (150.4)	$OW_{80}F_{80}$

measured by a nanoparticle tracking analyser (Nanosight NS300, Malvern, UK) (Zhou *et al.,* 2020). Air was used as a gas source to produce the nanobubbles.

As an experimental variable, the base fertilizers used in each greenhouse were 4.5 10^4 kg ha^{-1} of organic fertilizer (chicken manure, organic matter ≥ 45.0%, and total nutrients ≥ 5.0%), 937.5 kg ha^{-1} of N-P-K (15-15-15) and 480 kg ha^{-1} of diammonium phosphate (P ≥ 46.0%, N ≥ 18.0%), respectively. For the entire growth period, urea nitrogen (N ≥ 46.4%) was applied to watermelon and muskmelon plots under the $NW_{100}F_{100}$ treatment, four times and twice, respectively, in the amount of 178.5 kg ha^{-1} and 102 kg ha^{-1}.

As shown in Fig. 1, each plot had an area of 9.0 m^2 (1.55 × 6.0 m), and the distance between two adjacent plots was 0.6 m. The watermelon or muskmelon were both planted in narrow (0.60 m) and wide (0.95 m) rows, with 0.40 m plant spacing. There were 112 watermelon or muskmelon plants planted in all, 28 per plot. The distance between the adjacent treatments was 1.0 m, and the plastic film is vertically buried at a depth of 0.7 m with a boundary of treatment to prevent the lateral flow of the adjacent treatment. The subsurface drip irrigation (SDI) laterals with a 2.8 L h^{-1} flow rate were buried 10 cm underground and 5 cm to one side of the plants. Each lateral irrigated one row of the crop, and each plot included two laterals. TRIME-TDR (IMKO, Germany) was used to determine the soil moisture rate at a frequency of once every three days. The water content was determined using TRIME before irrigation, it was then calculated from the optimal upper limit of irrigation (Sheet1) of watermelon and muskmelon.

Stem thickness was determined using electronic vernier callipers. Three representative plants were selected from each plot. Growth was measured periodically using the crossover method at the basal stem of the crop from the vine extension stage. After the maturation of the plants, the roots and above-ground parts (excluding fruit) were placed in a blast drying oven and heated at a constant temperature of 105°C for 30 min. The dehydrated material was then further

