Design and experiment of a barrel-shaped aeroponic cultivation system

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Abstract: Theoretically, aeroponic cultivation is easy to make plant roots in a better growth environment. In order to give better play to the theoretical advantages of aeroponic cultivation, further optimize the structure of the aeroponic cultivation system, and make the aeroponic cultivation system more scientific and reasonable, a barrel-shaped aeroponic cultivation system is designed. The aeroponic cultivation system is composed of a monitoring and control system, power equipment, nutrient solution storage, and treatment facility, nutrient solution supply pipelines, aeroponic cultivation barrels, and nutrient solution return pipelines. The cultivation system working principle and its technical requirements were analyzed, and its structure for meeting the requirements of large-scale production was determined. A performance test of the barrel-shaped aeroponic cultivation system using cultivated narrow leaved Chinese chives was conducted. The Chinese chives were cultivated to 6 beds of the cultivation barrel. The system supplied nutrient solution every 30 min for 2 min each time. After 5 weeks growth, the length, leaf width, and single weight of Chinese chive ranged from 293-362 mm, 4.1-6.7 mm, and 3.48-5.47 g, respectively, the average length, leaf width, and single weight of Chinese chive were 327 mm, 5.1 mm, and 4.24 g, respectively, and there were no significant differences in the length, leaf width, and single weight of Chinese chive on 6 beds by One-way ANOVA. The test results showed that all the Chinese chive in each bed of the cultivation barrel grew well and uniform, which indicated that the circulation process of nutrient solution supply and return in the system was normal, the process of nutrient solution atomization in the system was uniform, and the aeroponic cultivation system operated normally and stable and could be applied in production.

Keywords: aeroponic cultivation, soilless cultivation, facility agriculture, Chinese chive
DOI: 10.25165/j.ijabe.20221504.7508

Citation: Qi S H, Ma Y F, Zhang M, Yin B Q, Xu Z Y, Liu S G. Design and experiment of a barrel-shaped aeroponic cultivation system. Int J Agric & Biol Eng, 2022; 15(4): 90–94.

1 Introduction

Aeroponic cultivation is a new soilless technology integrating plant nutrition, plant physiology, environmental ecology, agricultural automation, and horticultural crop cultivation[1,2]. In aeroponic cultivation, plant roots are placed in the air, and nutrient solution is regularly and quantitatively sprayed on them to better meet their needs for water, fertilizer, and oxygen[3-5]. Aeroponic cultivation creates a new type of environment for plant roots to replace the soil, substrate, and water environment[6,7]. Moreover, it is easier for plant roots to be in the most suitable environment for their growth[8]. Aeroponic cultivation can also eliminate the adverse impacts of soil and waterborne diseases and pests, maximize plant growth potential, and improve plant quality and yield[9,10]. It is superior in land utilization, water-saving, regulation of the root growth environment, and disease and pest prevention[11,12].

The aeroponic cultivation concept arose in the middle of the 20th century and the study of its technology followed[13]. Presently, aeroponic cultivation plant containers mainly include A-frame, cylindrical, or trapezoidal cultivation beds[14]. Researches have been well demonstrated the feasibility or superiority of aeroponic cultivation for many plants, such as vegetables[15-18], root plants[19-23], and medicinal plants[24-27], and highlighted its strong popularity and great development potential. Based on column-type aeroponic cultivation, a barrel-shaped aeroponic cultivation system was designed. The overall layout of barrels and the system composition structure were optimized, and assembled barrels were incorporated with a large atomization space to further increase cultivation area and reduce investment cost. This aeroponic cultivation system gives further play to the advantages of its technology and provides a reference for large-scale production of barrel-shaped aeroponic cultivation.

