Smart control system for the precision cultivation of black fungus

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Abstract: Black fungus, with high nutritional and medicinal value, has been cultivated in China for a long time, and Heilongjiang alone accounts for about 40% of the global output. At present, the cultivation of black fungus derives mainly from the inheritance of relatively primitive practices and experience of farmers, resulting in inconsistent quality of fungus. In this study, a smart control system for the precision cultivation of black fungus was designed by using intelligent detection and control technology. The system includes a precision culture test environment and remote control system. The precision cultivation environment contains four sub-independent environments. The key parameters such as temperature, humidity, and light behavior were collected and can be adjusted individually, according to the precision cultivation stages. The intelligent remote control system included a controller cabinet, sensors unit, temperature control unit, humidity control unit, light control unit, and information transmitting unit. The controller cabinet includes a key controller which can auto-control the temperature, and humidity, and lightly adjust components according to the precision cultivation conditions and processing. The temperature sensors were installed in a 3D array close to the fungus bags about 5 cm in rooms. The light tape was installed on the six walls and also had three colors (Red, Blue, and Green) which could be controlled independently in each room. The control strategy through the analysis of the data collected by all sensors, the current cultivate situation of the cultivation environment was obtained, and the heater, fan, light, and nozzle were regulated according to the strategy to maintain a suitable precision cultivation environment for fungus. To verify the feasibility of the precision cultivation processing and control system, the test result shows that the error of temperature control was about 0°C-1°C, the error of humidity control was about 1%-4%, and the error of illuminance control was about 0-50 lx; All the verification results show that the control system for precision cultivation has high precision and can meet the needs of exploring the "Black 29" fungus cultivation experiment environment. Based on the orthogonal experiment, the best combination of the temperature and humidity for each growth stage was also investigated in this study, further proving the reliability and feasibility of the control system for the precision cultivation of *Auricularia auricula*.

Keywords: black fungus, precision cultivation, smart control system, growth environment, remote control system, sensor
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1 Introduction

Black fungus, because of its high nutritional value and medical efficacy, has become a well-known food in China, and the market demand for high-quality fungus is increasing year by year. At present, there are more than 2000 kinds of wild edible fungi in China. The main cultivation process is bagging cultivation in greenhouse, which comes from traditional agronomy. It costs more manpower and material resources and is not suitable for automation and intelligent control[1,2]. Many studies have been conducted on cultivation techniques and alternatives substrate for fungus cultivation. Ko et al.[3] have compared the mycelial growth and basidiomycete formation of seven different edible mushrooms: All the tested substrate (rice bran, wheat bran, barley bran, Chinese cabbage, eggshell, and soybean powder) were found to be suitable for the mycelial growth of all the tested species. The possibility of mushroom production on oak sawdust substrate with 20% rice bran substrate was demonstrated with *H. coralloides*, which showed 26%-70% biological efficiency. Our results also showed that strain selection is important to improve biological efficiency and yield in black fungus cultivation[3,4]. Cunha et al.[5] have studied real-time parameter estimation of dynamic temperature models for greenhouse environmental control to estimate (in real-time) the parameters of the inside air temperature model described. The structure and parameters of the discrete-time dynamic climatic model were previously identified using data acquired during two different periods of the year. Several experiments showed that the second-order models identified achieved a close agreement between simulated and experimental data. For efficient use of these models in real-time control, a recursive identification technique is implemented for the estimation of the parameters. It is generally believed that the best culture temperature of mycelium is the best temperature for fruiting body growth. In order to verify the correctness of this theory.

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Zhang et al.[6] designed relevant experiments to explore the influence of mycelium on the growth of mycelium, fruiting body, and sprouting rate under different temperature conditions. The results showed that the mycelium grows well at 30°C-35°C, the quality of the fruiting body of the fungus is good, and the earpiece is neat; in addition, the temperature will also affect the color of the earpiece. When the temperature goes higher, the color of the earpiece becomes lighter, and the yellow earpiece appears locally. Yi et al.[7] put forward an integrated management and control strategy for the humidity factor during the period of the mushroom growing stage, aiming at solving the low-efficiency problem of growth of *Pleurotus eryngii* in a local mushroom production enterprise in Pengyang County in Ningxia, China. The temperature and humidity sensors were used to collect the relevant humidity data, and the data were processed and modeled by the controller. The humidity control strategy was studied based on the model, and the PID method was finally selected for environmental control through literature and field comparative experiments. Using Simulink to simulate and build PLC electrical system to verify the feasibility of the scheme, the PID algorithm can effectively regulate the moisture content in the growth environment of *Pleurotus eryngii*.