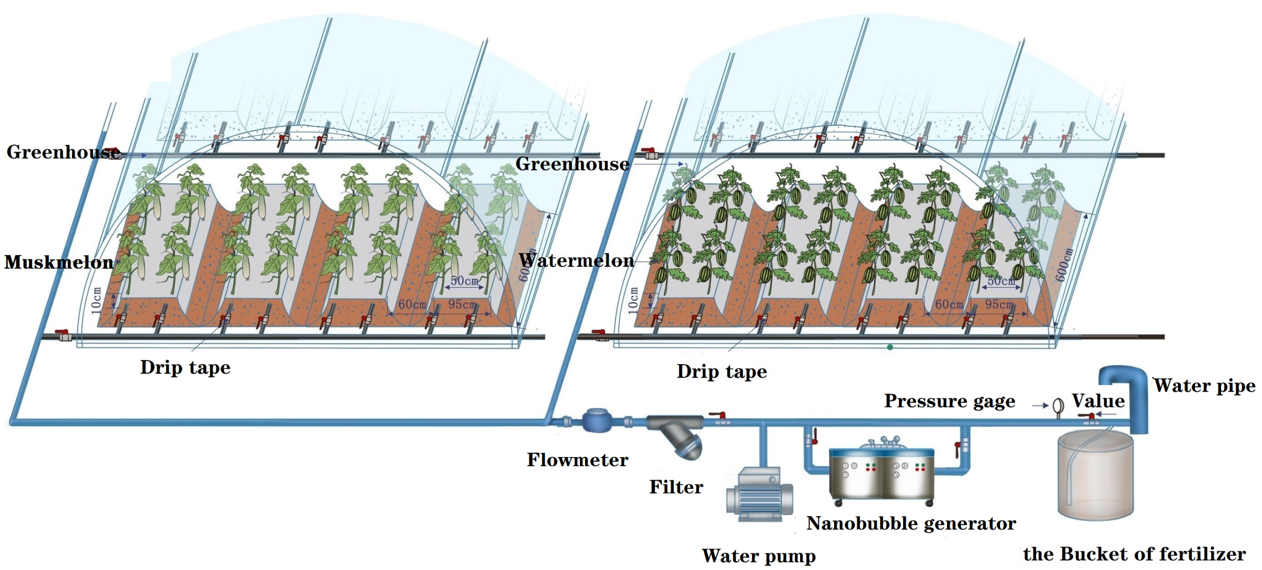

Fig. 1. Diagram of the test system layout and planting patterns.

dried to a constant weight at 75°C and weighed, and the ratio of root dry weight to above-ground dry weight was calculated.

Individual fruit was weighed on an electronic balance with an accuracy of 0.1 g. Each treatment consisted of four monopolies, converting the yield of the monopoly to hectares.

The irrigation water use efficiency (IWUE) is calculated according to Eq. (1):

$$IWUE = \frac{Y}{M}, \quad (1)$$

IWUE denotes the irrigation water use efficiency (kg m^{-3}); *Y* denotes the crop yield (kg ha^{-1}), and *M* denotes the irrigation quota (m^3).

Nitrogen fertilizer biased productivity is calculated according to Eq. (2):

$$PFPN = \frac{Y}{F}; \quad (2)$$

nitrogen partial productivity (*PFPN*) denotes nitrogen fertilizer bias productivity (kg kg^{-1}), *Y* is the yield in the nitrogen application zone (kg), and *F* represents the amount of nitrogen fertilizer input (kg).

The spring and fall watermelons were sampled on June the 29th and October the 2nd, respectively, which was 28 days after the anthesis period. The muskmelons were collected on July the 13th and October the 17th, respectively, which was 30 days after the anthesis period. Three watermelons or muskmelons with a similar size, ripeness and no surface defects were sampled, and the middle 1/3 of the melons were mixed together to obtain a mixture sampling for the purposes of fruit quality measurement. There are 3 mixture samplings for each treatment. Fruit soluble solids were determined using a handheld sugar meter; vitamin C was determined using the 2,6-dichloroindophenol titration, and the level of titratable acids were determined using NaOH titration, as described by Cao *et al.* (2007).

The water cost was calculated according to the unit water price (0.27 dollar m^{-3}) and the corresponding amount of irrigation water.

The electricity cost was \$ 0.12/(kW-h) and the total amount of electricity was calculated using Eq. (3):

$$E_0 = 0.5\ WFD, \quad (3)$$

where: *W* is the rated power of the micro and nanobubble generator *P* = 3.7 kW per 1 min of operation, then *W* = 0.062 kW; *F* denotes the frequency of operation, and *D* denotes the full reproduction period.

The fertilizer cost was estimated based on the amount of substrate and urea input as the accounting indicator, which was \$19.05 t^{-1} for chicken manure and \$ 261.90 t^{-1} for urea. The equipment and fittings costs were referred to as the annual input costs for the annual drip irrigation tape, including the PVC pipes and fittings.

Both the input and output values were converted from Chinese Yuan (¥) to US \$ using the average official exchange rate (1 \$ = 6.3 ¥). All of the yield and income data were converted into hectares by considering the sampling area.

GraphPad Prism 8 was used for data collation and mapping, IBM SPSS Statistics 20.0 was used to obtain the Analysis of variance (ANOVA). The increasing percentage data was the average obtained from the spring and fall. The values in a column (in one growing season) were followed by different letters which differ significantly at p = 0.05 using LSD's test.