2 Structure and principle

2.1 Overall Structure and working principle

The barrel-shaped aeroponic cultivation system is composed of aeroponic cultivation barrels, power equipment, nutrient solution storage, and treatment facility, nutrient solution supply pipelines, and nutrient solution return pipelines (Figure 1). All aeroponic cultivation barrels in the greenhouse are divided into several areas, and each area is regarded as a supply unit. When supplying nutrient solution to a supply unit in each round, it is pumped from the storage tank by water pump for supplying the nutrient solution, passed through a filter, conveyed to the micro nozzles in each aeroponic cultivation barrel of the supply unit through the nutrient solution supply pipelines, and sprayed on the plant roots. The unabsorbed nutrient solution falls down to the barrel holding tray

Received date: 2022-03-13 **Accepted date:** 2022-05-30

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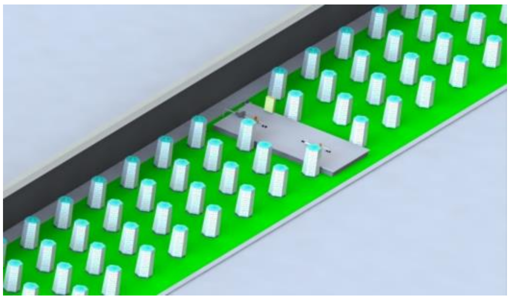
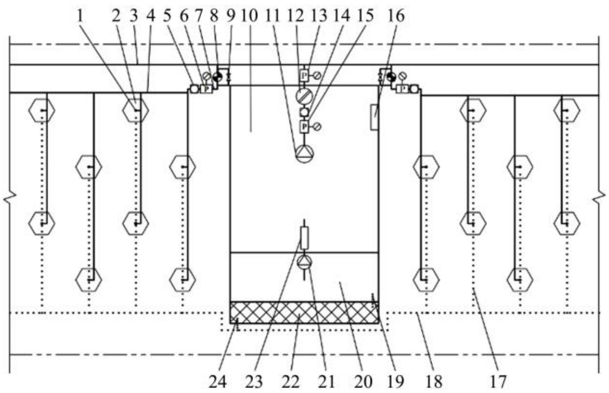
as droplets and collects into a stream. The stream flows into the nutrient solution return pipeline, is treated in the primary treatment tank, and then flows into the temporary storage tank. After the nutrient solution of a supply unit is completed, the supply unit solenoid valve is closed, and the solenoid valve of the next supply unit is opened to begin the supply of the next supply unit. In this way, the nutrient solution is supplied to each supply unit in turn until the end of a round. The process is repeated at preset times when the nutrient solution level in the temporary storage tank reaches it is maximum, then it is pumped to the storage tank via a disinfection and sterilization device until the nutrient solution level reaches a set minimum position.



a. Layout of the aeroponic cultivation barrels



b. Pipelines of the system

1. Micro nozzle 2. Aeroponic cultivation barrel 3. Main supply pipeline 4. Sub-branch supply pipeline 5. Flow sensor in branch supply pipeline 6. Pressure sensor in branch supply pipeline 7. Branch supply pipeline 8. Solenoid valve in branch supply pipeline 9. Manual control valve 10. Storage tank 11. Water pump for supplying nutrient solution 12. Filter 13. Pressure sensor 2 in main supply pipeline 14. Flow sensor in main supply pipeline 15. Pressure sensor 1 in main supply pipeline 16. Control box 17. Branch return pipeline 18. Main return pipeline 19. Outlet of primary treatment tank 20. Temporary storage tank 21. Water pump for returning nutrient solution to the storage tank 22. Primary treatment tank 23. Disinfection and sterilization device 24. Outlet of main return pipeline

