

Article

Sustainable Soilless Cultivation Mode: Cultivation Study on Droplet Settlement of Plant Roots under Ultrasonic Aeroponic Cultivation

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Abstract: In order to solve the effects of environmental factors on the droplet settlement of a nutrient solution on plant roots when planting plants with ultrasonic aeroponic cultivation, this study aimed to obtain a suitable wind speed range and atomization time through a nutrient solution atomization experiment, to obtain the best control scheme through a multi-environmental parameter combination cultivation experiment. Taking an ultrasonic aeroponic cultivation device as the research object, and lettuce as the test material, experiments were carried out on two factors affecting the wind speed of an axial fan and the atomization time of the nutrient amount of ultrasonic aeroponic cultivation plants; the suitable wind speed range was 1.0–2.5 m/s. The temperatures of the lettuce root zones in the upper, middle, and lower layers of the ultrasonic aeroponic cultivation device at different time periods were obtained by atomizing the nutrient solution. When the optimum temperature for the root growth of lettuce was 15–20 °C and the wind speed was 1.0–2.5 m/s, the continuous atomization time of the nutrient solution was 66–184 min. Using a quadratic orthogonal rotation combination design method, three main factors, namely wind speed, ambient temperature, and atomization time, were selected to test droplet settlement in the lettuce roots. The droplet settlement in the lettuce root system was measured. The droplet settlement regression equation in the lettuce root system was established. The reliability of the regression model was tested according to the significance condition, and a simplified quadratic orthogonal regression equation was obtained. The main effect analysis, single factor analysis, and interaction effect analysis were used to analyze the model, and the model was further verified. The verification results showed that the relative error between the predicted value and the actual value of the average root droplet sedimentation was 5.8%. The optimum wind speed was 2.5 m/s, the ambient temperature was 16 °C, and the atomization time was 184 min when the ultrasonic aeroponic cultivation device designed in this study was used to cultivate lettuce. It could provide a theoretical reference and an experimental basis for the control of the related growth environment parameters of plants cultivated using ultrasonic aeroponic cultivation.

Keywords: ultrasonic aeroponic cultivation; plant roots; droplet settlement; wind speed; temperature; atomization time



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1. Introduction

With the continuous growth of the global population, the deterioration of the natural environment, and the continuous reduction in cultivated land area around the world, the shortage of agricultural resources is becoming increasingly serious, and the global agricultural system is facing great challenges of sustainable development [1–5]. In order to alleviate the huge pressure brought about by population growth on resources and the environment, exploring new agricultural methods for sustainable development is an important scientific issue in our agricultural field at present [6–8]. The industrialized production mode of crops is an important technical means for the safe and sustainable development of fruits and vegetables in the future [9,10]. With the development of agricultural technology,

human agricultural production has generally experienced open-field cultivation, protected cultivation, plant factories, and other main forms, showing different cultivation modes. The soilless cultivation of plants refers to a cultivation method in which water, peat, vermiculite, and other media are used as the substrate to fix the plant roots, and the plant roots directly contact the nutrient solution. Soilless cultivation methods have changed from substrate cultivation to hydroponic cultivation, and then to aeroponic cultivation [11–13]. Aeroponic cultivation is a new agricultural technology that atomizes the nutrient solution into small settlements and sprays them directly on the surface of the plant roots to provide water and nutrients for growth [14–18]. The existing research mainly focuses on the aeroponic cultivation method of spraying with an atomizing nozzle. The research focuses on the comparison of crop cultivation modes, the setting of atomization parameters, and nutrient absorption effects [19–23].

In aeroponic cultivation technology, there is an ultrasonic aeroponic cultivation method. At present, there are very few studies on ultrasonic aeroponic cultivation technology [24,25]. An ultrasonic aeroponic cultivation system means that, when plants are cultivated via aerponics, the nutrient solution is atomized using an ultrasonic atomizer, and the atomized nutrient solution droplets are blown to each cultivation pipeline through air supply equipment, such as an axial flow fan, and they diffuse to each part of the root system, so that the plant root system hanging in the cultivation pipeline can uniformly absorb nutrients and water. Meanwhile, the system is faced with the continuous ultrasonic atomization of a nutrient solution, which can promote the temperature of the nutrient solution to rise continuously, affect the growth of plant roots, and lead to the decline of productivity; the continuous atomization can increase power consumption and production cost.

In ultrasonic aeroponic cultivation technology, the main problem lies in the lack of water supply for plant roots, and the main reason for this phenomenon lies in the settlement of plant root droplets. The settling amount of plant root droplets is mainly determined by atomization time and atomization amount. Tiwari et al. [26] reported that the atomized nutrient solution droplet sizes and spraying intervals can impact the chemical properties of the nutrient solution, biomass yield, root-to-shoot ratio and nutrient uptake of aeroponically cultivated plants. Four different nozzles, having droplet sizes $N1 = 11.24$, $N2 = 26.35$, $N3 = 17.38$ and $N4 = 4.89 \mu m$, were selected and misted at three nutrient solution spraying intervals of 30, 45 and 60 min, with a 5 min spraying time. The smaller the droplet size, the more stable the lateral root growth and biomass. Lakhari et al. [27] found the effects of different nutrient solution spraying intervals on the growth, development, and nutrient uptake parameters of the aeroponically cultivated lettuce plants. Zhang et al. [28] ensured that the experiment arranged a single factor and multi-level spray frequency optimization experiment (fixed spray time, set different intervals). After the fixed spray time increased the interval time in turn, the fresh weight, eigenvalue and three percentile eigenvalue showed a trend of first rising and then declining.

When using ultrasonic aeroponic cultivation technology to cultivate plants, the atomization effect of the nutrient solution in the plant root zone will directly affect the success or failure of aeroponic cultivation. If root droplet settlement is detected using a humidity sensor, it will fail due to the water droplets being attached to the sensor surface. Therefore, it is difficult to control the root zone environment of ultrasonic aeroponic cultivation by measuring the relative humidity. In order to study the amount of droplet settlement in the root systems of plants cultivated via ultrasonic aerponics, a method of measuring the amount of droplet settlement in the root system was proposed in this paper. The optimum growth environment for plants under ultrasonic aeroponic cultivation is obtained by measuring the amount of root droplet settlement. Inadequate supply of water and nutrients is avoided. The purpose of this study is to solve the effects of environmental factors on the droplet settlement of a nutrient solution on plant roots when planting plants with ultrasonic aeroponic cultivation. This study aimed to obtain a suitable wind speed range and atomization time through a nutrient solution atomization experiment, to obtain

the best control scheme through a multi-environmental parameter combination cultivation experiment. The appropriate wind speed range and the continuous atomization time range of nutrient solution were obtained through the experiment. Finally, the effects of different gradient wind speed, ambient temperature and atomization time on the droplet settlement of plant root nutrient solution were studied to achieve the best combination of environmental parameters. In this study, the effects of different gradients of wind speed, ambient temperature, and atomization time on the droplet settlement of plant root nutrient solution were studied using a quadratic orthogonal rotation combination design method in an ultrasonic aeroponic cultivation factory, with lettuce as the experimental plant. Through structural innovations in the use of ultrasonic aeroponic cultivation devices, and combined with aeroponic cultivation experiments, the problem of insufficient supply of water and nutrients to the root system of ultrasonic aeroponic cultivated plants and imprecise control of environmental parameters has been solved. This study discusses the suitable control scheme of the ultrasonic aeroponic cultivation of plants, which can meet the normal growth needs of plants, save energy, and increase efficiency to the maximum extent, providing a scientific basis for nutrient solution temperature adjustment, device structure optimization, and the reasonable planting of an ultrasonic aeroponic cultivation device, and promote the popularization of ultrasonic aeroponic cultivation technology.