RESULTS AND ANALYSIS

The effects of NBW irrigation combined with water and fertilizer reduction on the stem diameter and root-shoot ratio of watermelon and muskmelon are shown in Fig. 2. There was no significant difference ($p > 0.05$) in the stem diameter and root-shoot ratio of watermelon between NBW irrigation treatments combined with the reduced application of irrigation, fertilizer, and also both of them together, as compared with $NW_{100}F_{100}$. $OW_{80}F_{100}$ and $OW_{100}F_{80}$ have no significant effect on the root-shoot of muskmelon, however there was a significant increase in the root-shoot ratio of $OW_{80}F_{80}$. Compared with $NW_{100}F_{100}$, the $OW_{80}F_{100}$, $OW_{100}F_{80}$, and $OW_{80}F_{80}$ treatments increased the root-shoot ratio of muskmelon by 24.3, 93.6, and 81.0%, respectively.

The effects of NBW irrigation combined with reduced irrigation and fertilizer application on watermelon and muskmelon yield, IWUE, and PFPN (Table 3). The results showed that $OW_{80}F_{100}$ and $OW_{100}F_{80}$ had significant effects on watermelon yield, IWUE and PFPN for both crops ($p<0.05$). For watermelon, $OW_{80}F_{100}$ and $OW_{100}F_{80}$ increased the yield, IWUE and PFPN by 38.8 and 45.1, 58.1 and 57.1, 38.8 and 68.9%, respectively. With the simultaneous reduction by 20% of water and fertilizer amounts ($OW_{80}F_{80}$), watermelon yield, IWUE, and PFPN increased by 50.4, 82.6, and 68.9%, respectively. For muskmelon, $OW_{80}F_{100}$ and $OW_{100}F_{80}$ increased the yield, IWUE and PFPN by 7.1 and 51.6, 39.1 and 36.0, 7.1 and 51.6%, respectively. With the simultaneous reduction by 20% of water and fertilizer amounts ($OW_{80}F_{80}$), watermelon yield, IWUE and PFPN increased by 51.4, 70.2 and 30.4%, respectively.

The ANOVA results produced by the effects of NBW combined with reduced irrigation, reduced fertilizer application, and simultaneously reduced water and fertilizer application on the fruit quality of watermelon and muskmelon are shown in Table 4. NBW with SDI technology combined with reduced irrigation or reduced fertilizer application had a highly significant effect ($p < 0.01$) on the accumulation of total soluble solids (TSS) and vitamin C (VC). When compared to the $NW_{100}F_{100}$ treatment, the TSS in the $OW_{80}F_{100}$, $OW_{100}F_{80}$, and $OW_{80}F_{80}$ treatment of watermelon increased by 1.4, 7.7, and 7.8%, respectively, and