The traditional cultivation technology of black fungus is still based on human judgment with a rough growth environment control, there is no clear indicator for the transition between every stage, so it only can be judged manually by experienced professionals, which brings a series of problems. For example, the uneven distribution of temperature, humidity, and illumination in the cultivation room leads to a non-uniform growth quality of black fungus that can reduce its market competitiveness. In addition, the optimum growth conditions of black fungus at different stages were different. The traditional environmental control system cannot meet the needs for micro-environmental control for different stages of cultivation. A new control system, therefore, needs to be updated to realize the precision agronomic control for different growth stages. Currently, relevant researches on precision agronomic characteristics of black fungus are still in the preliminary stage. Previously, single factors of temperature, humidity, and illumination were mostly studied, but their interaction effect remains unclear. A precision control strategy is also needed to be developed[8-12]. The aim of this study was to improve the budding percentage and the ear size of the black fungus. Orthogonal experiments in different growth stages were designed to obtain the coupling relationship between temperature, humidity, and illumination. The obtained data information was used to develop the precision agronomical control strategy and system. Aiming at the problems of poor data collection, and low cultivation control accuracy of the control system, a precision control method was designed by analyzing the environmental data collected by the installed sensors. By means of real-time spray, ventilation, heating, and refrigeration, the precision and efficient control of the cultivation environment were realized. The intelligent control system was constructed by using intelligent detection and control technology. The gathered environmental information was calculated by the control program based on the obtained control method. The core controller can send out control instructions for temperature, humidity, and light behavior according to the control strategy. Environmental control equipment could be a system output layer to influence the cultivation environment of black fungus. Relying on the Institute of Microbiology of Heilongjiang Academy of Sciences, and the Institute of Intelligent Control of Jiamusi University, the experiments were conducted in the Research Center of Fermentation Engineering Technology of Heilongjiang Province, four fully closed cultivation workshops were developed and constructed. The cultivation experiments were conducted regarding “Black 29” primary parent species as test material using facility edible fungus technology from facility agronomy.

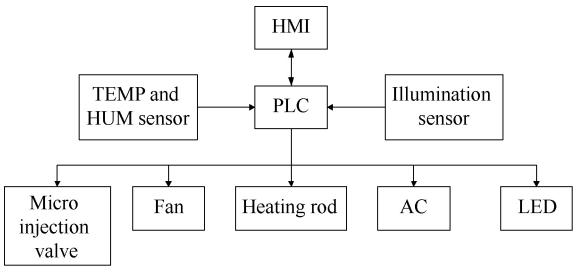
2 Materials and methods

2.1 Construction of cultivation environment and design of control system

Four closed-space black fungus cultivation workshops were constructed at the Fermentation Engineering Technology Research Center in Heilongjiang Province, which was supported by the Institute of Microbiology of Heilongjiang Academy of Sciences and the Institute of Intelligent Control Center of Jiamusi University. Every cultivation area of the four conjoined greenhouses is about 150 m^2. Using intelligent control technology, the hardware control system, and precise control algorithm software were designed.

2.1.1 Hardware construction of the control system for fungus cultivation environment

The control system (Figure 1) is composed of four parts: Programmable Logic Controller (PLC), Human Machine Interface (HMI), sensors, and output devices. The touch screen is the main interface in which the data can be modified, set, and displayed by Monitor and Control Generated System (MCGS) software. PLC is the core of the control system which is responsible for the collection of micro-environment information and the control of the output action. The sensors from Shandong Renke Control Technology Co., Ltd., China, can gather temperature, humidity, and illuminance data. Environmental control equipment includes fans, sprinkler valves, recharge lamps, heating pump, and so on.



