Article

Soil Aeration and Plastic Film Mulching Increase the Yield Potential and Quality of Tomato (*Solanum lycopersicum*)

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Abstract: Soil aeration and plastic film mulching have been reported to accelerate plant growth and increase fruit yield by improving the rhizosphere soil–air environment. The aim of this study was to investigate plant growth, fruit yield, irrigation water-use efficiency (IWUE) and fruit quality in response to a micro/nano-bubble aeration (MNBA) system and a subsurface artificial air layer aeration system (SAALA) under different treatments. The results indicated that both MNBA and SAALA positively influenced the plant dry weight, fruit yield, IWUE and fruit quality. In comparison with the no aeration treatment, the MNBA treatment increased the dry matter accumulation, fruit yield, IWUE, lycopene content and soluble protein content by 7.1%, 9.0%, 7.1%, 6.2% and 16.2%, respectively. Plastic film mulching (PFM) significantly improved the total dry weight, fruit yield and IWUE during both seasons. The increased yield in response to soil aeration during autumn was significantly greater than that during spring, and the yield increase in response to PFM was significantly greater in spring than in autumn. Moreover, the nutrition indices in response to both soil aeration and PFM were more significant during spring than autumn. Taking into account costs, efficiency and benefits, the optimal treatment was the MNBA and full (F) PFM combination.

Keywords: micro/nano-bubble aeration; subsurface artificial air layer aeration; plastic film mulching; tomato; quality

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1. Introduction

Oxygen (O₂) deficiency in agricultural soils under intensive irrigation is a well-known phenomenon, especially in fine-textured, poorly drained, clayey soils [1]. Previous studies have revealed that various physiological processes and components, such as nitrogen metabolism and translocation [2,3], root resistance to disease, photosynthesis, stomatal behaviour [4], relative membrane permeability, hydrogen peroxide activity, malondialdehyde content, pyruvate decarboxylase activity, alcohol dehydrogenase activity, and lactate dehydrogenase activity [5], can be altered under hypoxic stress. Other studies have also demonstrated the negative effects of O₂ deficiency in the root zone on plant growth, soil respiration and nutrient uptake [6,7].

Oxygen deficiency in agricultural soils is also enhanced by the use of plastic film mulching (PFM). PFM is largely used in many cultivations because it greatly reduces evaporation, increases the average soil temperature, decreases the diurnal variation in the temperature of the root zone, increases both topsoil moisture and water-use efficiency (WUE) and improves crop yield [8–12]. Mo et al.'s research [13] also found that PFM can effectively improve sunlight reflectance and decrease air flow, weed and pest pressure at the soil surface. In terms of the air phase, PFM inevitably blocks the air exchange between the soil and external environment. The O₂ content in the soil in turn decreases, which leads

to a reduction in respiration and reduces root growth [14]. Therefore, root zone hypoxic stress is further exacerbated by the use of plastic films.

The most effective means to cope with hypoxia has historically been to practise tillage. However, in recent years, various countermeasures and new techniques have emerged to address this issue, such as pump aeration [15], oxygenation [16], vacuum irrigation [17], micro/nano-bubble aeration (MNBA) [18] and the application of peroxides to the soil [19]. Injecting air into subsurface drip irrigation lines via an air compressor is an innovative approach referred to as pump aeration [15,20]. Oxygenation is the addition of O₂ or hydrogen peroxide to drip irrigation or subsurface drip irrigation systems of crop root zones [16,19]. Vacuum irrigation has become a popular irrigation method in recent years, in which Venturi equipment is attached to the main irrigation line; this method uses a vacuum to introduce air into the irrigation system [21]. In addition, irrigation water can be treated with a micro/nano-bubble generator. This process results in irrigation water containing air bubbles with a diameter between that of microbubbles (50 µm) and nanobubbles (200 nm), and the dissolved O₂ concentration exceeds the O₂ saturation value; this method is called micro/nanobubble irrigation (MNBA) [18]. These kinds of techniques can significantly improve the aerobic respiration of crop roots, increasing the soil microbial abundance and soil enzyme activity [17,22]. Many studies have also reported that soil aeration benefits crop yield and WUE. These techniques have been widely applied to herbs and orchards [17,21,23]. In response to these types of treatments, the yield of tomato (*Solanum lycopersicum* Mill.) [15], muskmelon [24], corn [17], cotton [25], onion [26], pepper [27], soybean, chickpea, pumpkin [26], and cucumber [28] have been shown to increase significantly, varying between 10% and 33%. Moreover, the qualities of the crops also improved.

Tomato is one of the most widely grown vegetable crop species in the world, and greenhouse production of tomato has been rapidly increasing [29]. Tomato is a high-value crop species whose fruits are widely appreciated for their characteristic aroma and flavour, bright red colour, juicy texture, and sweetness, all of which have played a major role in its rapid and widespread adoption as an important food commodity worldwide. Numerous previous studies have investigated the effects of soil aeration and PFM on tomato [20,30]. To our knowledge, few studies have examined the combined effects of soil aeration and PFM on tomato growth, quality and yield [15,21].

PFM and irrigation inhibit plant growth due to a lack of oxygen, and combined with one of the aeration treatments, are likely to diminish the negative effects of root zone oxygen stress. The objectives of this study were therefore to analyse the effects of MNBA and subsurface artificial air layer aeration (SAALA) on tomato dry matter accumulation, yield, irrigation water-use efficiency (IWUE), flavour, and nutrition and shape indices under three levels of PFM.

2. Materials and Methods

2.1. Site Description, Soil Details and Test Materials

This experiment was conducted in a greenhouse located at the Xi'an Agricultural Technology Spread centre (34°03' N, 108°52' E), Xi'an, Shaanxi Province, China, from March 2019 to January 2020. This site is on the Guanzhong Plain, which is a major food production area in northwestern China and is located at the southern edge of the Loess Plateau. The site is in the warm temperate, semihumid monsoon zone. The mean annual temperature is approximately 13.3 °C, the mean annual rainfall is approximately 552.2 mm, the average sunshine duration is 2225 h, and the mean annual frost-free period is 223 days. The greenhouse was 100 m-long in the north–south direction and 12 m-wide in the east–west direction. Tomato (*Solanum lycopersicum* Mill. 'Jingfan 401') plants (Jing-Yan-Yi-Nong Seed Sci-tech Co., Ltd., Beijing, China) were transplanted and harvested on 27 March 2019 and on 25 July 2019 for spring cultivation and on 23 August 2019 and 30 January 2020 for autumn cultivation. The physical and chemical soil properties of the upper soil layer (0–50 cm) at the experimental site were measured. Clay (<0.002 mm diameter soil

particles) accounted for 29.9% of the upper soil layer, silt (0.02–0.002 mm diameter soil particles) accounted for 43.9%, and gravel (2–0.02 mm diameter soil particles) accounted for 26.2%. The bulk density of the soil was 1.45 g cm^{-3} , the field capacity was 27.12%, the soil porosity was 49.12%, and the pH was 7.65. The soil consisted of 14.1 g kg^{-1} organic matter, 1.31 g kg^{-1} total nitrogen, 66.9 mg kg^{-1} available nitrogen, 9.52 g kg^{-1} total phosphorus, 94.0 mg kg^{-1} available phosphorus, 1.82 g kg^{-1} total potassium, and 89.1 mg kg^{-1} available potassium.