Figure 1 Structure of the aeroponic cultivation system

2.2 Key components of the aeroponic cultivation system

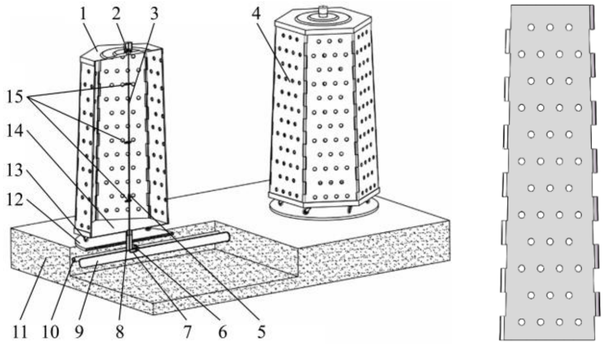
2.2.1 Aeroponic cultivation barrel

The aeroponic cultivation barrel contains a holding tray, 6 universal wheels, 6 beds, a positioning tray, a non-metallic bearing, and a micro nozzle suspension rod (Figure 2). The main body of the aeroponic cultivation barrel is a hexagonal truncated pyramid or hexagonal prism. The main cultivation area is composed of 6 beds through concave convex meshing. The aeroponic cultivation barrel is rotated daily at 60° around the standpipe of branch return pipeline without obstruction to ensure that the plants on each bed are exposed to uniform light.

In the greenhouse, daylight received by the plants depends on barrel form and spacing. Shielding of daylight by the barrels differs seasonally and regionally, which is related to regional solar altitude angle and solar azimuth. The calculations for solar altitude angle and solar azimuth[28] as Equation (1):

$$\begin{cases} \sin\alpha = \sin\varphi\cdot\sin\delta + \cos\varphi\cdot\cos\delta\cdot\cos\omega \\ \cos\beta = \dfrac{\sin\alpha\sin\varphi - \sin\delta}{\cos\alpha\cos\varphi} \end{cases} \tag{1}$$

where, α is the solar altitude angle, (°); φ is the geographic latitude, (°); δ is the solar declination angle, (°); ω is the solar time angle, (°); β is the solar azimuth, (°).



a. Related structure of the aeroponic cultivation barrels b. Bed

1. Positioning tray 2. Non-metallic bearing 3. Micro nozzle suspension rod 4. Bed 5. Pendant 6. Rubber plug 7. Atomization hose 8. Standpipe of branch return pipeline 9. Branch return pipeline 10. Branch supply pipeline 11. Soil 12. Support plate 13. Universal wheel 14. Holding tray 15. Micro nozzle

Figure 2 Structure and related structure of the aeroponic cultivation barrels

The relationships between shading generated by barrels in the north-south and east-west directions, and solar altitude angle and solar azimuth as Equation (2):

$$\begin{cases} l_1 = (\dfrac{h}{\tan\alpha} + R)\cdot|\cos\beta| \\ l_2 = (\dfrac{h}{\tan\alpha} + R)\cdot|\sin\beta| \end{cases} \tag{2}$$

where, l_1 is the length of shading of a barrel in the north-south direction, m; h is barrel height, m; R is maximum cross section diameter of a barrel, m; l_2 is the length of shading of a barrel in the east-west direction, m.

According to the requirement that there is no shading between adjacent barrels at noon on the winter solstice[29], and considering that the best illumination time period of photosynthesis for greenhouse plants during a day is 10:00-14:00[30], no barrels are placed within their generated shadow range from 10:00-14:00. Therefore, design calculation for row and column spacing as Equation (3):

$$\begin{cases} l_l = \dfrac{h}{2\tan\alpha_1} + R \\ l_c = \sqrt{(\dfrac{h}{\tan\alpha_2})^2 + (2R)^2 - l_l^2} \end{cases} \tag{3}$$

where, l_l is row spacing, m; α_1 is noon solar altitude angle on winter solstice, (°); l_c is column spacing, m; α_2 is solar altitude angle at 10:00 on winter solstice, (°).

For Aiwei farm on December 21, 2021 (winter solstice), the temporal changes in shading generated by aeroponic cultivation barrel A are shown in Figure 3. When the height of a barrel is 1.7 m, the row spacing is 2 m, and the column spacing is 2.2 m, no barrels are placed within their generated shadow range from 10:00-14:00. However, this is not the only layout design principle of aeroponic cultivation barrel, such as cultivation area, plant growth habit, light scattering, plant daylighting period, production time period, management mode, etc.