Note: HMI: Human Machine Interface; TEMP: Temperature; HUM: Humidity; PLC: Programmable Logic Controller; AC: Air Conditioner; LED: Light Emitting Diode. Same below.

Figure 1 Hardware structure chart of the control system for fungus cultivation environment

2.1.2 Software design of the control system for fungus cultivation environment

1) Design of control process of the control system

As Figure 2, firstly, the control system collects current environmental information about the workshop by the sensor network; and checks the working status of the device and gathers the environmental parameters of the best growth model, then makes a comparison between the current data and model data before sending out corresponding instructions for temperature adjustment, humidity adjustment, and illumination behavior. After execution of the action, the state of the device is feedback to the controller

(PLC) as one of the factors for the control strategy to decide the next control action until the preset model aim is reached.

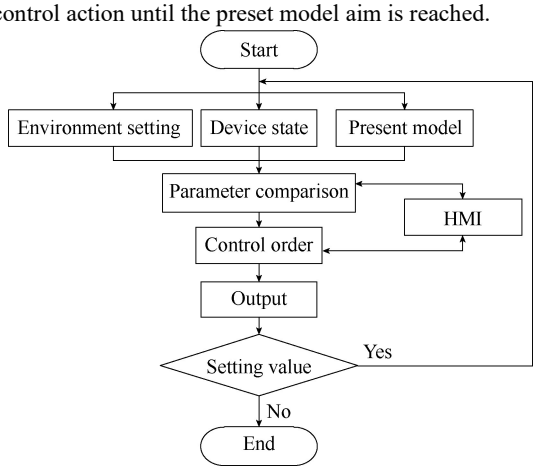


Figure 2 Control flow of control process

2) Design of HMI of control system

The HMI consists of the following models (Figure 3): curve display, parameter setting, and recipe operation (selection, editing, view, historical report, etc.); Control mode includes manual control and automatic control. Manual control is used for independent control and debugging, and automatic control operates devices according to the control strategy; Curve display is designed to show the changing trend of every environmental factor in the workshop; Parameter setting is designed to set the environment variables, timing, and remote control parameters; Formula selection is for selecting a suitable formula according to different Black fungus cultivated varieties so that scale production can be realized for later; Formula editing aims to add, modify, delete and other operations; Formula View intends to view all formulas and active formula; History report records environmental changes and generates reports that are stored in U flash disk.

2.1.3 Environmental control methods of cultivation workshop

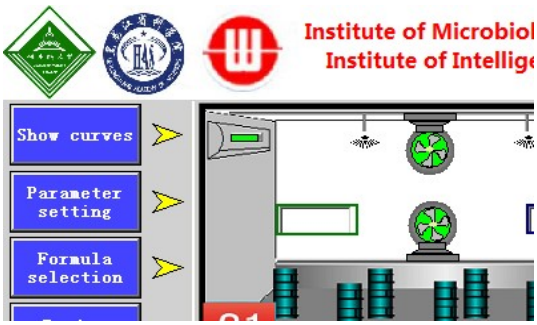
1) Precise environmental collection method of cultivation workshop

(1) Sensor layout and number

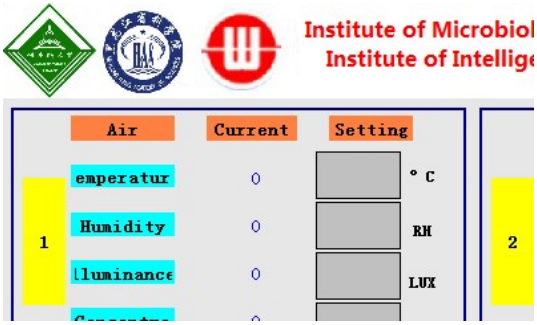
Most Black fungus production enterprises only use a single sensor to gather the environmental information, and the control strategy is too simple and primitive, which leads to poor accuracy of data acquisition in the environmental control system. The reaction time, system error, and other essential properties of all kinds of sensors cannot be suitable for cultivation control. In addition, the environment of the four build test workshops is non-uniform, there are differences in temperature, humidity, and illumination field. As for the newly designed control system, a 3D temperature and humidity sensor array was installed and each sensor is installed 5 cm close to the fungus bag, and three kinds of color (red, blue, yellow) tapes were installed along the Interior wall of the test room where the illumination was adjustable and the three colors also can be selected independently according to the cultivation strategy. All sensors can work well and the control method can improve the accuracy and effectiveness of data acquisition.