2.2. Experimental Design and Treatments

Each plot was 3.7 m in length and 1.5 m wide, with a total planting area of 5.55 m^2 . Two subsurface drip irrigation tubes (Qinchuan Water-saving Irrigation Equipment Engineering Co., Ltd., Yangling, China) with diameters of 16 mm were established in each cultivation area, and the spacing between the drip irrigation tubes was 0.50 m. Twenty-five-day-old seedlings were transplanted into the plots. The detailed information is shown in Figure A1. Further, 18 tomato seedlings plot^{-1} were planted in double rows, with a plant spacing of 0.40 m and row spacing of 0.50 m (Figure A1a). Guard rows were set up at both ends of the experimental field. The ridge width was 0.70 m, the height was 0.15 m, and the crop rows were aligned east to west (Figure A1a). The plastic film (Yinchuan Dingheng Plastic Film, Co., Ltd., Yinchuan, China) used was polyethylene (thickness, 0.026–0.029 mm; width, 1.20 m; colourless; density, 0.92 kg dm^{-3} ; tensile strength, 18–24 MPa).

The experimental design was a 3×3 full-factorial design. The experiment was arranged as a randomized complete block design, with three replicates for each combination of treatments, for a total of nine replicates (3 treatment repetitions $\times$ 3 sample repetitions). The experimental arrangement details are shown in Table 1. The experiment involved 3 levels of PFM (treatments), with F, H and N representing full, half and no treatments, respectively (Figure A1b). Similarly, SAALA, MNBA and CK represent subsurface artificial air layer aeration, micro/nano-bubble water aeration and no aeration treatment, respectively.

Table 1. Experimental design for the 9 treatment combinations.

Treatment Number	Plastic Film Mulching Treatment	Aeration Treatment
1	F	CK
2	H	CK
3	N	CK
4	F	SAALA
5	H	SAALA
6	N	SAALA
7	F	MNBA
8	H	MNBA
9	N	MNBA

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration.

Figure 1a shows the schematic field layout of the SAALA system. The concentration of O_2 in the atmosphere was higher than that in the soil. The rate of air exchange between the air and soil can be accelerated by SAALA. An air layer was dug before planting; the width of trench was 0.70 m, the length was 3.70 m, and the depth was 0.45 m. An iron screen was laid at a depth of 15 cm at the bottom of the groove, and gauze was added to cover the iron screen. Then, a layer of soil (15 cm deep) was added on top of the iron screen. To increase the O_2 concentration in the subsurface artificial air layer, both ends of the subsurface artificial air layer were connected to the outside air. Three plastic pipes were placed in the plots to connect the subsurface artificial air layer and outside air to increase the O_2 concentration in the subsurface artificial air layer. As shown in Figure 1b, the MNBA system consisted of several parts, including a water storage tank, an immersible pump, a filter, and a micro/nano-bubble generator (BS P-70, Besson Co., Ltd., Jinan, China). The main technical parameters of the micro/nano-bubble generator are shown in Table A1. Four micro/nano-bubble generators were arranged at the bottom of the tank. Air was

mixed with water in the tank by a micro/nano-bubble generator, and then high-density, uniform air was injected into the soil through the subsurface drip irrigation system. The CK treatment was irrigated exclusively with drip irrigation.

Figure 1. Sketch map of (a) subsurface artificial air layer aeration and (b) micro–nano-bubble water aeration.

Before transplanting, the soil was rototilled, and the experimental fields were fertilized with 300 kg ha^{-1} of compound fertilizer (18% N, 15% P_2O_5 , and 12% K_2O) and 900 kg ha^{-1} of diammonium phosphate (18% N and 46% P_2O_5). The fertilizer was broadcast uniformly as a basal fertilizer in each plot. Plants were irrigated at 5-day intervals using the drip irrigation system. The irrigation amount was 1.2 times the water surface evaporation, with the same irrigation amount applied to each plot. Detailed information on the irrigation date and amount is specified in Table A2. During the experimental period, all agronomic management practices for tomato, including pollination, branch stem pruning, pest control, etc., were consistent with local production practices.

2.3. Measurements

2.3.1. Fruit, Dry Matter Accumulation and IWUE

Fruit yield was measured during the fruit mature period, and the spring and autumn tomato fruits were harvested at 100–120 and 130–160 days after transplanting, respectively. Dry matter accumulation (stem, leaf, and root dry matter) was measured after all fruit yields were measured. The IWUE, defined as the ratio of fruit yield (kg) to the irrigation amount, was calculated as $\text{IWUE} = (\text{Y I}^{-1})$, where IWUE is the irrigation water-use efficiency (kg m^{-3}), Y is the fruit yield (kg) and I is the amount of applied water (m^3).

2.3.2. Shape, Nutrition and Flavour of Tomato Fruits

The shape, nutrition and flavour of fresh tomato fruits were measured. Fruit width and length of the first 9 ripe fruits were measured using a digital Vernier calliper (MNT-150T, Mei-Nai-Te Co., Ltd., Shanghai, China). The hardness of the fruits was determined using a hardness tester (GY-1, Tuo-Pu-Yun-Nong Co., Ltd., HangZhou, China). After the measurement of fruit shape, the fruits were sliced and juiced with a domestic juicer after removing the skin and seeds. The juice was decanted and subjected to a series of tests to measure the following nutrition and flavour parameters: vitamin C (VC) content, soluble solids content, lycopene content, soluble protein content, soluble sugars and titratable acid. The VC content was measured by molybdenum blue colourimetry. This method is based on the reaction of ascorbic acid (VC) with ammonium phosphomolybdate in the presence of SO_4^{2-} and PO_4^{3-} , generating blue molybdenum, which has a maximum absorption at 760 nm. This VC assay method is accurate, repeatable, and insensitive to interference by the presence of common reducing sugars [31]. A hand-held refractometer (Atago Co., Ltd., Tokyo, Japan) was used to directly measure the soluble solids of the blended fruits. Lycopene was extracted with 2% dichloromethane and petroleum as solvents to enhance the solubility of lycopene, and the absorption at 502 nm was subsequently measured.

by an ultraviolet spectrophotometer [32]. The soluble protein content was determined using Coomassie brilliant blue [31], and the soluble sugar content was measured by the anthrone colourimetry method [31]. Titratable acid was determined by diluting an aliquot of the blended fruits and titrating against 0.1 mol L⁻¹ NaOH using phenolphthalein as an indicator [33]. Last, the sugar/acid ratio was determined by dividing the soluble sugar concentration by the titratable acid content.