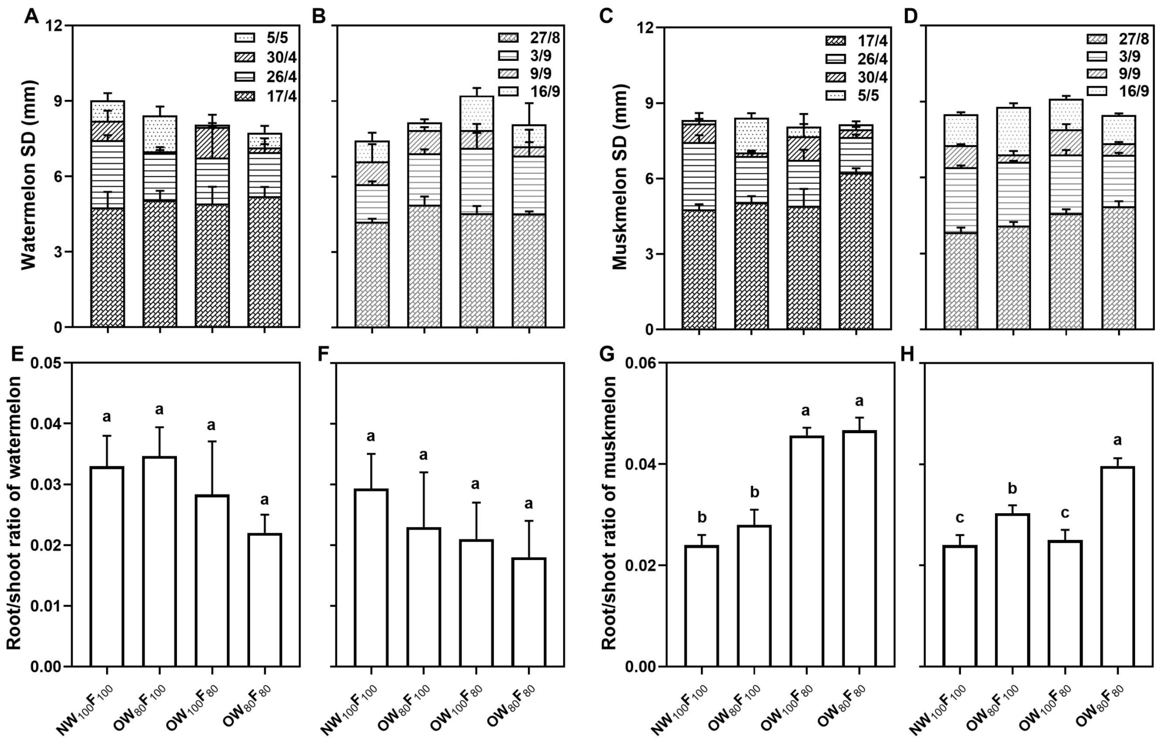

Fig. 2. Effects of nanobubble water drip irrigation on plant stem diameter and root-shoot ratio.

Table 3. Effect of NBW irrigation on yield, IWUE, and PFPN

Crops	Treatments	Spring			Fall		
		PFPN (t t^{-1})	IWUE (kg m^{-3})	Yield (10^3 kg hm^{-2})	PFP_N (t t^{-1})	IWUE (kg m^{-3})	Yield (10^3 kg hm^{-2})
Watermelon	$NW_{100}F_{100}$	136.7±12.4c	11.7±1.0c	30.5±2.8b	125.7±8.0c	11.5±0.7c	28.1±1.8b
	$OW_{80F10}0$	177.5±19.1b	14.0±1.9b	39.7±4.3a	185.7±18.3b	22.5±2.2a	41.5±4.1a
	$OW_{100}F_{80}$	247.2±35.0a	18.4±2.6b	44.2±6.3a	228.8±18.1a	18.0±1.4b	40.9±3.2a
	$OW_{80}F_{80}$	228.4±36.4a	18.5±3.7a	40.8±6.5a	236.0±19.8a	23.7±2.0a	42.2±3.6a
Muskmelon	$NW_{100}F_{100}$	189.6±30.2b	20.8±3.4c	35.6±5.7b	135.6±18.4b	9.1±1.2b	25.5±3.6a
	$OW_{80}F_{100}$	215.7±19.3b	28.2±2.5b	40.6±3.6ab	136.2±20.0b	13.0±1.9a	25.6±3.8a
	$OW_{100}F_{80}$	311.4±59.5a	25.3±4.8bc	46.8±8.9a	188.6±23.7a	13.7±1.7a	28.4±3.6a
	$OW_{80}F_{80}$	318.9±25.2a	37.7±3.0a	48.0±3.8a	196.5±21.7a	14.5±1.6a	29.5±3.7a

Different lowercase letters after the numbers in the table indicate between-group variability.

VC increased by 41.7, 31.5 and 50.1%. When compared to the $NW_{100}F_{100}$ treatment, the TSS in the $OW_{80}F_{100}$, $OW_{100}F_{80}$, and $OW_{80}F_{80}$ treatment of muskmelon increased by 20.9, 30.7, and 9.6%, respectively, and VC increased by 47.5, 33.9, and 80.1%.