(2) Data processing

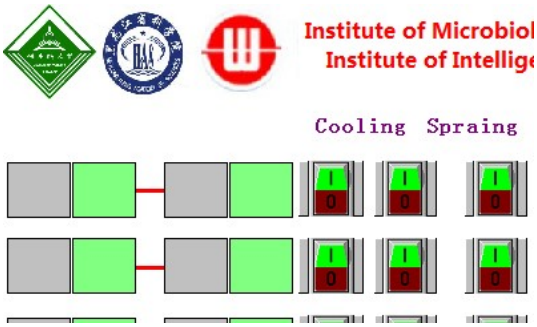
The data processing method is shown in Figure 4. D120, D124, D128, and D132 are data registers of PLC, which store the environmental parameters collected by sensors No.1, 2, 3, and 4 respectively. First, the sum of the data values of sensor 1 and sensor 2 is obtained and stored in the data register D270 by using the internal addition instruction of PLC: ADD D120 D124 D270; Then add sensor 3 data value to D271: ADD D270 D128 D271; Then add sensor 4 data value and stored in D272, which is the sum of the data values of four sensors: ADD D271 D132 D272; Finally, average the four sensors' data and store it in D16 as the final data value: DIA D272 K4 D16.



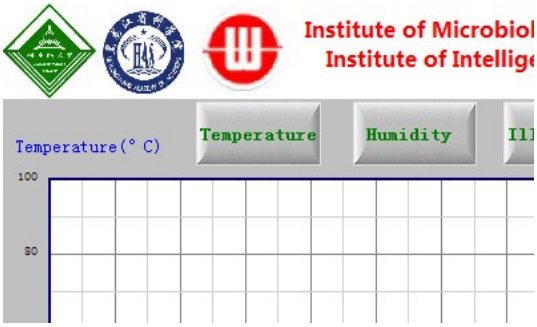
a. Main interface of HMI



b. Setting interface of HMI



c. Recipe interface of HMI



d. Historical curve of HMI

Figure 3 Design chart of HMI of control system

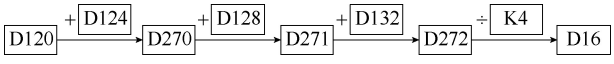


Figure 4 Data processing method diagram

2) Precise environmental control collection method of cultivation workshop

The flow chart of the precise control method is shown in Figure 5. The current environmental parameters were obtained by

multiple sensors, which were calculated and compared with the environmental setting parameters by the central processor, and PLC issues the environmental regulation instructions when the temperature is higher than the preset range, turning on the air cooler in real-time to cool the air until it reaches the preset range; when the temperature is lower than the optimal parameter setting range, start the heating fan in real-time until the current value reaches the setting range; when the humidity is higher than the preset range, turn on the ventilation motor in real time to discharge the humidity in the workshop until it reaches the preset range; when the humidity is lower than the preset range, start the spray in real time and supplement the humidity in the workshop until it reaches the preset range. The start and stop times of each environmental regulation instruction can be set according to different target ranges. Until the control system reaches a steady state, the current environmental parameters of the workshop are in the best environmental range. The feasibility of this control method is verified by building an intelligent control system. The central controller is PLC, and the control method is integrated into the control system through a programming language.