2.3.3. Economic Analysis and Evaluation

Economic analysis and evaluation were based on additional labour, electricity and plastic film mulching cost, as well as the depreciation of equipment of each treatment compared with CK. The total income was calculated by multiplying the total yield by local average price for the year.

2.4. Data Analysis

Data from the experiment were analysed statistically using SPSS 22 (IBM, Armonk, New York, NY, USA). The experimental data were analysed using two-way ANOVA in SPSS. Multiple comparisons using Duncan's test were completed when the ANOVA indicated significant differences ($p \leq 0.05$). All figures were constructed using the graphing software OriginPro 9.0 (Origin Lab Corporation, Northampton, MA, USA) and Photoshop CS5 (Adobe Systems, Inc., San Jose, CA, USA).

3. Results

3.1. Effects of Soil Aeration and PFM on Dry Matter Accumulation of Tomato

As shown in Table 2, both the MNBA and SAALA treatments had a significant effect on dry matter accumulation. Moreover, PFM increased the dry matter accumulation of tomato under each aeration treatment in both the spring and autumn seasons. The total dry weight of the tomato plants was 100.11–131.67 g plant⁻¹ in the spring and 80.36–120.23 g plant⁻¹ in autumn. During the spring season, PFM had a significant effect on the leaf, root, and total dry weight of the tomato plants but not on the stem dry weight or the root/shoot ratio. Soil aeration had a significant effect on the leaf, root, and total dry weight of the tomato plants. Compared with PFM, soil aeration resulted in significant increases in the stem, leaf, root, and total dry weight of tomato plants. During the autumn season, the results showed that PFM had a significant effect on the stems, leaves, roots, total dry weight and root/shoot ratio of the tomato plants. Furthermore, soil aeration had a significant effect on the root and total dry weight of the tomato plants but not on the stems, leaves or root/shoot ratio. The ANOVA F-value showed that the interaction between soil aeration and PFM was not significant for any of the variables.

Table 2. Effects of different aeration treatments on the stem, leaf and root dry weight and the root–shoot ratio of a single tomato for spring and autumn tomatoes 120 and 160 days after planting.

Season		Tomato in Spring					Tomato in Autumn				
Treatments	Stem (g)	Leaves/(g)	Root/(g)	Total Dry Weight/(g)	Root-Shoot Ratio/(%)	Stems (g)	Leaves/(g)	Root/(g)	Total Dry Weight/(g)	Root-Shoot Ratio/(%)	
F-CK	58.0 ± 19.9 ab	48.9 ± 10.2 bc	6.6 ± 0.4 bc	113.5 ± 22.8 bc	0.07 ± 0.02 ab	56.8 ± 12.0 ab	40.5 ± 7.0 bc	5.2 ± 0.4 bcd	102.5 ± 9.5 bc	0.05 ± 0.01 d	
H-CK	55.3 ± 1.6 ab	46.0 ± 8.2 bc	6.3 ± 1.9 bc	107.5 ± 7.3 bc	0.06 ± 0.02 ab	47.6 ± 16.5 bc	42.9 ± 7.7 ab	4.4 ± 0.9 d	94.9 ± 21.5 bcd	0.05 ± 0.01 cd	
N-CK	51.9 ± 2.8 b	42.8 ± 2.1 c	5.5 ± 0.3 c	100.1 ± 2.1 c	0.06 ± 0 b	41.9 ± 8.4 c	33.8 ± 7.3 a	4.7 ± 0.2 d	80.4 ± 15.5 d	0.08 ± 0.02 ab	
F-SAALA	65.8 ± 0.0 a	57.4 ± 1.6 a	8.5 ± 1.5 a	131.7 ± 1.7 a	0.07 ± 0.01 ab	63.5 ± 7.9 a	49.4 ± 6.1 a	7.3 ± 0.2 a	120.2 ± 10.7 a	0.05 ± 0 d	
H-SAALA	62.3 ± 15.6 ab	49.2 ± 10.4 abc	7.0 ± 0.4 b	118.5 ± 18.5 ab	0.06 ± 0.01 ab	50.7 ± 13.2 bc	43.4 ± 11.4 ab	7.1 ± 0.8 a	101.1 ± 20.5 bc	0.07 ± 0.01 bc	
N-SAALA	59.6 ± 1.6 ab	46.6 ± 8.0 bc	6.6 ± 0.6 bc	112.8 ± 8.6 bc	0.06 ± 0.01 ab	50.5 ± 11.5 bc	35.7 ± 6.1 bc	5.5 ± 0.3 bc	91.8 ± 17.3 bcd	0.09 ± 0.01 a	
F-MNBA	60.9 ± 13.0 ab	51.83 ± 8.8 ab	8.4 ± 1.5 a	121.2 ± 14.9 ab	0.08 ± 0.02 a	57.5 ± 10.7 ab	44.6 ± 10.8 ab	5.9 ± 0.3 b	108.0 ± 10.1 ab	0.07 ± 0.01 b	
H-MNBA	60.5 ± 4.8 ab	48.47 ± 8.7 bc	7.2 ± 1.2 b	116.1 ± 8.5 b	0.07 ± 0.01 ab	50.5 ± 10.4 bc	39.6 ± 8.3 bc	5.0 ± 1.6 cd	95.1 ± 18.1 bcd	0.05 ± 0.01 cd	
N-MNBA	52.4 ± 9.9 b	46.94 ± 6.6 bc	7.3 ± 0.3 b	106.7 ± 13.0 bc	0.08 ± 0.01 a	41.7 ± 4.7 c	39.4 ± 5.0 bc	4.4 ± 0.9 d	85.7 ± 9.1 cd	0.06 ± 0.02 bc	
					F-value						
Plastic film mulching (P)	2.4 ns	4.4 *	8.0 **	7.4 **	1.0 ns	9.6 **	6.1 **	6.3 **	12.5 **	13.6 **	
Aeration (A)	4.1 *	4.7 *	26.5 **	11.3 **	3.5 ns	1.7 ns	2.2 ns	21.2 **	4.0 *	1.3 ns	
P × A	0.1 ns	0.2 ns	1.4 ns	0.1 ns	0.5 ns	0.0 ns	1.4 ns	2.8 ns	0.4 ns	1.0 ns	

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro–nano-bubble water aeration. Data are presented as the mean ± standard deviation ($n = 9$). Different lowercase letters in the same column indicate significant differences between treatments (Duncan's test, $p < 0.05$). ANOVA F-values for main and interaction effects were not significant (ns) or were significant at the $\leq 5\%$ (*) and $\leq 1\%$ (**) levels. Bold number indicate significant differences at the $\leq 5\%$ level.