2. Materials and Methods

2.1. Test Device

This research team designed an ultrasonic aeroponic plant cultivation factory (Figure 1). The exterior structure of the plant was cuboid (850 mm × 390 mm × 1350 mm), the exterior support frame was fastened by profiles, and six cultivation pipelines were arranged inside. In order to facilitate experimental observation, a transparent acrylic plate was selected as the material, which must be treated in a dark environment or with shading in actual cultivation and production. There were three layers of cultivation pipelines, including the upper, middle, and lower layers, with two pipelines in each layer, with a length of 600 mm and a symmetrical distribution. In order to facilitate the recirculation of the nutrient solution, the bottom was designed as a semicircle with a radius of 50 mm. There were 6 planting holes on each cultivation pipeline, all with a diameter of 32 mm, and the distance between the centers of the holes was 100 mm. Planting baskets were placed in the planting holes, and the required plants were planted in the planting baskets. A plant growth lamp was installed above the cultivation pipeline for adjusting the illumination required by the plant growth. A nutrient solution storage box was arranged at the bottom of the device, in which the uniformly prepared nutrient solution was arranged, an ultrasonic nebulizer was placed at the bottom of the box for the ultrasonic atomization of the nutrient solution, and the ultrasonic nebulizer was connected to an intermittent switch to control the spraying frequency. The upper cover plate of the nutrient solution storage tank was drilled with two holes with a diameter of 80 mm, and PVC adapters with a diameter of 100 mm were fastened to the holes. Two axial fans (150 mm × 150 mm) with adjustable wind speed were fixed on the left and right sides, which could adjust the atomization amount in the mist conveying pipeline by controlling the wind speed of the axial fans and promoting the mist circulation in the mist conveying pipeline. The PVC pipeline had the function of conveying mist and making the condensed nutrient solution droplets return to the nutrient solution storage box. The exterior of the device was encapsulated with a black acrylic plate. Axial flow fans were installed on the side to promote airflow circulation in the ultrasonic plant aeroponic cultivation factory.

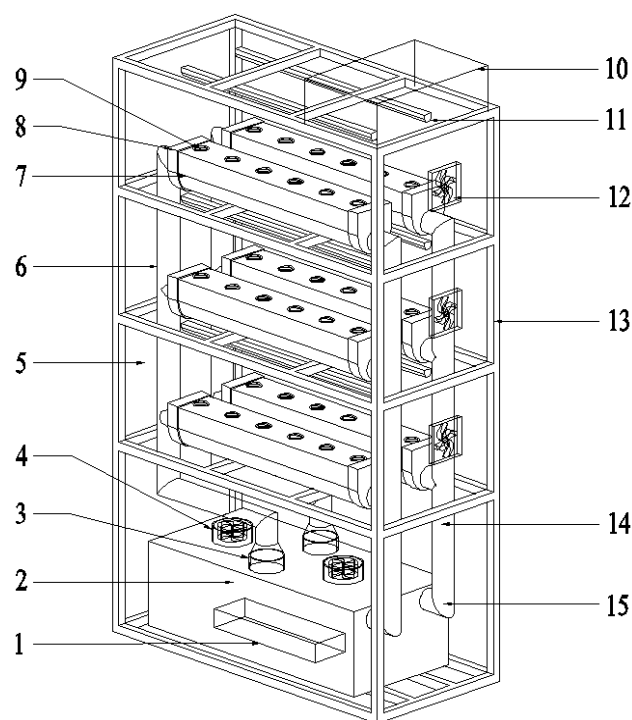


Figure 1. Structural schematic diagram of ultrasonic plant wave aeroponic cultivation factory. Note: 1. Ultrasonic nebulizer. 2. Nutrient solution storage box. 3. PVC adapter. 4. Axial flow fan. 5. Black acrylic plate. 6. PVC mist pipeline. 7. Cultivation pipeline. 8. Cover. 9. Planting hole. 10. Control box. 11. Plant growth lamp. 12. Axial flow fan. 13. Profile support frame. 14. Return pipeline. 15. Adapter.

2.2. Working Principle

The working principle of the ultrasonic plant aeroponic cultivation factory is shown in Figure 2. An ultrasonic nebulizer placed at the bottom of the nutrient solution supply and return box was used to atomize the nutrient solution, and the atomized nutrient solution was transported to the cultivation pipeline through a PVC pipeline through an axial fan with adjustable wind speed. A continuous mist of nutrient solution could gradually accumulate in the root zone of the plants and condense into mist droplets, which could provide the water and nutrients needed by the plant roots and make the plants grow normally. It could directly send the mist generated by the ultrasonic nebulizer into the root zone space without installing a pipeline system and could also directly put the oscillating head generating the ultrasonic mist into the water body of the cultivation system. In order to make the ultrasonic aeroponic have better dispersibility, it could be matched with fans or other air supply methods to blow and spread the settled mist.

2.3. Ultrasonic Nebulizer

The basic principle of the atomizing nutrient solution with an ultrasonic nebulizer [29–31]: the oscillation signal from the main circuit board was amplified using a high-power triode and was transmitted to the ultrasonic wafer. The ultrasonic wafer converted the electric energy into ultrasonic energy, and through the ultrasonic high-frequency oscillation, the nutrient solution at a normal temperature was atomized into 1–5 tiny mist particles, so that the water and fertilizer were in a cloud state, and the plant roots were in the mist to obtain water and fertilizer. Usually, after a single nebulizer atomizes the nutrient solution, the mist formation could reach about $300 \text{ mL} \cdot \text{h}^{-1}$. The ultrasonic nebulizer is shown in Figure 3. The ultrasonic atomization effect of nutrient solution is shown in Figure 4.

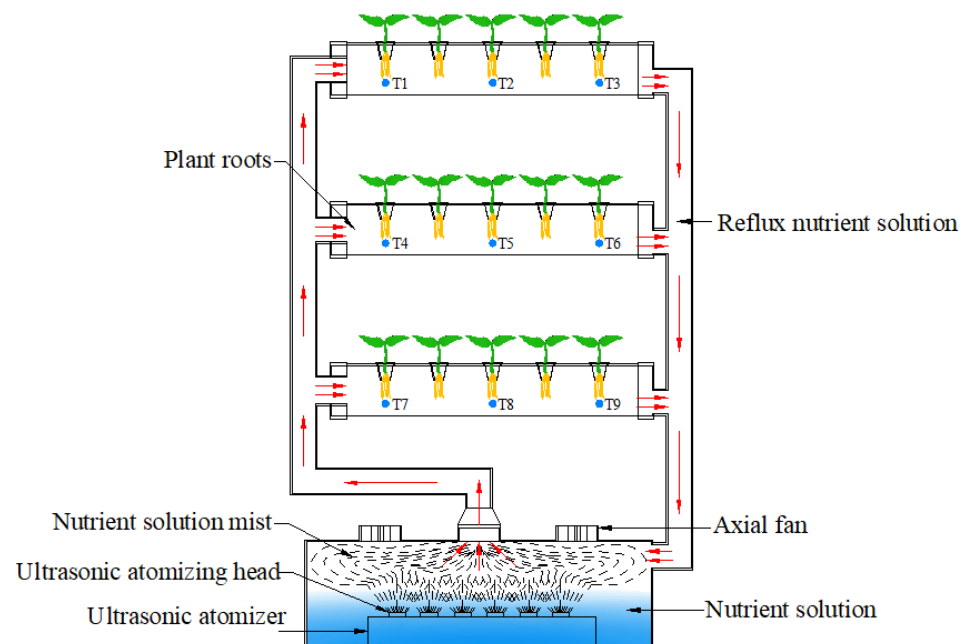


Figure 2. Schematic diagram of ultrasonic aeroponic cultivation. Note: ● indicates the temperature monitoring point.

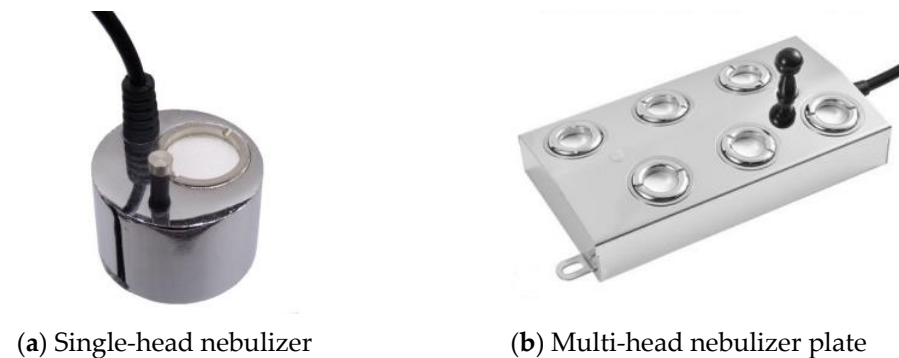


Figure 3. Ultrasonic nebulizer.

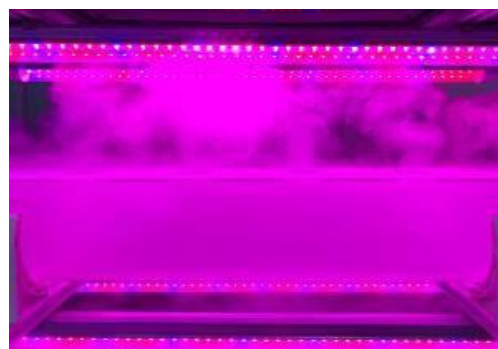


Figure 4. Ultrasonic atomization of the nutrient solution.