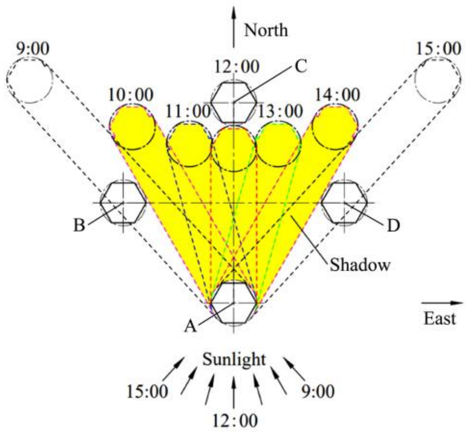


Figure 3 Temporal changes in shading generated by aeroponic cultivation barrel A

2.2.2 Nutrient solution storage and treatment facility

The nutrient solution storage and treatment facility, located in the middle of the greenhouse, includes three tanks: one for storage of nutrient solution, another for temporary storage of returning nutrient solution, and one for primary treatment of returning nutrient solution. It is a rectangular brick and concrete waterproof structure.

2.2.3 Power equipment

Power equipment includes water pumps for supplying nutrient solution and for returning the nutrient solution to the storage tank. Considering that the working time of the water pump for supplying nutrient solution is far less than the non-working time, and supplying nutrient solution to all barrels simultaneously will increase power consumption, the barrels in the greenhouse are divided into several supply units to reticulate nutrient solution in turn. The water pump power selection for supplying nutrient solution requires that all micro nozzles in every supply unit be atomized normally.

2.2.4 Supply and return pipeline of nutrient solution

The nutrient solution supply pipelines include main, branch, and sub-branch supply pipelines, atomization hoses, and micro nozzles. All main nutrient solution supply pipelines are located below ground. The atomization hose extends into the branch return pipeline from the preset hole, enters into the aeroponic cultivation barrel along the standpipe of branch return pipeline, and is connected to the micro nozzles suspended on the axis of each barrel. According to barrel height and micro nozzle spray coverage, micro nozzles are evenly distributed in different heights and directions to ensure even nutrient solution supply to all roots.

The nutrient solution return pipelines include main, and branch return pipelines. The main return pipelines are inclined towards the nutrient solution storage and treatment facility to ensure that there is no nutrient solution in the pipelines, and to speed up nutrient solution return. Nutrient solution return depends entirely on gravity.

3 Control strategy of the aeroponic cultivation system

The monitoring and control system is composed of PLC, a nutrient solution EC sensor and liquid level sensors in the storage tank, liquid level sensors in the temporary storage tank, pressure and flow sensors in the main supply pipelines, and pressure and flow sensors and solenoid valves in the branch supply pipelines of each supply unit. The monitoring and control system flow chart is shown in Figure 4.