3.2. Effects of Soil Aeration and PFM on Fruit Yield and IWUE

The effects of soil aeration and PFM on the fruit yield and IWUE of tomato are shown in Table 3. The fruit yield and IWUE in the spring season were higher than those in the autumn season. Fruit yield and IWUE increased with increasing PFM in response to the N, H to F treatments during both the spring and autumn seasons. In the spring, the F treatment under the CK, SAALA and MNBA treatments increased the fruit yield by 35.5%, 31.1%, and 29.2%, respectively, compared with the yield of the N treatment. Both the MNBA and SAALA treatments had a significantly higher fruit yield and IWUE than did the CK treatment during both the spring and autumn seasons. PFM had a significant ($p \leq 0.01$) impact on fruit yield and IWUE in the spring season but no significant impact during autumn. The interaction between aeration and PFM had no significant ($p > 0.05$) effect on fruit yield or IWUE.

Table 3. Effects of different aeration treatments on fruit yield and irrigation water-use efficiency (IWUE) of tomato.

Season	Tomato in Spring		Tomato in Autumn	
Treatments	Fruit Yield (g/plant)	IWUE for Fruit (kg/m ³)	Fruit Yield (g/plant)	IWUE for Fruit (kg/m ³)
F-CK	2412.9 ± 616.9 abc	21.7 ± 5.6 abc	1995.6 ± 471.4 bc	14.1 ± 3.3 bc
H-CK	2068.8 ± 730.3 bc	18.6 ± 6.6 bc	1904.4 ± 388.8 bc	13.5 ± 2.8 bc
N-CK	1781.3 ± 174.7 c	16.0 ± 1.6 c	1737.8 ± 330.4 c	12.3 ± 2.3 c
F-SAALA	3014.0 ± 580.3 a	27.1 ± 5.2 a	2512.2 ± 79.7 a	17.8 ± 0.6 a
H-SAALA	2519.2 ± 585.5 ab	22.7 ± 5.3 ab	2090.0 ± 370.05 ab	14.8 ± 2.6 bc
N-SAALA	2299.4 ± 318.5 bc	20.7 ± 2.9 bc	2136.7 ± 290.3 abc	15.1 ± 2.1 abc
F-MNBA	2602.4 ± 604.1 ab	23.4 ± 5.4 ab	2166.7 ± 333.3 ab	15.3 ± 2.4 ab
H-MNBA	2210.3 ± 419.2 bc	19.9 ± 3.8 bc	2204.4 ± 484.9 ab	15.6 ± 3.4 ab
N-MNBA	2014.8 ± 767.9 bc	18.1 ± 6.9 bc	2081.1 ± 402.1 bc	14.7 ± 2.9 bc
		F-value		
Plastic film mulching (P)	6.9 **	6.9 **	2.3 ns	2.3 ns
Aeration (A)	6.3 *	6.3 *	11.9 **	11.9 **
P × A	0.0 ns	0.0 ns	0.2 ns	0.2 ns

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration. Data are presented as the mean ± standard deviation ($n = 9$). Different lowercase letters in the same column indicate significant differences between treatments (Duncan's test, $p < 0.05$). ANOVA F-values for main and interaction effects were not significant (ns) or were significant at the $\leq 5\%$ (*) and $\leq 1\%$ (**) levels. Bold number indicate significant differences at the $\leq 5\%$ level.

3.3. Effects of Soil Aeration and PFM on Tomato Flavour Indices

The data presented in Table 4 show that increasing the mulch-covered area significantly and progressively decreased the soluble sugar and titratable acid contents in both the spring and autumn seasons. The soluble sugar content decreased from 3.61% to 2.99% when the mulch-covered area changed from the N to F levels during the spring season and decreased from 5.11% to 3.61% during autumn. A similar situation of PFM-induced decreases in flavour indices also occurred under the MNBA and SAALA treatments. Soil aeration, mulch-covered area and the aeration volume × line depth interaction had significant effects on the sugar/acid ratio during the autumn season but had no significant effects during spring. Moreover, aeration had a significant impact on the titratable acid content during spring and had a significant impact on the soluble sugar content and sugar/acid ratio during autumn. The two-factor interaction had a significant impact on the titratable acid content during the spring season and on the sugar/acid ratio during the autumn season.

Table 4. Effects of different aeration treatments on flavour indices of tomato.

Treatments	Soluble Sugar (%)	Tomato in Spring Titratable Acid (Weight %)	Sugar/Acid Ratio	Soluble Sugar (%)	Tomato in Autumn Titratable Acid (Weight %)	Sugar/Acid Ratio
F-CK	3.0 ± 0.6 b	0.41 ± 0.02 d	7.2 ± 1.3 ab	3.6 ± 0.4 bc	0.95 ± 0.04 c	3.8 ± 0.5 b
H-CK	3.5 ± 1.2 ab	0.46 ± 0.03 c	7.6 ± 2.9 ab	3.5 ± 1.2 bc	1.05 ± 0.06 ab	3.3 ± 1.2 b
N-CK	3.6 ± 0.4 ab	0.47 ± 0.02 abc	7.7 ± 0.8 ab	5.1 ± 1.5 a	0.97 ± 0.09 bc	5.4 ± 1.7 a
F-SAALA	3.6 ± 0.2 ab	0.47 ± 0.01 abc	7.8 ± 0.4 ab	3.4 ± 1.0 bc	0.94 ± 0.01 c	3.6 ± 1.1 b
H-SAALA	3.2 ± 1.0 ab	0.47 ± 0 abc	7.2 ± 2.2 ab	3.6 ± 0.2 bc	1 ± 0.07 abc	3.6 ± 0.3 b
N-SAALA	4.1 ± 0.6 a	0.48 ± 0.02 a	8.7 ± 1.4 a	4.2 ± 0.6 b	1.07 ± 0.08 a	3.9 ± 0.8 b
F-MNBA	3.0 ± 0.8 b	0.46 ± 0.02 bc	6.6 ± 1.7 b	3.1 ± 0.7 c	0.99 ± 0.1 abc	3.1 ± 0.8 b
H-MNBA	3.4 ± 0.5 ab	0.47 ± 0.03 abc	7.2 ± 1.1 ab	3.4 ± 0.5 bc	1.02 ± 0.12 abc	3.4 ± 0.5 b
N-MNBA	4.0 ± 0.3 a	0.48 ± 0.01 ab	8.3 ± 0.7 ab	4.0 ± 0.3 b	1.01 ± 0.07 abc	4.0 ± 0.4 b
			F-value			
Plastic film mulching (P)	4.9 **	20.8 **	1.9 ns	14.1 **	5.3 **	12.0 **
Aeration (A)	1.7 ns	33.2 **	0.0 ns	4.8 *	0.8 ns	6.2 *
P × A	0.8 ns	7.0 **	0.8 ns	2.4 ns	2.6 ns	4.1 *