2.4. Component Materials and Equipment

The temperature in the aeroponic plant factory was collected using a waterproof temperature sensor. The temperature measurement range of the temperature probe (4 mm × 30 mm × 200 mm) was −50–250 °C, and the accuracy was ±0.15 °C. The ultrasonic atomizer (153 mm × 85 mm × 28 mm) was a 6-head atomizer with a power of 250 W, and the atomization frequency was 1.7 MHz. The wind speed was controlled

by an axial fan (120 mm × 120 mm × 38 mm), the rotation speed was 0–2350 r/min, and the wind speed range was 0–5 m/s. Planting baskets (45 mm × 45 mm × 31.5 mm) were used for crop cultivation. The nutrient solution was stored in a plastic box (620 mm × 430 mm × 320 mm). A PVC pipeline ($r = 50$ mm) was used for mist transportation. The external structure was built with aluminum profiles (1350 mm × 20 mm × 20 mm, 850 mm × 20 mm × 20 mm, and 350 mm × 20 mm × 20 mm). The aeroponic cultivation pipeline (600 mm × 150 mm × 150 mm) was made of acrylic board. The plant supplement light used red and blue LED lights, the length was 60 mm, 15 W. The voltage was regulated by an electronic voltage regulator, with an adjustable voltage of 0–220 V. The power supply used a switching power supply of 220 V to 24 V. The temperature adjustment was controlled by a temperature controller. The temperature was recorded with a data logger (model MIK-R6000F, Meacon Automation technology Co., Ltd, Hangzhou, China), the display screen was 7 inches, the data sampling period was 1 s, and the recording interval was 1 s–60 min. The wind speed value was recorded with a hand-held anemometer; the measuring range was 0.3–45 m/s, the measurement error was $\pm 3\%$, and the resolution was 0.001. The electronic scale was used to measure the weight, to an accuracy of 0.001 g. The materials and equipment are shown in Figure 5.

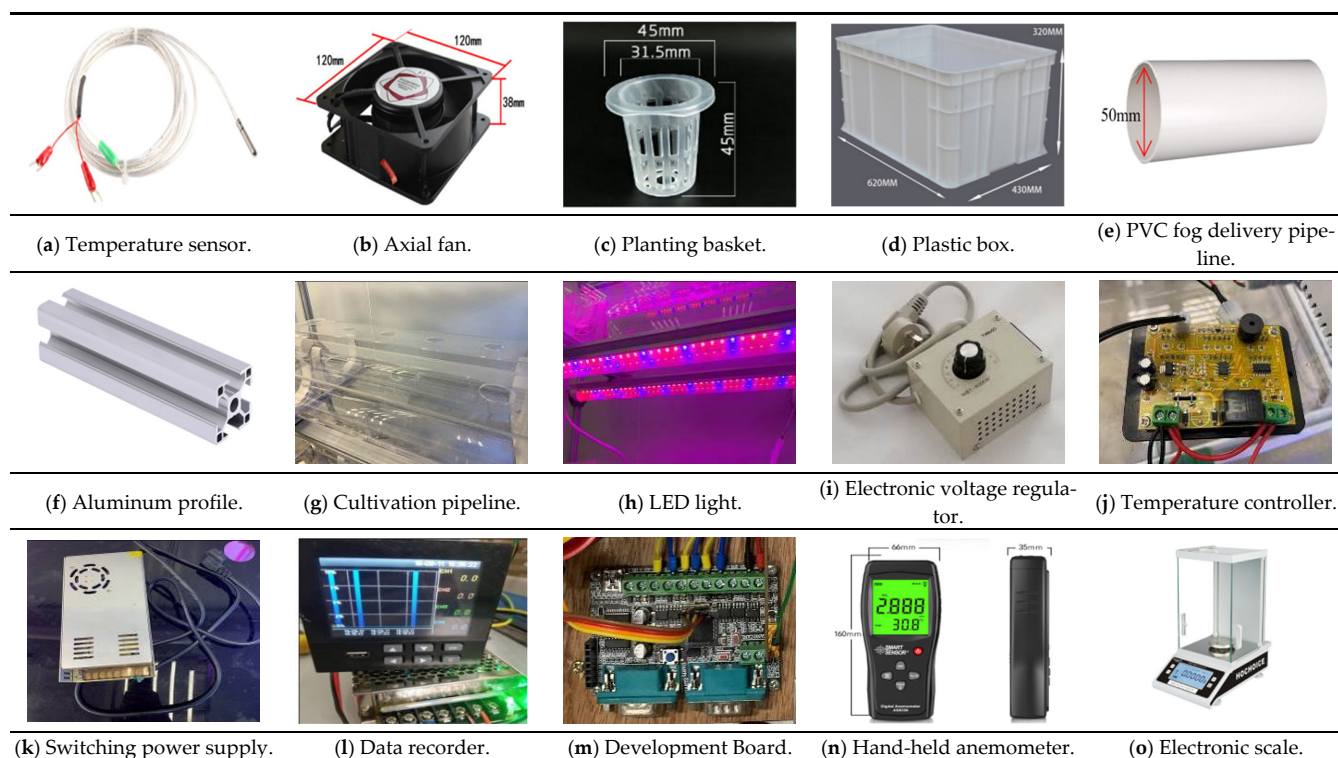


Figure 5. Materials and equipment of ultrasonic aeroponic plant cultivation factory.

2.5. Test Conditions

Lettuce seeds were put on a square seedling sponge for seedling raising; when the roots of the seedlings grew to 5–7 cm, they were planted, and they were planted in aeroponic cultivation planting holes for testing. The illumination settings for lettuce in the growing period: the light period was 16 h (06:00–23:00), the dark period was 8 h (23:00–07:00), the temperature (20 ± 0.5 °C), humidity (70–80%), and the nutrient solution had an EC value of 1.6–1.8 ms/cm and a pH value of 5.8–6.2.

2.6. Test Method and Data Analysis

When the ultrasonic nebulizer continuously atomized the nutrient solution, the temperature of the nutrient solution in the storage box could rise continuously, due to the continuous release of energy from the nebulizer. After heating up, the nutrient solution

mist was transported to the cultivation pipeline, which resulted in a temperature increase in the pipeline. The cultivation pipeline had three layers: upper, middle, and lower. Because of the different layer heights, the temperature in the pipeline was different, which affected the normal growth of the lettuce roots. At the same time, the continuous atomization time could affect the amount of droplet settlement and the nutrient supply of the plant roots, so it was necessary to set multiple groups of atomization times for the experiments [32].

Firstly, the two main parameters of wind speed range and atomization time needed to be determined. The atomized nutrient solution was transported to each layer of the cultivation pipeline using an axial flow fan; because the height of each layer of the cultivation pipeline was different, the droplet settlement of the nutrient solution in each layer of the cultivation pipeline was also different. In order to ensure that the atomized nutrient solution could be transported to the upper, middle, and lower layers of the cultivation pipelines, the wind speed value of the axial flow fan should be maintained at an appropriate range. The experimental wind speed started at 0 m/s and ended at 5 m/s, and a suitable wind speed range was obtained. Because the suitable temperature for lettuce root growth was 18–22 °C, the atomization experiment of the nutrient solution was carried out within the range of ensuring a root zone temperature of 18–22 °C and combined with a suitable wind speed range. The nutrient solution was atomized from 0 min to 300 min, and a suitable atomization time range was obtained. The temperature in the cultivation pipeline was adjusted by controlling the range of wind speed and atomization time [33].

According to the wind speed range and atomization time obtained from the experiment, combined with the ambient temperature, the influence of wind speed, ambient temperature, and atomization time on the droplet settlement of plant roots was analyzed using a quadratic orthogonal rotation combination design method, and each factor was divided into different levels for experiments. The amount and temperature of the droplets deposited in the lettuce roots were measured in the upper, middle, and lower layers of cultivation, and the best combination of parameters for controlling was explored. The precipitation of the nutrient solution mist droplets is shown in Figure 6.