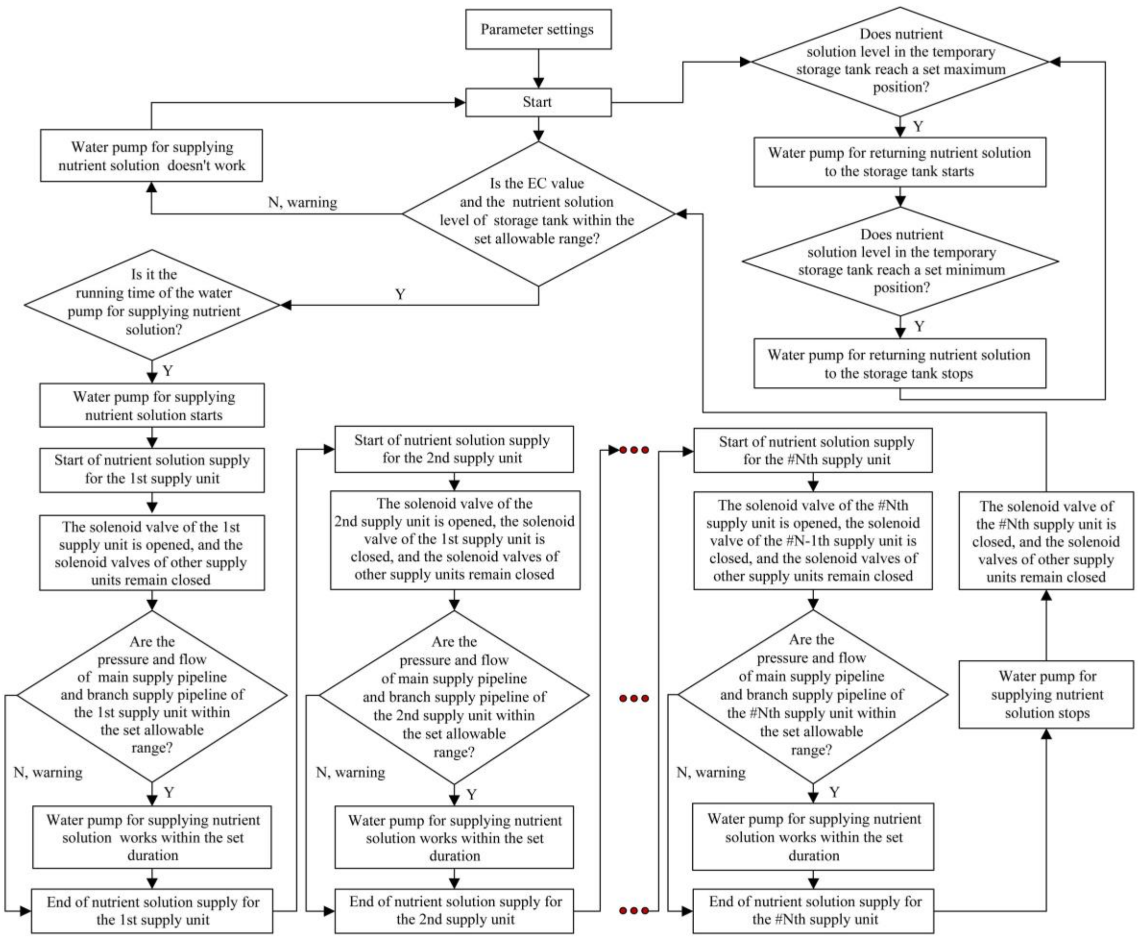


Figure 4 Monitoring and control system flow chart

4 Performance test of the aeroponic cultivation system

4.1 Test condition

This study was conducted in the 1000 m^2 Aiwei farm (121.62°E, 37.24°N) greenhouse, Yantai City, Shandong Province, China. The test was from January 2-February 5, 2022, and the temperature variation in the greenhouse was 9℃-25℃.

4.2 Plant cultivation and nutrient solution

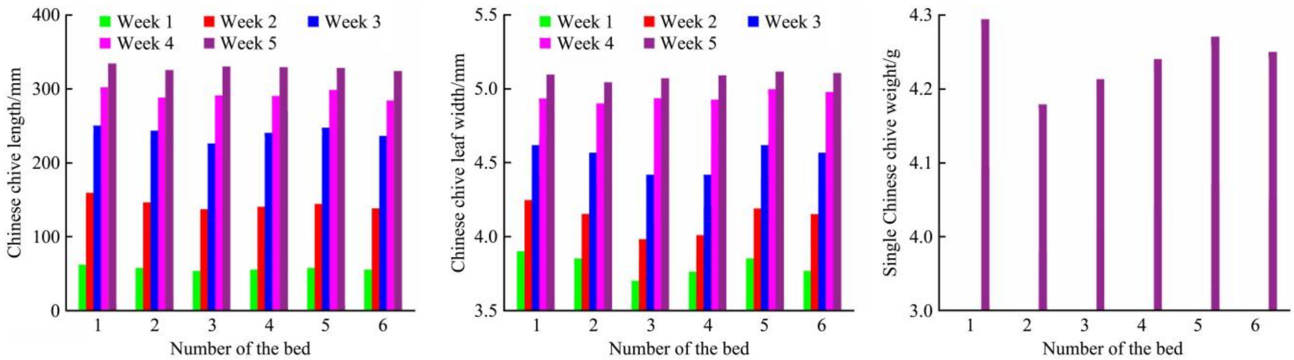
Narrow leaved Chinese chives were cultivated in April 2021, and the chive roots were used in this study. The general nutrient solution formula of the South China Agricultural University was used, and the EC of the nutrient solution was controlled at 1.6-1.7 ms/cm.