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration. Data are presented as the mean ± standard deviation ($n = 9$). Different lowercase letters in the same column indicate significant differences between treatments (Duncan's test, $p < 0.05$). ANOVA F-values for main and interaction effects were not significant (ns) or were significant at the $\leq 5\%$ (*) and $\leq 1\%$ (**) levels. Bold number indicate significant differences at the $\leq 5\%$ level.

3.4. Effects of Soil Aeration and PFM on Tomato Nutritional Quality

The VC, soluble solids, lycopene and soluble protein contents were selected to characterize tomato nutritional quality and are presented in Table 5. Among the results of the single-factor analyses, PFM had a significant impact on the soluble solids, lycopene and soluble protein contents during spring and on the soluble protein content during autumn. In addition, the soluble solids and soluble protein contents gradually increased with increasing mulch-covered area. Fruit nutritional quality was found to be greater in the aeration treatments than in the CK treatment. Aeration had a significant impact on all four nutrition indices during spring and on the lycopene content and soluble protein content during autumn. However, there were no significant differences in soluble solids during autumn. The two-factor interaction had a significant impact on the lycopene and soluble protein contents during the spring season and on the VC content during the autumn season, but there was no significant impact on VC and soluble solids content during the spring season or on the soluble solids, lycopene, soluble protein contents during the autumn season.

Table 5. Effects of different aeration treatments on nutritional indices of tomato.

Season	Tomato in Spring				Tomato in Autumn			
Treatments	Vitamin C Content (mg/100 g)	Soluble Solids (%)	Lycopene Content (ug/g)	Soluble Protein (%)	Vitamin C Content (mg/100 g)	Soluble Solids (%)	Lycopene Content (ug/g)	Soluble Protein (%)
F-CK	21.5 ± 0.9 c	5.0 ± 0.3 ab	51.3 ± 5.5 b	1.97 ± 0.08 bc	23.3 ± 1.1 b	4.9 ± 0.4 a	42.9 ± 4.5 b	1.98 ± 0.07 b
H-CK	22.6 ± 1.9 bc	4.9 ± 0.3 bc	55.0 ± 4.0 ab	1.96 ± 0.08 bc	25.0 ± 2.0 ab	4.9 ± 0.2 a	41.8 ± 5.3 b	1.96 ± 0.07 b
N-CK	23.6 ± 1.4 bc	4.5 ± 0.6 c	47.3 ± 6.2 c	1.93 ± 0.07 c	25.9 ± 2.6 a	4.7 ± 0.7 a	43.6 ± 2.0 b	1.83 ± 0.1 b
F-SAALA	25.3 ± 3.1 ab	5.2 ± 0.4 a	56.0 ± 3.5 a	2.44 ± 0.11 a	26.0 ± 1.4 a	5.1 ± 0.5 a	48.5 ± 1.1 a	2.03 ± 0.05 a
H-SAALA	23.3 ± 1.7 bc	5.1 ± 0.5 ab	56.7 ± 3.5 a	2.34 ± 0.11 a	25.5 ± 1.7 a	5.0 ± 0.5 a	43.2 ± 4.5 b	1.99 ± 0.09 b
N-SAALA	26.8 ± 3.1 a	4.7 ± 0.4 bc	56.3 ± 2.9 a	1.95 ± 0.1 bc	25.0 ± 1.4 ab	4.9 ± 0.5 a	43.2 ± 2.0 b	1.98 ± 0.06 b
F-MNBA	25.0 ± 2.7 ab	5.1 ± 0.4 ab	55.7 ± 2.9 a	2.38 ± 0.1 a	25.6 ± 1.3 a	5.1 ± 0.3 a	45.2 ± 4.6 ab	1.98 ± 0.08 ab
H-MNBA	24.6 ± 3.3 ab	5.1 ± 0.3 ab	56.0 ± 2.5 a	2.39 ± 0.11 a	25.4 ± 1.9 a	4.8 ± 0.2 a	43.9 ± 1.4 b	1.98 ± 0.09 b
N-MNBA	25.0 ± 2.7 ab	4.8 ± 0.5 bc	55.1 ± 2.6 ab	2.03 ± 0.07 b	25.1 ± 2.5 ab	5.0 ± 0.6 a	44.0 ± 2.4 b	1.92 ± 0.08 b
				F-value				
Plastic film mulching (P)	2.6 ns	7.5 **	6.0 **	36.4 **	2.4 ns	1.0 ns	2.2 ns	10.5 **
Aeration (A)	16.2 **	5.4 *	24.5 **	162.7 **	1.6 ns	1.6 ns	4.9 *	8.7 **
P × A	1.2 ns	0.0 ns	4.6 *	25.3 **	4.8 *	0.5 ns	1.7 ns	2.9 ns

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration. Data are presented as the mean ± standard deviation ($n = 9$). Different lowercase letters in the same column indicate significant differences between treatments (Duncan's test, $p < 0.05$). ANOVA F-values for main and interaction effects were not significant (ns) or were significant at the $\leq 5\%$ (*) and $\leq 1\%$ (**) levels. Bold number indicate significant differences at the $\leq 5\%$ level.

3.5. Effects of Soil Aeration and PFM on Tomato Shape

The impacts of soil aeration and PFM on the shape indices of tomato are shown in Table 6. During the spring season, PFM had a marked effect on fruit length, width, weight and hardness, and soil aeration markedly influenced the fruit width, length and individual weight. Aeration did not significantly affect the hardness in either the spring or autumn. Compared with the N treatment, PFM resulted in a higher fruit hardness. The F treatment presented had the highest fruit length, fruit width and individual fruit weight during spring. The interaction of soil aeration and PFM notably affected the fruit width. However, there were no significant differences in fruit length, width, and single fruit weight during autumn. Figure 2 shows the relationships between fruit weight, fruit width and fruit length. Figure 2a,b shows the fruit width and fruit length are important factors that affect fruit shape, which is important for fruit weight. Figure 2c shows a high coefficient of determination for the relationship of tomato fruit width and fruit length during the aeration and PFM treatments. Relationships between fruit weight and width, fruit weight and length and fruit width and length were modelled using $\ln(y) = 2.64 + 0.31 \times \ln(x)$, $\ln(y) = 2.28 + 0.36 \times \ln(x)$ and $\ln(y) = 1.11 + 0.75 \times \ln(x)$, respectively.