The economic applicability of the analysis of NBW drip irrigation combined with water and fertilizer reduction is shown in Table 5. A unit price of \$ 0.27 m^{-3} was adopted, according to the water consumption of watermelon under the $OW_{80}F_{100}$, $OW_{100}F_{80}$, $OW_{80}F_{80}$, and $NW_{100}F_{100}$ treatments, the annual average water cost of these treatments were: 2 735.0, 2 838.3, 2 609.7 and 2 871.8 \$, respectively. In summary, the total cost of each of the four respective treatments of watermelon were: 3 297.5, 3 278.8, 3 278.8, and 3 297.5 \$. Similarly, the annual water inputs of muskmelon were: 2 054.1, 2 142.6, 1 946.8, 2 171.4 \$, respectively. Muskmelons benefit from agronomic management differently from watermelons during the stage of fruit expansion and full bloom under the same applications. Therefore, the annual fertilizer input of the four treatments were: 3 257.5, 3 246.8, 3 246.8, and 3 257.5 \$. According to the annual net income, the order of income of watermelon treated with different NBs was $OW_{100}F_{80}$>$OW_{80}F_{80}$>$OW_{80}F_{100}$, which increased on average by 58.0, 54.9 and 50.5%, respectively

Table 4. Effects of NBW irrigation on fruit quality of watermelon and muskmelon

Crops	Treatments	Spring			Fall		
		TSS (%)	VC (mg 100 g^{-1})	OA (‰)	TSS (%)	VC (mg 100 g^{-1})	OA (‰)
	NW100F100	10.0±0.1b	1.5±0.0c	124.0±2.4a	11.7±0.1c	3.0±0.3c	69.1±15.0ab
	OW80F100	10.0±0.1b	1.8±0.0b	126.7±1.5a	12.1±0.1b	5.1±0.3a	47.9±0.0b
	OW100F80	11.0±0.1a	2.0±0.1a	131.0±5.6a	12.4±0.2a	4.1±0.3b	93.1±15.5a
Watermelon	OW80F80	11.0±0.1a	1.8±0.1b	150.0±21.6a	12.4±0.1a	5.6±0.0a	69.6±15.1ab
				F-values			
	F	150.0**	0.0ns	4.3ns	13.3**	5.4*	2.7ns
	W	0.0ns	33.1**	2.9ns	0.1ns	52.3**	3.2ns
	NW100F100	6.0±0.1d	1.4±0.0d	172.6±2.4a	10.3±0.1c	2.8±0.1d	191.6±41.7a
	OW80F100	8.1±0.1b	1.9±0.0b	141.0±1.40b	11.0±0.2a	4.5±0.1b	161.7±14.8a
	OW100F80	9.6±0.4a	1.8±0.0c	147.6±11.2b	10.6±0.1b	3.9±0.1c	199.2±0.0a
Muskmelon	OW80F80	7.1±0.1c	2.6±0.0a	105.3±1.40c	10.5±0.1b	4.9±0.1a	159.2±14.5a
				F-values			
	F	36.3**	1355.3**	38.6**	34.1**	31.4**	0.0ns
	W	213.8**	1741.4**	54.4**	2.1ns	197.9**	3.0ns

TSS – total soluble solid, OA – organic acid. Different lowercase letters after the numbers indicate between-group variability, *p<0.05 and **p<0.01 levels represent significant differences, and ns indicates non-significant differences.