4.3 Test method

The aeroponic cultivation system was used to cultivate a crop of Chinese chives for 35 d. Before transplanting, healthy Chinese chive roots were selected and soaked in 16℃ water for 2 h. A cluster (2-6) of Chinese chives was planted in each of the 42 planting holes in each bed. The aeroponic cultivation system was set to supply nutrient solution every 30 min for 2 min each time. Chinese chive length was measured with a ruler and Chinese chive leaf width with a vernier caliper every 7 d. To minimize the influence of disturbance generated during measurement, only 2 Chinese chives were selected for measurement in each planting hole. There were 84 test samples in each bed. At the end of the growth period, the test samples harvested were weighed separately.

4.4 Results

Figure 5 lists the results of all test samples, the final length and width of Chinese chive ranged in 293-362 mm and 4.1-6.7 mm with an average of 327 mm and 5.1 mm, respectively. The weight of single Chinese chive was ranged in 3.48-5.47 g with an average of 4.24 g. Overall growth on the 6 beds was good, indicating the aeroponic cultivation environment can meet Chinese chive growth requirements.



a. Chinese chive length b. Chinese chive leaf width c. Single Chinese chive weight

Figure 5 Chinese chive growth at different stages

The six aeroponic cultivation barrel beds were divided into 6 groups, and a one-way ANOVA using SPSS was conducted (Table 1). There were no significant differences in Chinese chive length, Chinese chive leaf width, and single Chinese chive weight between the 6 beds at 95% confidence, indicating that Chinese chive growth on the 6 beds was balanced, and that performance of the aeroponic cultivation system was good.

Table 1 Variance analysis results

Item	Source	Sum of square	df	Mean square	*F* value
Chinese chive length	Group	1947.063	5	389.413	1.511
	Error	128362.429	498	257.756	
	Total	130309.492	503		
Chinese chive leaf width	Group	0.743	5	0.149	1.708
	Error	43.334	498	0.087	
	Total	44.077	503		
Single Chinese chive weight	Group	0.711	5	0.142	1.689
	Error	41.956	498	0.084	
	Total	42.667	503		

Note: $F_{0.05}(5, 498)=2.23$; $F_{0.01}(5, 498)=3.06$.

5 Conclusions

Based on aeroponic cultivation technology, combined with greenhouse plant growth and production environment conditions, this study designed a barrel-shaped aeroponic cultivation system. This cultivation system could meet the cultivation requirements of leafy vegetables, herbs, and herbaceous garden ornamental plants. The system is composed of a monitoring and control system, power equipment, nutrient solution storage and treatment facility, nutrient solution supply pipelines, aeroponic cultivation barrels, and nutrient solution return pipelines. The working principle of the aeroponic cultivation system and its technical requirements were analyzed, and its structure for meeting the requirements of large-scale production was determined.

This work conducted a performance test of the barrel-shaped aeroponic cultivation system using cultivated Chinese chives. After 5 weeks of growth, the range of the length, leaf width, and single weight of Chinese chive were 293-362 mm, 4.1-6.7 mm, and 3.48-5.47 g, respectively. In all test samples, the average Chinese chive length and width were 327 mm and 5.1 mm, respectively. The average weight of single Chinese chive was 4.24 g, and overall Chinese chives grew well. The Chinese chive growth on the 6 beds was uniform, which confirmed that the performance of the aeroponic cultivation system was good.

Acknowledgements

This work was financially supported by the Major Agricultural Application Technology Innovation Project of Shandong Province of China (SD2019NJ001 and SD2019NJ009).

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