Table 6. Effects of different aeration treatments on shape indices of tomato.

Season	Tomato in Spring				Tomato in Autumn			
Treatments	Fruit Length (mm)	Fruit Width (mm)	Single Fruit Weight (g)	Hardness (Kpa/m ²)	Fruit Length (mm)	Fruit Width (mm)	Single Fruit Weight (g)	Hardness (Kpa/m ²)
F-CK	50.9 ± 6.0 abc	54.7 ± 1.4 ab	89.2 ± 15.7 abc	10.6 ± 0.8 b	41.7 ± 7.9 a	47.4 ± 7.9 a	77.2 ± 13.7 a	11.6 ± 0.8 ab
H-CK	44.2 ± 9.1 c	48.1 ± 5.8 c	60.6 ± 21.5 d	11.4 ± 0.9 ab	38.0 ± 5.0 a	46.9 ± 7.8 a	79.2 ± 18.4 a	11.9 ± 1.2 ab
N-CK	44.1 ± 4.6 c	51.7 ± 3.8 bc	66.0 ± 14.9 cd	12.2 ± 0.9 a	39.0 ± 8.4 a	44.9 ± 7.1 a	65.2 ± 10.3 a	12.0 ± 1.1 ab
F-SAALA	54.3 ± 6.7 a	59.0 ± 4.4 a	108.7 ± 28.4 a	10.5 ± 1.0 b	48.3 ± 9.7 a	49.4 ± 5.8 a	71.8 ± 16.5 a	12.8 ± 0.9 ab
H-SAALA	51.1 ± 3.8 ab	57.7 ± 3.3 a	96.9 ± 18.8 ab	11.3 ± 1.1 b	45.0 ± 9.6 a	48.3 ± 7.6 a	77.3 ± 13.2 a	11.9 ± 1.1 ab
N-SAALA	49.0 ± 4.7 abc	53.9 ± 2.8 b	80.6 ± 15.8 cd	11.5 ± 1.3 ab	47.7 ± 8.6 a	50.5 ± 7.9 a	75.4 ± 16.3 a	11.8 ± 1.0 a
F-MNBA	53.1 ± 7.1 ab	59.0 ± 5.1 a	108.2 ± 31.3 a	11.1 ± 1.0 b	43.7 ± 6.7 a	50.3 ± 9.2 a	81.6 ± 14.3 a	11.8 ± 1.1 b
H-MNBA	50.2 ± 5.0 abc	58.8 ± 4.3 a	80.2 ± 22.9 bcd	10.8 ± 0.9 b	42.5 ± 10.3 a	50.4 ± 8.0 a	67.6 ± 14.7 a	12.7 ± 0.7 ab
N-MNBA	46.0 ± 7.7 bc	50.5 ± 6.5 bc	69.8 ± 23.7 cd	11.2 ± 1.1 ab	41.4 ± 8.8 a	51.7 ± 3.3 a	78.0 ± 18.9 a	12.1 ± 0.7 ab
				F-value				
Plastic film mulching (P)	7.1 **	7.3 **	9.8 **	6.3 **	0.3 ns	0.2 ns	1.5 ns	0.2 ns
Aeration (A)	6.8 *	20.0 **	10.9 **	2.4 ns	2.6 ns	1.7 ns	0.2 ns	1.8 ns
P × A	0.7 ns	7.4 **	1.4 ns	1.6 ns	1.6 ns	0.2 ns	2.4 ns	0.9 ns

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration. Data are presented as the mean ± standard deviation ($n = 9$). Different lowercase letters in the same column indicate significant differences between treatments (Duncan's test, $p < 0.05$). ANOVA F-values for main and interaction effects were not significant (ns) or were significant at the ≤5% (*) and ≤1% (**) levels. Bold number indicate significant differences at the ≤5% level.

Figure 2. Relationships between (a) fruit weight and width, (b) fruit weight and length (c) fruit width and length.

3.6. Economic Analysis and Evaluation

The results of an economic analysis of the soil aeration and PFM treatments in a 100 m-long greenhouse are shown in Table 7. Two skilled farmers could complete the required PFM work for the whole greenhouse. The local skilled farmer price was 150 CNY day^{−1}. The F and H film required CNY 300 for additional labour costs. Additional labour costs for the installation of SAALA and MNBA systems were CNY 1000 and

CNY 150, respectively. The electricity cost for the MNBA treatment was approximately CNY 60. The costs of the F, H, and N PFM were CNY 100, CNY 50, and CNY 0, respectively. We estimated that the depreciation of the SAALA and MNBA systems was CNY 6000 and CNY 1500, respectively. The total yield was calculated according to the average fruit yield per plant (the data are shown in Table 3) multiplied by the number of total plants in the greenhouse (2376 plants greenhouse⁻¹). The tomato price varied greatly from year to year, and the local average price for the year was 4.5 CNY kg⁻¹. The total income was calculated by multiplying the total yield by 4.5. As shown in Table 7, both the PFM and MNBA treatments increased the income. The calculated maximum additional income was detected in response to the F-MNBA treatment combination. Compared with the N-CK treatment, the F-MNBA treatment combination gained an additional income of CNY 6669 during spring and CNY 2476 during autumn. Notably, all the computations were based on the cost and yield, and measurements of fruit quality did not involve computational processes. If fruit quality is considered, these investments will result in increased profits.

Table 7. Economic analysis of soil aeration and plastic film mulch treatments in a 100-m-long greenhouse.

Season	Treatments	Additional Labor Cost for Plastic Film Mulch (CNY)	Additional Labor Cost for Soil Aeration (CNY)	Additional Electricity (CNY)	Plastic Film Cost (CNY)	Depreciation of the Equipment (CNY)	Total Yield (kg)	Total Income (CNY)	Additional Income Compared with NCK (CNY)
Spring	F-CK	300	0	0	100	0	5733	25,799	6353
	H-CK	300	0	0	50	0	4915	22,119	2723
	N-CK	0	0	0	0	0	4232	19,046	0
	F-SAALA	300	1000	0	100	6000	7161	32,226	5780
	H-SAALA	300	1000	0	50	6000	5986	26,936	540
	N-SAALA	0	1000	0	0	6000	5463	24,585	−1461
	F-MNBA	300	150	60	100	1500	6183	27,825	6669
	H-MNBA	300	150	60	50	1500	5252	23,632	2526
	N-MNBA	0	150	60	0	1500	4787	21,542	786
Autumn	F-CK	300	0	0	100	0	4741	21,337	2357
	H-CK	300	0	0	50	0	4525	20,362	1432
	N-CK	0	0	0	0	0	4129	18,580	0
	F-SAALA	300	1000	0	100	6000	5969	26,861	881
	H-SAALA	300	1000	0	50	6000	4966	22,346	−3584
	N-SAALA	0	1000	0	0	6000	5077	22,845	−2735
	F-MNBA	300	150	60	100	1500	5148	23,166	2476
	H-MNBA	300	150	60	50	1500	5238	23,570	2930
	N-MNBA	0	150	60	0	1500	4945	22,251	1961

Note: F, full film covering; H, half film covering; N, no film covering; CK, no aeration treatment; SAALA, subsurface artificial air layer aeration; MNBA, micro-nano-bubble water aeration.