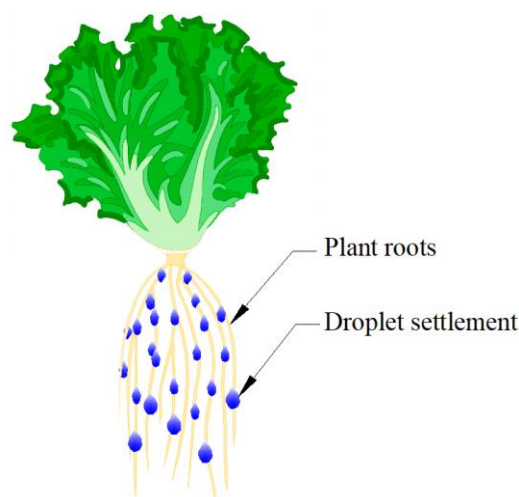


Figure 6. Schematic diagram of nutrient solution droplet settlement.

The wind speed of the axial flow fan is adjusted by controlling the electronic pressure regulator. Before each test, the hand-held anemometer was used to measure the wind speed. When measuring the wind speed, the probe of the hand-held anemometer was close to the outlet of the axial flow fan to record the wind speed value.

For temperature sampling, the temperature near the root system in the cultivation pipeline was collected using temperature sensors, and the sensors were distributed. Because the two sides of the cultivation pipeline were symmetrically distributed, only one side of the cultivation pipeline was tested. Three temperature collection points were arranged in each layer of pipelines, with a total of three layers of pipelines and nine collection points.

The weight of root settlement was measured using an electronic scale. Root settlement refers to the number of nutrient droplets atomized by an ultrasonic wave blown to the root zone using an axial flow fan and deposited onto the root system of plants, which was directly related to the nutrients and water that plants can absorb. Before each atomization test, the nutrient solution was dried on the fixed cotton plant and root system, weighed, and weighed again after atomization, then the difference between before and after was calculated to obtain the root droplet settlement. In order to reduce the test error, the plants in the same position were measured and averaged in the upper, middle, and lower layers of the cultivation device.

The lettuce cultivated in the upper, middle, and lower layers of pipelines in the ultrasonic plant aeroponic cultivation factory was analyzed. The number of leaves of raw vegetables were counted manually. Leaf length, leaf width, and root length of lettuce were measured using a vernier caliper. When measuring the fresh weight of lettuce, the water in the corresponding part of the lettuce was absorbed by the absorbent paper first, and then the dry weight of the lettuce was measured using an electronic scale.

Statistical analysis of the data was carried out using SPSS 25.0 (IBM Corp., Armonk, NY, USA). The analysis diagrams were plotted using Origin 2020 (OriginLab, Northampton, MA, USA). The plant root droplet settlement data were processed and analyzed using DPS V7.05. A quadratic regression model was developed using a quadratic orthogonal rotational combination design and an analysis of variance. Using a data optimization procedure, the environmental parameters that affect the root settlement of ultrasonic aerosol plants are optimized.

2.7. Experimental Design

A quadratic orthogonal rotation combination design method was used to test the settlement number of droplets in lettuce roots. The number of quadratic orthogonal rotation combination in the design area could not be determined according to the number of processing repetitions, which had the advantages of less test times and no correlation between regression coefficients. The central point processing method was used for data processing. Three main factors in ultrasonic aeroponic cultivation, namely wind speed X_1 , ambient temperature X_2 , and continuous atomization time X_3 , were selected as factors affecting the amount of droplet settlement in the lettuce roots, and the changes of droplet settlement in the lettuce roots were analyzed. According to the experimental results and actual parameters, the upper and lower limits of each factor were determined, in which the range of the wind speed was 1–2.5 m/s, the ambient temperature outside the cultivation pipeline was 15–20 °C, and the optimum range of continuous atomization time was 66–184 min. Each factor was set with five levels, each factor was set with a zero level (Z_{0j}) and change interval (Δ_j), and the 5 levels of ambient temperature were set to 20 °C, 18.987 °C, 17.5 °C, 16.013 °C, and 15 °C, respectively, which were directly realized by the control system. The 5 levels of wind speed were 2.5 m/s⁻¹, 2.196 m/s⁻¹, 1.75 m/s⁻¹, 1.304 m/s⁻¹, and 1 m/s⁻¹, respectively; and the 5 levels of atomization time were 184 min, 160.081 min, 125 min, 89.919 min, and 66 min, respectively. The factor level table is shown in Table 1. According to the orthogonal rotation combination design method of 3 factors and 5 levels, 23 groups of experiments were arranged to measure the droplet settlements and temperatures of lettuce roots in the upper, middle, and lower layers. The data were analyzed using DPS software, the regression equation was established, and the significance test and equation simplification were carried out. Because the experiment aims to find the best combination parameters, the effect of nutrient solution temperature on the droplet settlement of the lettuce root was not considered, and the initial value of the nutrient solution was set to the lowest temperature known in the previous experiment of 18 °C. The root droplet settlement amount was the weight difference before and after the droplet settlement of the lettuce root, and the droplet settlement weight was taken as the average value of a single plant.

Table 1. Three factors and 5 levels coding table.

Levels	Factors		
	Wind Speed (m/s)	Ambient Temperature (°C)	Atomization Time (min)
Zero Level (Z_{0j})	1.75	17.5	125
Change Interval (Δ_j)	0.375	1.25	29.5
1.6818	2.5	20	184
1	2.196	18.987	160.081
0	1.75	17.5	125
−1	1.304	16.013	89.919
−1.6818	1	15	66

3. Results

3.1. Optimization Experiment of Plant Root Zone Temperature

3.1.1. Influence of Wind Speed Value on Mist Transportation

The growth environment of plant aeroponic cultivation mainly revolves around the root system, and so it is particularly important to control the root zone temperature and the axial fan wind speed in the root system growth environment. When using an ultrasonic nebulizer to atomize the nutrient solution, the temperature of the nutrient solution gradually rose due to the heat dissipation of the nebulizer, and the heated mist was transported to the cultivation pipeline, which led to a rise in the root zone temperature of the lettuce and affected the normal growth of the lettuce. However, the wind speed determines the amount of atomization transported, affects the root zone heating time, and determines the atomization time interval. Therefore, it is necessary to ensure that the wind speed can transport the nutrient solution atomized by air to the upper, middle, and lower cultivation pipelines, adjust the atomization time value of the ultrasonic nebulizer according to the wind speed range, and control the lettuce root system to be in the suitable growth temperature range of 18–22 °C. In this paper, different gradient wind speed values were set for the axial flow fan, and a pre-test was carried out under the condition of no lettuce planting. The results show that when the wind speed was 0.2 m/s, the saturation mist could enter the lower cultivation pipeline and begin to overflow from the planting hole; when the wind speed was 0.5 m/s, the middle pipeline could enter the saturated mist and begin to overflow from the planting hole; when the wind speed was 1.0 m/s, the upper cultivation pipeline could enter the saturated mist and begin to overflow from the planting hole. When the wind speed was 2.5 m/s, the mist pipeline was basically saturated. In conclusion, in order to ensure that the mist amount needed for lettuce root growth could be reached in the upper, middle, and lower layers of the cultivation pipelines, the appropriate wind speed should be in the range of 1.0–2.5 m/s.

3.1.2. Optimization of Root Zone Temperature Range

According to the suitable wind speed range of 1–2.5 m/s and the suitable temperature for lettuce growth of 15–20 °C, two groups of parameters were set to carry out the experiment, and the time range of continuous atomization was obtained. The measured temperature was nine monitoring points of upper, middle, and lower cultivation pipelines. According to the data of the previous experiment, the following parameter values were set. Group A: the temperature outside the cultivation pipeline was 15 °C and the wind speed was 1 m/s, which could obtain the longest continuous atomization time. Group B: the temperature outside the cultivation pipeline was 20 °C, the wind speed was 2.5 m/s, and the shortest continuous atomization time could be obtained. In order to ensure the root growth in the optimum temperature environment of 18–22 °C, the initial temperature of the nutrient solution was set at 18 °C. Under the condition of the Group A parameters (Tables 2 and 3), the data analysis of the temperature change of continuous atomization and stop atomization shows that, when the temperature outside the cultivation pipeline was 15 °C and the wind speed was 1 m/s, the temperature inside the cultivation pipeline began to decrease rapidly with the nutrient solution with the initial temperature of 18 °C, and the

temperature at the measuring point began to be lower than 18 °C. After the temperature dropped to a stable state, it gradually began to rise. At the 110th min, the temperature exceeded 19 °C. By the 184th min, the temperature at measuring point 7 exceeded 22 °C. It could be concluded that when the initial temperature of nutrient solution was 18 °C, in order to ensure root growth in the optimum temperature environment of 18–22 °C, the longest continuous atomization time of the nutrient solution was 184 min. Under the condition of the Group B parameters (Tables 4 and 5), the analysis of the temperature change data of continuous atomization and stop atomization showed that when the temperature outside the cultivation pipeline was 20 °C and the wind speed was 2.5 m/s, after continuous atomization with nutrient solution with an initial temperature of 18 °C, the temperature inside the cultivation pipeline began to decrease gradually and slowly, and the temperature at some monitoring points began to be lower than 18 °C. At 28 min, the temperature began to rise and gradually increased, and at 66 min, monitoring point 9 began to exceed 22 °C. When the time of stopping atomization reached 32 min, the temperature was at its lowest value, and the atomization time could last the longest at this time. When the atomization time reached 34 min, the temperature began to rise slowly. It could be concluded that when the initial temperature of the nutrient solution was 18 °C, in order to ensure that root growth remained in the optimum temperature environment of 18–22 °C, the longest continuous atomization time of nutrient solution was 66 min. According to the test results, it could be seen that the continuous atomization time ranged from 66 min to 184 min.