Table 5. Effect of nanometer bubble water irrigation on economic benefits

Seasonal	Treat-ments	Annual input ($ ha^{-1})						Annual output ($ ha^{-1})	Benefit ($ ha^{-1})
		Materials	Water	Fertilizer	Labor	Device	Electricity		
					Watermelon				
Spring	$NW_{100}F_{100}$	522.1	2 343.2	3 297.5	1 273.7	11.0	193.5	38 755.6	31 114.5
	$OW_{80}F_{100}$	522.1	2 270.7	3 297.5	1 273.7	11.0	276.1	50 412.7	42 761.5
	$OW_{100}F_{80}$	522.1	2 336.1	3 278.8	1 273.7	11.0	192.9	56 127.0	48 512.3
	$OW_{80}F_{80}$	522.1	2 007.3	3 278.8	1 273.7	11.0	254.4	51 809.5	44 462.2
Fall	$NW_{100}F_{100}$	522.1	3 400.5	3 297.5	1 273.7	11.0	280.8	35 682.5	26 896.8
	$OW_{80}F_{100}$	522.1	3 199.3	3 297.5	1 273.7	11.0	352.8	52 698.4	44 041.9
	$OW_{100}F_{80}$	522.1	3 340.4	3 278.8	1 273.7	11.0	275.9	51 936.5	43 234.5
	$OW_{80}F_{80}$	522.1	3 212.2	3 278.8	1 273.7	11.0	353.9	53 587.3	44 935.5
					Muskmelon				
Spring	$NW_{100}F_{100}$	522.1	2 008.4	3 257.5	1 302.3	11.0	165.9	33 904.8	26 637.6
	$OW_{80}F_{100}$	522.1	1 946.3	3 257.5	1 302.3	11.0	249.3	38 666.7	31 378.1
	$OW_{100}F_{80}$	522.1	2 002.4	3 246.8	1 302.3	11.0	165.4	44 571.4	37 321.5
	$OW_{80}F_{80}$	522.1	1 720.5	3 246.8	1 302.3	11.0	230.7	45 714.3	38 680.8
Fall	$NW_{100}F_{100}$	522.1	2 334.4	3 257.5	1 302.3	11.0	192.8	24 285.7	16 665.6
	$OW_{80}F_{100}$	522.1	2 161.9	3 257.5	1 302.3	11.0	267.2	24 381.0	16 859.0
	$OW_{100}F_{80}$	522.1	2 282.9	3 246.8	1 302.3	11.0	188.5	27 047.6	19 494.0
	$OW_{80}F_{80}$	522.1	2 173.0	3 246.8	1 302.3	11.0	268.1	28 095.2	20 572.0

The annual materials input including PVC pipes and fittings of subsurface drip irrigation tape. The cost of each nanobubble generator is about 1 317.5 $, which is used for a control unit and depreciated for 10 years.

when compared with the control group. Compared with the control group, the annual net income of muskmelon was ranked as $OW_{80}F_{80}$>$OW_{100}F_{80}$>$OW_{80}F_{100}$, which increased on average by 34.3, 28.0 and 9.4%, respectively.

DISCUSSION

Achieving synergistic increases in crop yield and quality in the greenhouse environment has become an issue of interest in the field of protected agriculture (Ouyang *et al.,* 2019). Various studies have shown that aerated irrigation is an effective way to achieve an improved crop yield and quality. However, the question of whether aerated drip irrigation can achieve these goals under reduced water and fertilizer application conditions is still unclear. An appropriate decrease in irrigation water amount within the tolerable threshold could reduce crop growth redundancy without affecting crop yield (Santos *et al.*, 2007; Du *et al.,* 2011). In the presented study, it was found that although a decline in the amount of irrigation or fertilization with nanobubbles produces no significant differences in the individual growth indexes, the crop yield and quality were still enhanced to a significant extent. The main reason for this was that the high root-shoot ratio could bring about root redundancy, which may be due to the decrease in the transportation of photosynthetic products to reproductive organs and as a consequence adversely affects the aboveground biological yield and economic benefit of the crop (Hu *et al.,* 2008). It is noteworthy that the improvement in crop yield and quality largely depends on the effective intake of soil nutrient. Therefore, balancing photosynthetic productivity and nutrient absorption is particularly important for crop growth (Bailey *et al.,* 2019). NBW may serve to enhance photosynthesis, stimulate GA hormone secretion, as well as affecting the distribution of microbial communities by increasing soil oxygen content which effectively promotes the absorption and transformation of nutrients by crops. (Wang *et al.,* 2020; Zhou *et al.,* 2020; Motoka *et al.,* 2013; Wu *et al.*, 2019). All of these factors further promoted yield increases. In addition, it was found that $OW_{80}F_{80}$ increased watermelon OA content and decreased muskmelon OA content. This result may have been caused by the different growth patterns of the two melons. Muskmelon is fructuous and has a longer growing season than watermelon. As a result, more fertilizer is needed in the elongation and enlargement period to ensure nutrient supply and absorption (Nie *et al.,* 2004).