4. Discussion

4.1. Plant Growth, Yield and Quality of Tomato Fruits under Soil Aeration Treatment

Tomato fruit yield and quality in terms of flavour, nutrition and shape are affected by various environmental factors, such as light, temperature, water, nutrients, pollutants and soil air, and have been extensively studied [18,34–37]. Zhou et al. [38] reported that plants respond to low-O₂ stress by altering their photosynthesis, respiration and biosynthesis of endogenous phytohormones. Previous studies have also shown that root zone hypoxia results in the accumulation of ethanol, ethylene and abscisic acid, accompanied by a reduction in photosynthesis, which affects plant growth and fruit yield [4,39–41]. Tomato is a moderately O₂-demanding plant species, and its main roots are distributed within 0–40 cm of the soil surface [42]. Soil aeration has been reported to play an important role in improving soil physical and chemical properties, facilitating tomato plant growth, increasing fruit yield, and maximizing WUE [15,22]. Similar results were obtained in this study; compared with drip irrigation, both MNBA and SAALA improved the dry matter accumulation and yield of tomato plants as well as the flavour, nutrition and shape of the tomato fruits. Other studies have also shown that MNBA increases IWUE, crop yield and quality [43,44]. In the present study, compared with the CK, MNBA improved dry matter accumulation (Table 2), and MNBA increased IWUE and the soluble protein content

in both spring and autumn (Tables 3 and 5). This could be due to hypoxia stress under CK conditions in the soil causing a reduction in plant growth, and the applied MNBA treatments alleviated root zone hypoxia. Liu et al. [18] indicated that MNBA increased IWUE, crop yield and quality, which is in agreement with our results. In general, MNBA provides O₂ in the root zone for the growth of tomato plants.

MNBA had positive effects not only on plant growth and yield but also on fruit quality indices (VC, soluble solids, lycopene, soluble protein, soluble sugar, and titratable acid contents as well as the sugar/acid ratio) (Tables 2, 4 and 5). Nevertheless, the results differed during the spring and autumn. Increases in the stem, leaf, root and total dry weight of tomato plants under aeration treatment were found in the spring season, but there were no significant differences in stem or leaf dry weight during autumn (Table 2). Similar results were also found for the flavour and nutrition indices, where the aeration treatments led to a significant increase in titratable acid, VC, and soluble solid contents in the spring season; the increases were not significant during autumn (Tables 4 and 5). A search of the literature revealed no previous reports on MNBA application efficiency during different seasons. Liu's research showed that the ratio of micro/nanobubbles to water in an MNBA system more significant for tomato and cucumber yields during spring than during autumn, but that the oxygenation frequency of MNBA during autumn was more significant [18]. We speculate that this phenomenon may be due to the different weather conditions during spring and autumn. As a general rule, light intensity, temperature, evaporation, humidity, plant bioactivity, and growth rate during spring were higher than those during autumn. Moreover, the O₂ demand for plant roots was higher during the spring season than during the autumn season. Therefore, the growing season is short during spring (120 days in this study) and long during autumn (160 days in this study). This also explains why O₂ demand became more important during spring than autumn and why soil aeration was more significant during the spring season.

As shown in Table 2, compared with the CK treatment, the SAALA treatment increased the total dry weight during the spring and autumn by 12.99% and 12.76%, respectively. Fruit yield during the spring and autumn also increased by 25.06% and 19.53%, respectively (Table 3). The reason for the lower O₂ and higher CO₂ concentration of the air in the soil pores compared with the outside air is that the air in soil pores is exchanged only through the soil surface under conventional farming practices. Due to the presence of the subsurface air layer, the fluidity and exchange of the air in the soil increased, which increased the O₂ concentration in the soil. Furthermore, the subsurface artificial air layer has a unique structure that can prevent water accumulation at the bottom of the plough layer. Thus, compared with the CK treatment, the subsurface SAALA treatment significantly increased the root dry weight and improved other growth indicators (Table 2). Therefore, we speculate that hypoxia stress occurs universally in the CK treatment and that the SAALA treatment can effectively relieve hypoxia stress. The roots grew better in the SAALA treatment than in the other treatment, absorbed more water and nutrients, and affected the yield and quality potential of the tomato plants. Although no previous reports are available on SAALA, other researchers have reported similar observations of soil aeration on plant growth [45,46].

4.2. Plant Growth, Fruit Yield and Quality under PFM Treatment

The application of PFM for crop management, especially in arid and semiarid regions, has been studied extensively. Previous studies have shown that PFM increases soil water availability and soil temperature, thus increasing various root growth parameters, including root length density, dry weight, surface area and volume, which further increase nutrient and water uptake [11,47]. Soil moisture is critical for plants to maintain their growth, especially under high soil-temperature conditions [48]. The ability of tomato plants to absorb water and minerals from the soil is attributed primarily to their extensive root system. In the present study, root dry weight markedly increased under PFM treatment during both spring and autumn in tomato (Table 2). Moreover, the total dry weight significantly increased in response to PFM. It was demonstrated that PFM could effectively

improve root growth as well as water and nutrient uptake, and could, to some extent, affect the performance of plant growth [49]. The conclusion of that study is consistent with our results. We also found that the total dry weight of the plants was significantly higher under the PFM treatment than under the N treatment in both the MNBA and SAALA treatments (Table 2). This finding suggests that PFM is practical and adaptable under aeration. Although this study did not measure the physiological indices of plants, other studies have shown that PFM increases the topsoil temperature and moisture content as well as the WUE, all of which have positive effects on photosynthesis and fruit yield [11,50]. Therefore, we hypothesized that an increased net photosynthesis rate is one of the main mechanisms by which PFM increases plant growth. In addition, soil enzyme and microbial activities have been shown to be affected by soil PFM treatments [30]. All these changes could interact and affect nutrient cycling and nutrient bioaccessibility, affecting plant growth [51].