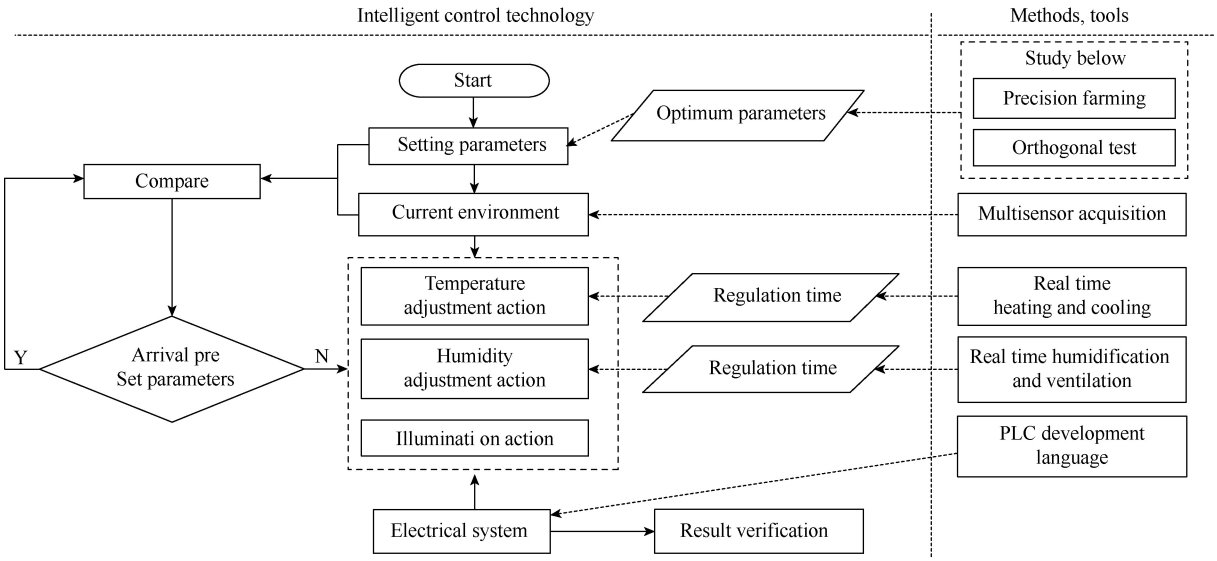


Figure 5 Control processes and methods

2.1.4 Control system regulation accuracy verification test

From July to August 2018, two verification tests were completed in the same workshop. The automatic operation mode was selected, and the control system just controlled the spray, fan, heater, and light to adjust the environmental parameters to reach the setting range according to the temperature, humidity, and illuminate preset parameters. The test was completed, and the data used for regulation and control was recorded in files. The results of the two tests are summarized in Table 1.

Table 1 Experiment results of environment control precision

Times	Kind	Temperature /°C	Humidity /%	Illuminance /lx	Control time/min
First experiment	Before	29	68	0	20
	Setting value	25	75	0	
	After	26	76	0	
	Error	1	1	0	
Second experiment	Before	29	76	0	12
	Setting value	25	85	900	
	After	25	86	850	
	Error	0	1	50	

It can be seen from the results that the two tests use the same control strategy, but the regulation error and time are different. In the first test, the error of temperature control is 1°C, the error of humidity control is 1%, and the error of illuminate control is 0; In the second test, the error of temperature control is 0°C, the error of humidity control is 1%, and the error of illuminate control is 50 lx. Both test errors are within the allowable range, which can provide precise environmental control requirements for the next step in exploring "Black 29" precision agronomy. As for the air conditioning, the cooling operation will dehumidify the environment, but the workshop also needs suitable humidification, there is a conflict between them, so it makes the environment adjustment and control time longer. In the first test, the humidity level was low, and the air conditioning dehumidification had a strong inhibition effect on the humidity rise, while the second humidity level was high, and the air conditioning dehumidification had a weak inhibition effect on the humidity rise, so the first test time on the adjustment is longer than the second test. The above verification results show that the control system has high precision of environmental control, which can meet the needs of the next step to explore the "Black 29" Black fungus agricultural experiment environment.

2.2 Agronomic experiment methods

2.2.1 Production of cultivated species

Premium Black 29 original species were prepared in June 2018 by the Culture Collection Center, Institute of Microbiology, Heilongjiang Academy of Sciences, and had good activity. The cultivated species are packed separately from the original species: Mixed tree sawdust 67.0%, cottonseed hull 15.0%, wheat bran 15.0%, gypsum powder 1%, and calcium carbonate 1.0%. Dissolved sucrose 1.0% of the proper amount of water and added it to the mixture, with a final water content of 63.5%. 500 g of culture material of the original species was bottled in a 500 mL dropping bottle. 1000 g wet culture material of cultivated species was bottled into a 16.5×33.0 mm^2 polypropylene bag. Each test tube mother specie was inoculated with five bottles of original species, and each bottle of original species was inoculated with

thirty bags of cultivated species.