Table 2. Change in temperature monitoring point data during continuous atomization under Group A parameters.

Continuous Atomization Time (min)	Nutrient Solution Temperature (°C)	Temperature of Measuring Point in the Root Zone of Cultivation Pipeline (°C)								
		Upper			Middle			Lower		
		1	2	3	4	5	6	7	8	9
0	18	18.84	18.49	17.99	17.7	17.81	18.74	19.24	19.92	20.46
60	31.17	17.16	16.77	16.95	17.67	16.84	17.63	18.34	17.73	18.38
110	36.56	17.98	18.31	19.06	19.31	17.95	18.27	19.96	19.06	19.71
112	36.81	18.13	18.6	19.24	19.46	18.17	18.34	20.36	19.46	19.85
160	39.18	18.48	19.92	20.46	20.17	19.17	18.88	21.5	20.35	20.82
184	39.61	20.53	20.17	20.82	20.42	19.45	20.53	22.22	21.1	21.9

Table 3. Change in temperature monitoring point data during stop atomization under Group A parameters.

Stop Atomization Time (min)	Temperature of Measuring Point in the Root Zone of Cultivation Pipeline (°C)								
	Upper			Middle			Lower		
	1	2	3	4	5	6	7	8	9
0	20.53	20.17	20.82	20.42	19.45	20.53	22.22	21.1	21.9
2	19.49	18.88	18.48	18.52	18.77	19.06	20.42	20.89	21.71
4	18.84	18.49	17.99	17.7	17.81	18.74	19.24	19.92	20.46

Table 4. Change in temperature monitoring point data during continuous atomization under Group B parameters.

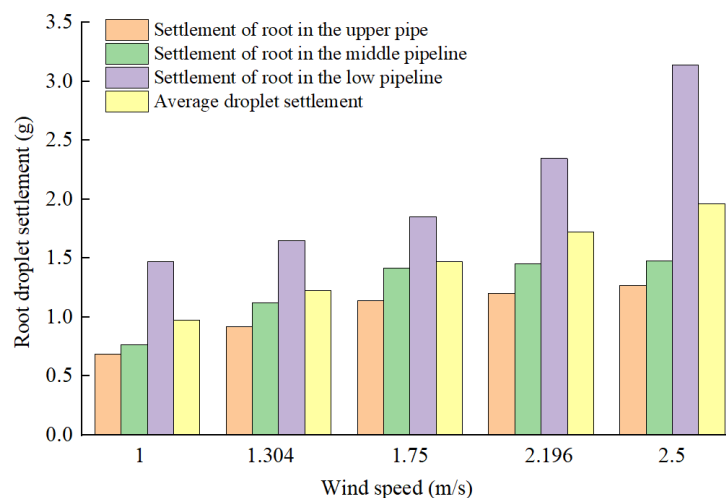
Continuous Atomization Time (min)	Nutrient Solution Temperature (°C)	Temperature of Measuring Point in the Root Zone of Cultivation Pipeline (°C)								
		Upper			Middle			Lower		
		1	2	3	4	5	6	7	8	9
0	18.00	18.89	19.28	18.89	18.53	18.49	18.49	18.28	18.31	18.53
12	21.1	18.05	18.31	17.91	17.81	17.66	17.77	17.55	17.52	17.77
26	24.18	18.48	18.38	18.45	18.42	17.91	18.49	18.45	17.95	18.52
28	24.68	18.59	18.45	18.45	18.38	18.02	18.56	18.63	18.13	18.74
64	31.17	20.17	19.71	20.35	20.82	20.07	21.11	21.47	20.79	21.97
66	31.42	20.25	19.85	20.57	20.97	20.1	21.18	21.72	20.97	22.12

Table 5. Change in temperature monitoring point data during stop atomization under Group B parameters.

Stop Atomization Time (min)	Temperature of Measuring Point in the Root Zone of Cultivation Pipeline (°C)								
	Upper			Middle				Lower	
	1	2	3	4	5	6	7	8	9
0	20.25	19.85	20.57	20.97	20.1	21.18	21.72	20.97	22.12
10	19.42	19.68	19.5	19.21	19.17	19.46	19.64	19.53	19.93
20	19.06	19.35	19.1	18.74	18.74	18.92	18.85	18.85	19.06
30	18.92	19.21	18.85	18.53	18.49	18.64	18.31	18.28	18.6
32	18.85	19.21	18.81	18.53	18.49	18.6	18.24	18.24	18.38
34	18.89	19.28	18.89	18.53	18.49	18.49	18.28	18.31	18.53

3.2. Experiment on the Droplet Settlement of Plant Roots

The ambient temperature and atomization time were fixed at zero level, and the change trend of the droplet settlement of the plant root nutrient solution with the wind speed was analyzed (Figure 7). The wind speed and ambient temperature were fixed at zero, and the trend of the amount of nutrient solution droplet settlement with the atomization time was analyzed (Figure 8). The results show that the root droplet settlement value had a linear relationship with wind speed and atomization time. For the root system droplet settlement value of the three-layer pipeline, the middle pipeline was the largest, the upper pipeline was the second-largest, and the lowest was the lower pipeline with the most nutrient solution mist. The reason for this was that the height of the lower pipeline was low, and the mist of the nutrient solution was affected by the height and gravity; the mist floated down and was concentrated in the lower pipeline. The upper pipeline was far away from the nutrient solution storage tank below, and the wind speed reaching the upper layer was small due to the height, resulting in relatively less nutrient solution mist in the upper layer.

**Figure 7.** The change trend of plant root droplet settlement with wind speed.

A quadratic orthogonal rotation combination design method was used for cultivation experiments, plant root settlement parameters were collected, and the average root droplet settlement of a single plant was calculated. Twenty-three groups of droplet deposition and temperature data were measured (Table 6). The results showed that, among all the combinations, the maximum droplet settlement in the upper pipeline was 2.047 g, the minimum was 0.19 g, and the average was 1.224 g. The maximum droplet precipitation in the middle pipeline was 2.16 g, the minimum was 0.547 g, and the average was 1.251 g. The maximum value of droplet settlement in the lower pipeline was 3.14 g, the minimum value was 0.687 g, and the average value was 1.55 g. According to the droplet settlement data of the upper, middle, and lower pipelines, the droplet settlement of plant roots in the lower pipeline was larger than that of the middle pipeline, and the droplet settlement of plant roots in the upper pipeline was the smallest.

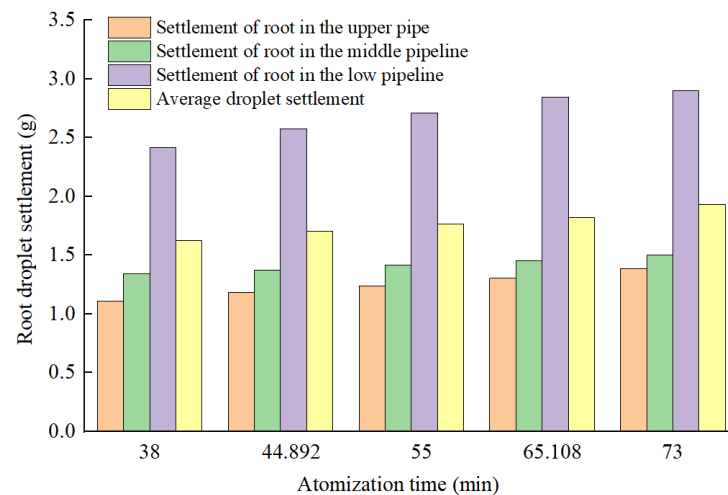


Figure 8. The change trend of plant root droplet settlement with atomization time.