Our results also showed that NBW could still improve crop water and nitrogen use efficiency even with a 20% reduction in water and fertilizer inputs. Similar findings were reported by Zhou (2019) and Cai (2016), who observed that the WUE of tomato and rice increased by 16.9 and 13.4%, respectively. This method of aeration irrigation increased the nitrogen efficiency of tomato, cucumber and rice respectively (Liu *et al.,* 2019; Cai, 2016). This may be due to the slow migration and long retention time of nanobubbles in water (Uchida *et al.,* 2011), which increases the effective action time of oxygen in water (Takahashi *et al.*, 2007), and promotes the physiological activities of plant cells while enhancing the uptake of water and nutrients by the root system (Bhattarai *et al.*, 2008; Bennicelli *el al.*, 1999). In conclusion, reducing the application quantities of water and fertilizer during NBW positively impacted crop yield, quality, water and fertilizer use efficiency. Aerated irrigation with NBW effectively achieved savings in agricultural water and fertilizer application and ameliorated environmental pollution. Therefore, $OW_{80}F_{80}$ was recommended as an appropriate aerated-irrigation strategy for greenhouse watermelon and muskmelon.

It was indicated that NBW irrigation achieves synergistic improvements in crop yield and quality under the conditions of reduced water and fertilizer application. However, the application of NBW irrigation inevitably increased production inputs, such as equipment costs, electricity costs and maintenance costs. At present, the economic feasibility of NBW irrigation in greenhouse production is still unclear. According to the results of this paper, it was found that the highest comprehensive benefits were attained by the use of NBW combined with a simultaneous reduction in water and fertilizer application. From an environmental and ecological point of view, NBW reduces the amount of irrigation water and chemical fertilizer, which is important in reducing water input, and alleviating soil and air pollution caused by the excessive application of chemical fertilizers (Jägermeyr *et al.,* 2015). At present, the application of NBW in agriculture is still in its infancy (Liu *et al.,* 2019), however, it has been established that NBW SDI technology achieves water and fertilizer savings, which is in line with the goal of sustainable agricultural development. Moreover, this technology can also ensure crop yields and improve crop quality, which perfectly satisfies the aims of both farmers and consumers (Jing, 2019; Dou *et al.,* 2019). We believe that the future application of this technology to high-quality crop varieties or value-added herbs is highly likely. Further studies are required to increase the experimental treatment gradients in order to clarify the specific water and fertilizer saving potentials and the optimal production of NBW irrigation.

CONCLUSIONS

1. This study found that under NBW conditions, a separate 20% reduction in irrigation or in the amount of fertilizer applied, or even a 20% reduction in both could still improve the yield, vitamin C, total soluble solids, irrigation water use efficiency, and the nitrogen partial productivity of greenhouse crops by 7.1-50.4, 1.4-30.7, 31.5-80.1, 36.0-82.6, 7.1-81.4%.

2. Although nanobubble water increased additional inputs such as equipment and electricity costs, it reduced the amounts of applied irrigation and fertilizer and improved the yield and quality of the greenhouse crops, resulting in higher overall benefits than ordinary underground drip irrigation. Therefore, the use of OW80F80 is recommended as a suitable aeration irrigation technique for watermelon and muskmelon in a greenhouse environment.

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