PFM significantly increased IWUE, as suggested by Zhang et al., [52] and Fan et al., [53]. In the present study, IWUE significantly increased in response to PFM during the spring but not during autumn (Table 3). We speculate that the relatively high atmospheric and soil temperatures during the spring are accompanied by increased evaporation and transpiration. PFM restricts evaporation, thereby improving the IWUE substantially. In contrast, evaporation is relatively low during autumn. Therefore, no significant differences in IWUE were observed between the PFM and N treatments. These results are consistent with those of Díaz-Pérez [54], who reported that plastic mulch affected plant growth, and the effect of mulch was more dramatic in the spring season than in the autumn season.

In addition to fruit yield, fruit quality was also affected by the PFM treatment. It is well-known that soluble sugar and titratable acid contents affect fruit flavour. PFM resulted in a relatively low accumulation of soluble sugar and titratable acid contents in the fruits in both the spring and autumn (Table 4), which implied that the PFM treatment decreased the flavour indices of the tomato fruits. Previous studies have shown that a high soil water content leads to a decrease in both fruit flavour and nutritional quality [36,55]. We postulated that PFM increases soil moisture [11] and that high soil moisture leads to a decrease in soluble solids and soluble protein contents in the fruits. Furthermore, this study showed that the soluble solids content, lycopene content and shape indices of the tomato fruits significantly increased in response to the PFM treatment during the spring season (Tables 5 and 6). Lycopene is specifically important for the human diet and has been linked to a reduced risk of prostate cancer and heart disease [56]. Xia's research [57] suggested that PFM treatment has a positive impact on lycopene content, which is consistent with our results.

4.3. Correlations between Plant Growth, Fruit Yield and Fruit Quality under Soil Aeration and PFM Treatments

A large number of studies have shown that plant performance and fruit yield promote soil physicochemical properties, such as soil moisture, temperature, air concentration, pH, and microbial activity [15,16,58]. However, no previous studies have examined the specific correlations between plant performance and quality under soil aeration and PFM. A previous study showed that a low O₂ supply can decrease root and shoot growth of tomato while decreasing root total respiration and hydrolytic ATPase activities [59]. Figure 3 shows the correlations between tomato plant performance, fruit flavour, fruit nutrition and fruit shape indicators. Root dry weight was significantly positively correlated with fruit weight during both the spring (Figure 3a) and autumn (Figure 3b) ($p < 0.01$). Furthermore, fruit weight was significantly positively correlated with VC and soluble protein contents. Overall, our results indicate that both soil aeration and PFM increased dry matter accumulation, plant growth and quality of tomato.

Figure 3. Pearson correlation between growth and quality parameters of tomato during spring (a) and autumn (b) under soil aeration and plastic film mulch treatments. * Significant at the 5%; ** Significant at the 1% (2-tailed).

5. Conclusions

The results of this experiment showed that it is feasible to configure the installation and operation of commercially available PFM and SAALA and MNBA systems to regulate the rootzone environment and indirectly influence tomato plant growth, yield and fruit quality. Both MNBA and SAALA increased the plant dry weight, fruit yield and IWUE. In comparison with the no aeration treatment, the MNBA treatment increased dry matter accumulation, fruit yield, IWUE, lycopene content and soluble protein content during the spring season by 7.1%, 9.0%, 7.1%, 6.2% and 16.2%, respectively, while those during autumn increased by 4.0%, 14.4%, 4.0%, 3.8% and 1.7%, respectively. During the spring season, SAALA increased dry matter accumulation, fruit yield, IWUE, lycopene content and soluble protein content by 13.0%, 25.1%, 13.0%, 2.9% and 15.1%, respectively, while those during autumn increased by 12.8%, 19.5%, 12.8%, 5.2% and 4.1%, respectively. The total dry weight, fruit yield and IWUE increased in response to the PFM treatment. Nevertheless, PFM decreased the content of soluble protein. The increased yield in response to soil aeration during autumn was more significant than that during the spring, and the increased yield in response to PFM during the spring was more significant than that during autumn. Considering the effects of cost, efficiency and benefits, the greatest economic benefits were obtained in the MNBA and F PFM treatment combination. These findings suggest that soil aeration and PFM treatment cause significant changes in soil physical and chemical properties, which subsequently affect plant performance and fruit quality.

Author Contributions: Y.L. and Z.Z. conceived the idea for this study. Y.L. and M.Z. supervised the project. J.W. collected the samples. Y.L., M.Z. and J.W. performed the composting experiment. M.Z. and Y.L. performed laboratory work. Y.L. and M.Z. conducted data analysis. Y.L. and M.Z. wrote and revised the manuscript. All authors have read and agreed to the published version of the manuscript.

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Appendix A

Table A1. Main technical parameters of the micro–nano generator.

Indicators	Parameters	Indicators	Parameters
Operating voltage	220 V~50 Hz	Power	300 W
Working pressure	0–0.30 Mpa	Bubble rise velocity	10–15 mm/s
Bubble size	700 nm–2 μ m	Air content	0–90%

Table A2. Irrigation date and amount during both growing seasons.

Spring		Autumn	
Irrigation Date	Irrigation Amount (mm)	Irrigation Date	Irrigation Amount (mm)
9 April 2019	26.23	4 September 2019	25.80
14 April 2019	9.41	9 September 2019	25.88
19 April 2019	25.38	14 September 2019	5.07
24 April 2019	13.07	19 September 2019	4.13
29 April 2019	13.84	24 September 2019	16.61
4 May 2019	17.75	29 September 2019	19.39
9 May 2019	22.89	4 October 2019	9.16
14 May 2019	10.45	9 October 2019	5.87
19 May 2019	16.62	14 October 2019	7.21
24 May 2019	33.16	19 October 2019	8.78
29 May 2019	26.37	24 October 2019	6.47
3 June 2019	22.84	29 October 2019	10.58
8 June 2019	24.29	3 November 2019	9.15
13 June 2019	20.29	8 November 2019	6.88
18 June 2019	21.68	13 November 2019	7.11
23 June 2019	6.71	18 November 2019	8.77
28 June 2019	15.51	23 November 2019	8.55
3 July 2019	20.65	28 November 2019	5.26
8 July 2019	35.05	3 December 2019	6.34
13 July 2019	26.34	8 December 2019	8.99
15 July 2019	15.12	13 December 2019	10.68
Total irrigation amount	423.64	18 December 2019	7.06
		23 December 2019	7.66
		28 December 2019	6.78
		2 January 2020	7.05
		7 January 2020	6.64
		12 January 2020	5.64
		17 January 2020	4.32
		Total irrigation amount	261.83

Figure A1. (a) Experimental arrangement of aeration and (b) plastic film mulch treatments.

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