Table 6. Test results of droplet settlement.

Number	Wind Speed X_1 (m/s ⁻¹)	Ambient Temperature X_2 (°C)	Atomization Time X_3 (min)	Upper Pipeline	Middle Pipeline	Lower Pipeline	Average
				Y_1 (g)	Y_2 (g)	Y_3 (g)	Y_4 (g)
1	1	1	1	1.763	0.547	1.943	1.418
2	1	1	−1	1.150	0.847	1.227	1.075
3	1	−1	1	1.717	1.743	2.267	1.909
4	1	−1	−1	1.383	1.403	1.390	1.392
5	−1	1	1	0.390	1.163	1.230	0.928
6	−1	1	−1	0.190	0.693	1.347	0.743
7	−1	−1	1	1.430	2.160	1.670	1.753
8	−1	−1	−1	1.160	0.950	1.257	1.122
9	−1.6818	0	0	0.687	0.767	1.470	0.975
10	1.6818	0	0	1.270	1.477	3.140	1.962
11	0	−1.6818	0	2.047	1.383	2.153	1.861
12	0	1.6818	0	1.333	0.817	0.687	0.946
13	0	0	−1.6818	1.110	1.343	2.417	1.623
14	0	0	1.6818	1.387	1.503	2.900	1.930
15	0	0	0	1.137	1.417	1.850	1.468
16	0	0	0	0.860	1.347	1.200	1.136
17	0	0	0	1.063	1.213	1.170	1.149
18	0	0	0	0.903	1.227	1.110	1.080
19	0	0	0	0.737	1.237	0.983	0.986
20	0	0	0	0.950	1.237	1.167	1.118
21	0	0	0	1.037	1.640	0.913	1.197
22	0	0	0	1.080	1.310	1.110	1.167
23	0	0	0	1.030	1.353	1.103	1.162

3.3. Establishment and Verification of the Plant Root Droplet Settlement Model

3.3.1. Regression Equation Establishment

Regression analysis was carried out on 23 groups of experimental data of droplet settlement in the lettuce root system. Taking droplet settlement in the root system as the objective function, the mathematical regression equations of wind speed, ambient temperature, and atomization time were established using a quadratic regression general rotation combination calculation program:

$$Y_1 = 0.981 + 0.28X_1 - 0.249X_2 + 0.138X_3 - 0.037X_1^2 + 0.215X_2^2 + 0.059X_3^2 + 0.228X_1X_2 + 0.06X_1X_3 + 0.026X_2X_3 \quad (1)$$

$$Y_2 = 1.332 + 0.056X_1 - 0.29X_2 + 0.146X_3 - 0.078X_1^2 - 0.086X_2^2 + 0.028X_3^2 - 0.062X_1X_2 - 0.205X_1X_3 - 0.173X_2X_3 \quad (2)$$

$$Y_3 = 1.192 + 0.303X_1 - 0.242X_2 + 0.198X_3 + 0.265X_1^2 - 0.048X_2^2 + 0.39X_3^2 - 0.017X_1X_2 + 0.162X_1X_3 - 0.086X_2X_3 \quad (3)$$

$$Y_4 = 1.689 + 0.213X_1 - 0.26X_2 + 0.161X_3 + 0.05X_1^2 + 0.027X_2^2 + 0.159X_3^2 + 0.05X_1X_2 + 0.006X_1X_3 - 0.078X_2X_3 \quad (4)$$

where, Y_1 , Y_2 , Y_3 and Y_4 are the root droplet settlement of upper, middle and lower pipelines and average plants, respectively (g); X_1 is the wind speed (m/s^{-1}); X_2 is the ambient temperature ($^{\circ}\text{C}$); and X_3 is atomization time (min).

3.3.2. Significance Test of Regression Equation

In order to test the reliability of the regression model, a significance test and variance analysis were carried out on the regression equation according to the regression term at a 0.05 significance level (Table 7). Looking up the table, we can see that $F_{0.05}(9, 13) = 2.71$ and $F_{0.01}(5, 8) = 6.63$. By analyzing the data in Table 7, regression items: $F_1 = 12.528 > F_{0.05}(9, 13) = 2.71$, $F_2 = 5.42 > F_{0.05}(9, 13) = 2.71$, and $F_3 = 3.460 > F_{0.05}(9, 13) = 2.71$, the regression model was extremely significant; misfit term: $F_4 = 3.371 < F_{0.01}(5, 8) = 6.63$, $F_5 = 5.129 < F_{0.01}(5, 8) = 6.63$, and $F_6 = 5.834 < F_{0.01}(5, 8) = 6.63$; the misfit term was not significant. The quadratic regression model had a good fitting effect and can be used to predict the droplet settlement of plant roots.

3.3.3. Significance Test of Regression Coefficient

The regression coefficients of the quadratic regression models Y_1 , Y_2 , Y_3 , and Y_4 were tested using a t -test. After eliminating the insignificant terms, the simplified quadratic orthogonal regression equation was as follows:

$$Y_1 = 1.7739 + 0.3431X_1 + 0.3808X_2 + 0.5607X_4 \quad (5)$$

$$Y_2 = 1.9538 + 0.5725X_1 + 0.4145X_2 + 0.6243X_4 \quad (6)$$

$$Y_3 = 1.5996 + 0.4642X_1 + 0.2503X_2 + 0.4731X_4 \quad (7)$$

$$Y_4 = 1.7767 + 0.4596X_1 + 0.3487X_2 + 0.5533X_4 \quad (8)$$

3.4. Analysis of Plant Root Droplet Settlement Model

3.4.1. Analysis of Main Effects

For the quadratic regression model, it was necessary to consider the first and second terms of a factor to analyze the importance of the factors. Therefore, the contribution rate analysis method was used to sort the experimental factors according to the contribution rate. The results showed that the ambient temperature had little effect on the amount of droplet settlement of plant roots, but the amount of droplet settlement of plant roots in the upper pipeline and wind speed had the greatest effect, followed by the atomization time; and the amount of atomization had the smallest effect. In the middle pipeline, the amount of droplet settlement and atomization had the greatest influence, followed by atomization time, and the influence of wind speed was the smallest. The lower pipeline was the same as the middle pipeline.

3.4.2. Single Effect Analysis

The effects of wind speed (X_1), ambient temperature (X_2), and atomization time (X_3) on the droplet settlement of plant roots were studied via the dimension reduction method; that is, when other factors were fixed at a zero level, the influence of a single factor on the experimental results was analyzed (Table 8).

Let X_i be -1.682 , -1 , 0 , 1 , and 1.682 , respectively; the corresponding predicted settlement values of plant root droplets are calculated by Equations (9)–(20), and the curve effect diagrams of different levels of a single factor on the settlement values of root droplets were obtained, respectively (Figure 9). It could be seen from the analysis that the settlement amount increased with the increase in wind speed, decreased with the increase in ambient temperature, and increased with the increase in atomization time.

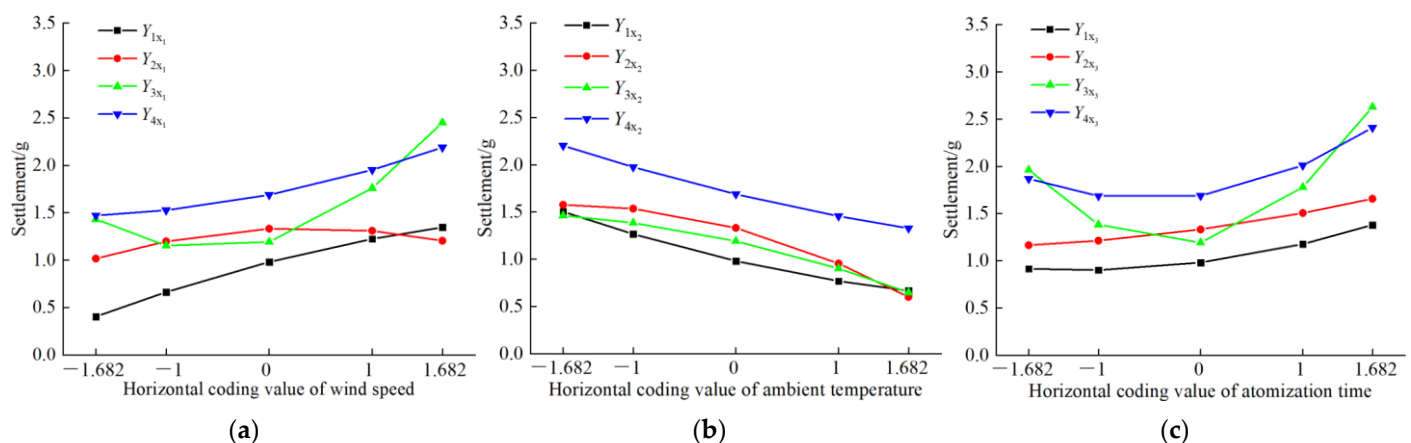
Table 7. Results of variance analysis of regression equation of droplet settlement.

Source of Difference	Sum of Square				Degree of Freedom	Mean Square				F Value				p Value			
	Y ₁	Y ₂	Y ₃	Y ₄		Y ₁	Y ₂	Y ₃	Y ₄	Y ₁	Y ₂	Y ₃	Y ₄	Y ₁	Y ₂	Y ₃	Y ₄
X ₁	1.0705	0.0432	1.2499	0.6192	1	1.0705	0.0432	1.2499	0.6192	35.1309	0.9116	6.0784	15.8978	0.0001 **	0.3571	0.0284 *	0.0016
X ₂	0.8454	1.147	0.7986	0.9232	1	0.8454	1.147	0.7986	0.9232	27.7438	24.2055	3.8837	23.7045	0.0002 **	0.0003 **	0.0704	0.0003
X ₃	0.2596	0.2897	0.5343	0.3519	1	0.2596	0.2897	0.5343	0.3519	8.5193	6.1136	2.5984	9.0359	0.012 *	0.028 *	0.1310	0.0101
X ₁ ²	0.0234	0.0958	1.0942	0.0377	1	0.0234	0.0958	1.0942	0.0377	0.7672	2.0225	5.3211	0.969	0.397	0.1785	0.0382 *	0.3429
X ₂ ²	0.734	0.1161	0.0440	0.0104	1	0.734	0.1161	0.0440	0.0104	24.0903	2.451	0.2141	0.2673	0.0003 **	0.1415	0.6512	0.6138
X ₃ ²	0.053	0.0138	2.3953	0.3986	1	0.053	0.0138	2.3953	0.3986	1.7398	0.2916	11.6484	10.234	0.2099	0.5983	0.0046 **	0.007
X ₁ X ₂	0.4154	0.031	0.0023	0.0196	1	0.4154	0.031	0.0023	0.0196	13.6334	0.6542	0.0114	0.5033	0.0027 **	0.4332	0.9166	0.4906
X ₁ X ₃	0.0284	0.3362	0.2103	0.0002	1	0.0284	0.3362	0.2103	0.0002	0.9334	7.0947	1.0226	0.0062	0.3516	0.0195 *	0.3304	0.9384
X ₂ X ₃	0.0055	0.2381	0.0597	0.048	1	0.0055	0.2381	0.0597	0.048	0.1792	5.0235	0.2903	1.2337	0.679	0.0431 *	0.5992	0.2868
regression	3.4357	2.3114	6.4039	2.4119	9	0.3817	0.2568	0.7115	0.268	F ₁ = 12.528	F ₂ = 5.42	F ₃ = 3.46	F ₂ = 6.881	0.0003 **	0.0079 **	0.0343 *	0.0033
residual	0.3961	0.616	2.6732	0.5063	13	0.0305	0.0474	0.2056	0.0389								
Lack of fit	0.2686	0.4696	2.0979	0.371	5	0.0537	0.0939	0.4196	0.0742	F ₄ = 3.371	F ₅ = 5.129	F ₆ = 5.834	F ₁ = 4.385	0.0359	0.0081	0.0049	0.0147
error	0.1275	0.1465	0.5754	0.1354	8	0.0159	0.0183	0.0719	0.0169								
Total sum	3.8318	2.9275	9.0771	0.5162	22												

Note: ** $p < 0.01$, indicates a very significant difference, * $p < 0.05$, indicates a significant difference.

Table 8. Regression sub-model of single factor on droplet settlement of plant root system.

Factor	Model
Wind speed	$Y_{1x_1} = 0.981 + 0.28X_1 - 0.037X_1^2$ (9)
	$Y_{2x_1} = 1.332 + 0.056X_1 - 0.078X_1^2$ (10)
	$Y_{3x_1} = 1.192 + 0.303X_1 + 0.265X_1^2$ (11)
	$Y_{4x_1} = 1.689 + 0.213X_1 + 0.05X_1^2$ (12)
Ambient temperature	$Y_{1x_2} = 0.981 - 0.249X_2 + 0.215X_2^2$ (13)
	$Y_{2x_2} = 1.332 - 0.29X_2 - 0.086X_2^2$ (14)
	$Y_{3x_2} = 1.192 - 0.242X_2 - 0.048X_2^2$ (15)
	$Y_{4x_2} = 1.689 - 0.26X_2 + 0.027X_2^2$ (16)
Atomization time	$Y_{1x_3} = 0.981 + 0.138X_3 + 0.059X_3^2$ (17)
	$Y_{2x_3} = 1.332 + 0.146X_3 + 0.028X_3^2$ (18)
	$Y_{3x_3} = 1.192 + 0.198X_3 + 0.39X_3^2$ (19)
	$Y_{4x_3} = 1.689 + 0.161X_3 + 0.159X_3^2$ (20)

**Figure 9.** (a) Effects of wind speed on droplet settlement; (b) effects of ambient temperature on droplet settlement; (c) effects of atomization time on droplet settlement. Note: indicates the temperature monitoring point.

3.4.3. Analysis of Interaction Effects

Any one factor among wind speed, ambient temperature, and atomization time was set to 0; the binary quadratic equations of the other two factors could be obtained; the interaction models of wind speed and ambient temperature, wind speed and atomization time, and ambient temperature and atomization time could be calculated by analyzing the average droplet settlement of plant roots (Table 9), and the interaction surface maps were drawn, respectively (Figure 10). The results showed that with the increase in wind speed and atomization time, the settlement amount increased gradually, and the interaction between wind speed and ambient temperature, atomization amount and ambient temperature, and atomization amount and atomization time, was significant.

Table 9. Interaction model of pairwise factors.

Factor	Model
Wind Speed And Ambient Temperature	$Y_4 = 1.689 + 0.213X_1 - 0.26X_2 + 0.05X_1^2 + 0.027X_2^2 + 0.05X_1X_2$ (21)
Wind Speed And Atomization Time	$Y_4 = 1.689 + 0.213X_1 + 0.161X_3 + 0.05X_1^2 + 0.159X_3^2 + 0.006X_1X_3$ (22)
Ambient Temperature And Atomization Time	$Y_4 = 1.689 - 0.26X_2 + 0.161X_3 + 0.027X_2^2 + 0.159X_3^2 - 0.078X_2X_3$ (23)

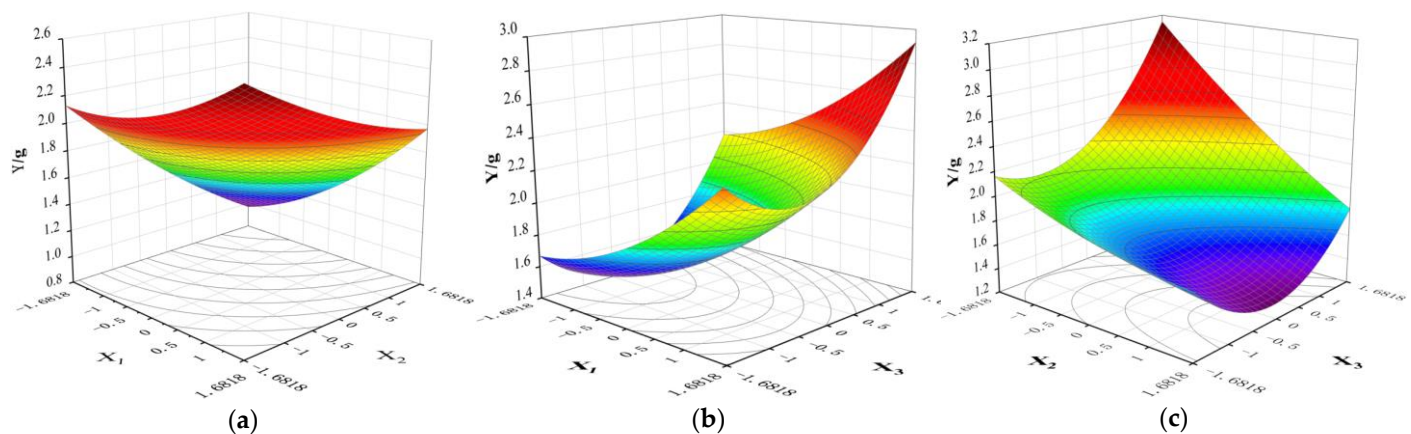


Figure 10. Effect of interaction of two factors on average atomization settlement of plant roots: (a) Interaction between wind speed and ambient temperature; (b) interaction between wind speed and atomization time; (c) interaction between ambient temperature and atomization time. The different colors represent different heights.

3.4.4. Optimization of Regression Equation

The software was used to simulate and analyze the coupling regression model of wind speed, ambient temperature, and atomization time under different horizontal conditions, among which included 69 schemes with settlement greater than 1.31 g (Table 10). By optimizing the quadratic regression model, the optimum combination of conditions for the maximum value of Y_4 (average root settlement) was as follows: $X_1 = 1.6818$, $X_2 = -1.6818$, $X_3 = 1.6818$; that is, the wind speed was 2.5 m/s^{-1} , the ambient temperature was 15°C , and atomization time was 184 min.

Table 10. Frequency analysis of horizontal combination of schemes with settlement greater than 1.31 g.

Level	X_1 Wind Speed (m/s^{-1})		X_2 Ambient Temperature ($^\circ\text{C}$)		X_3 Atomization Time (min)	
	Time	Frequency	Time	Frequency	Time	Frequency
−1.6818	6	0.087	23	0.3333	13	0.1884
−1	10	0.1449	20	0.2899	9	0.1304
0	15	0.2174	15	0.2174	9	0.1304
1	18	0.2609	7	0.1014	16	0.2319
1.6818	20	0.2899	4	0.058	22	0.3188
Average						
Coding		0.457		−0.652		0.321
Standard Error		0.135		0.125		0.157
95% Confidence Interval		0.192–0.722		−0.896–−0.407		0.014–0.628
Optimum Scheme		1.836–2.072		16.169–16.895		125.491–147.031

3.4.5. Model Verification

In order to verify the reliability of the regression model and prediction results, the fitting effect of the model is verified via experiments. Three repeated experiments were carried out on the combined conditions of the average atomization settlement of the plant roots. The maximum absolute error between the predicted value and the actual value was 0.26 g, and the relative error was 5.8%, which had no significant difference with the verified value, and the predicted value was basically consistent with the verified value. Further validation is needed for the rationality of the mathematical regression model of root droplet settlement change, which could be used as a basis for regulating wind speed, ambient temperature, and atomization time, so as to obtain a suitable droplet settlement environment for root growth.

4. Discussion

The cultivation mode of the ultrasonic aeroponic cultivation technology is relatively simple. There is no pipeline system for nutrient solution circulation, so that the atomization and utilization of the nutrient solution are completed in the same root zone ambient space. An ultrasonic atomizer is simply installed in the plastic box. The bottom of the box contains the nutrient solution, which directly provides an atomized nutrient solution to the root system through high-frequency vibration. This cultivation mode is suitable for container-style indoor cultivation because the mist is an ultra-fine mist [34–36]. When using ultrasonic aeroponic cultivation technology to cultivate plants, after atomizing the nutrient solution with an ultrasonic nebulizer, the number of nutrient solution droplets deposited and attached to the plant roots is defined as the number of root droplets settling. The amount of droplet settlement on the plant roots can directly affect the absorption of water and nutrition by the roots. Therefore, the amount of droplet settlement of the roots under different atomization times is used as one of the bases for regulating root nutrition and water, and the weight of droplet settlement of plant roots is used as the amount of droplet settlement of the roots. Due to the lack of relevant literature research and technical information, agricultural practitioners have not fully used this cultivation technique. Therefore, this study aimed to provide researchers, agricultural personnel, and interested parties with relevant knowledge on the development and planting techniques of ultrasonic aeroponic cultivation for plants.

When using ultrasonic aeroponic cultivation technology to cultivate plants, if the ultrasonic atomization time is short, the number of nutrient solution droplets deposited on the plant roots will be small, which is not enough to meet the nutritional needs of the plants. The longer the ultrasonic atomization time is, the greater the number of nutrient solution droplets deposited on the plant roots is, and the energy consumption will increase. Root zone temperature will also increase with an increase in atomization time, which leads to a situation beyond the normal growth range of the plants and inhibits the normal physiological activities of the plant roots. Although the increased droplet settlement of plant roots cannot show inhibition effect, it can reduce the effective utilization rate of the nutrient solution mist, which is not conducive to improvements in energy saving and efficiency. In order to satisfy the normal growth of the plant roots, the relative humidity of the atomized nutrient solution droplets is generally over 90%, and even reaches 100%, accompanied by root condensation [37]. The droplet settlement of the nutrient solution on the plant roots directly determines the water and nutrition requirements of plant growth. Meanwhile, the continuous ultrasonic atomization of the nutrient solution could lead to a continuous increase in nutrient solution temperature, which could affect the growth of the plant roots and lead to a decrease in its productivity. The continuous atomization could increase the power consumption and the extra cost. In actual cultivation and production, the growth environment of the root system was a relatively complex problem. At present, there are still many problems in mist cultivation via ultrasonic atomization, such as the changes of pH and EC after the atomization of nutrient solution, the optimization of mist pipeline layout, etc. Meanwhile, as the temperature of the nutrient solution gradually increased under ultrasonic atomization, there was no feasible method to dynamically control the temperature, and there were other factors affecting the temperature change in the cultivation pipeline. If we want to control the temperature of the nutrient solution and optimize the root zone temperature environment, we must develop facilities or equipment for controlling the temperature of the nutrient solution in the future.

In terms of the current studies, the development of an ultrasonic aeroponic cultivation technology has great development space, and there is still a lot of room for development. However, this technology has not been fully developed, and there are still many problems that remain to be further studied. The most impressive result of this study is that the root growth environment of lettuce was significantly improved in ultrasonic aeroponic cultivation. An ultrasonic aeroponic cultivation device was designed for cultivating lettuce. There should be more forms of these devices in the future. In this study, only lettuce was used as the research object of ultrasonic aeroponic cultivation, and the change law of droplet settlement in lettuce root system was studied. However, this can only explain the ultrasonic aeroponic cultivation of specific plants, so it is necessary for agricultural scientists to further explore the change law of root droplet settlement of different plants through different nutrient solutions [38,39].

5. Conclusions

In order to solve the effects of wind speed, ambient temperature, and atomization time on the droplet settlement of a nutrient solution on plant roots when planting plants with ultrasonic aeroponic cultivation, this study aimed to obtain a suitable wind speed range and atomization time through a nutrient solution atomization experiment, to obtain the best control scheme through a multi-environmental parameter combination cultivation experiment. Taking an ultrasonic aeroponic cultivation device as the research object, and lettuce as the test material, experiments were carried out on two factors affecting the wind speed of an axial fan and the atomization time of the nutrient amount of ultrasonic aeroponic cultivation plants. Different gradient wind speed values were set for the axial flow fan, and the suitable wind speed range was 1.0–2.5 m/s. When the minimum wind speed was 1.0 m/s and the maximum wind speed was 2.5 m/s, the temperatures of the lettuce root zones in the upper, middle, and lower layers of the ultrasonic aeroponic cultivation device at different time periods were obtained by atomizing the nutrient solution. When the optimum temperature for the root growth of lettuce was 15–20 °C and the wind speed was 1.0–2.5 m/s, the continuous atomization time of the nutrient solution was 66–184 min. Using a quadratic orthogonal rotation combination design method, three main factors, namely wind speed, ambient temperature, and atomization time, were selected to test droplet settlement in the lettuce roots. Twenty-three groups of experiments were set up according to the orthogonal rotation combination design method of three factors and five levels. The droplet settlement in the lettuce root system was measured. The droplet settlement regression equation in the lettuce root system was established. The reliability of the regression model was tested according to the significance condition, and a simplified quadratic orthogonal regression equation was obtained. The main effect analysis, single factor analysis, and interaction effect analysis were used to analyze the model, and the model was further verified. The verification results showed that the relative error between the predicted value and the actual value of the average root droplet sedimentation was 5.8%. The optimum wind speed was 2.5 m/s, the ambient temperature was 16 °C, and the atomization time was 184 min when the ultrasonic aeroponic cultivation device designed in this study was used to cultivate lettuce. It could provide a theoretical reference and an experimental basis for the control of the related growth environment parameters of plants cultivated using ultrasonic aeroponic cultivation.

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