2.2.2 Design of agronomic experimental methods

The experiment was conducted in the building experimental workshop at the Institute of Microbiology of Heilongjiang Academy of Sciences from July to September 2018. After the culture materials were bagged according to the requirements, they were cultured in a professional culture workshop. When the mycelium was full of the whole bag, it went through a 15-day ripening stage, and then the holes were pricked with a pricking machine. Each of the bacteria was bound with 100 holes, and the bag hung on the support of the Culture Workshop. Under the control of the culture environment and control system, the budding stage experiment (10 d) will be carried out, then the ear growing stage experiment (15 d) be carried out[13-15].

1) Design of agronomic experimental methods of the budding stage

In the budding stage of black fungus, the existing research results and planting experience show that the important influencing factors are temperature (denoted by A in Table 2) and relative humidity (denoted by B in Table 2). The empirical temperature range is 22°C-32°C, and the relative humidity is 87%-98%. The median of the empirical range of impact factors was taken as level 0, and the upper and lower bounds of the empirical range as level 1 and −1, respectively, so as to obtain the factor level values of level 0, level 1, and level −1 in Table 2, as well as the change value of each factor level, that is, the change value of temperature is 5°C, and the change value of relative humidity is 5.5%. Realizing the orthogonal experiment through Design of Expert (https://www.statease.com/software/design-expert/), the valuable experience had to be added to the factor level range to ensure the rationality of the value of the factor level range in the experiment. The factor level values of 1.414 and −1.414 were obtained by adding or subtracting the factor level change value of 1.414 times from level 0. Therefore, for relative humidity, the level of 1.414 is obtained by calculating 92.500+1.414×5.500=100.280. The relative humidity level exceeded 100%, the maximum upper limit of the relative humidity value, so in the real experiment the upper limit value of 100% was used instead. For this reason, remarks were also added in Table 2.

The level values of these influencing factors have been determined, and the control system proposed in this study is to realize that the level values of these influencing factors can remain unchanged during the experiment.

Table 2 lists that the mycelium can grow between 6°C-35°C, according to the current research results: 20°C, 25°C, and 35°C have different effects on the budding percentage. On the 9th day of the budding stage, all the buds in the 20°C and 25°C treatment groups sprouted, but only 20% in the 35°C treatment group. It can be seen that the temperature has a great influence on the budding percentage. If the temperature is too high (35°C), the mycelium will be inhibited, the budding time will be delayed, and the budding percentage will be low. In addition, the growth and metabolism of mycelium require an amount of water. During the growth of black fungus, water is needed for spore germination, mycelium growth, budding, and fruiting body maturation. According to the current research, the budding stage lasts for 10 d, and the general environmental requirements of black fungus were got in the budding stage, on the basis of which we can expand the level range appropriately, and set a reasonable factor level, the temperature is 22°C-32°C, the humidity is 87%-98%. Because sitting ear-base time is shorter compared with the budding stage and growing stage, the influence of light on the budding percentage is not considered, only two factors and three levels of the orthogonal experiment were designed, and five groups are set in the central point test, eight groups are set in the non-central point test, a total of thirteen groups of tests. Explore the influence of factors A: Temperature (°C), B: Humidity (%) on a budding percentage at three levels, and consider their interaction AB[16,17].

Table 2 Factors and levels for the orthogonal experiment in the budding stage

Coded value	A: Temperature/°C	B: Humidity/%
−γ level (−1.414)	19.93	84.72
Low level (−1)	22.00	87.00
0 level (0)	27	92.5
High level (1)	32	98
γ level (1.414)	34.07	100.28*
Varying spacing	5	5.5

Note: *This value is replaced by 100% in the subsequent practical experiment because it is calculated by Design Expert and has exceeded the upper limit of the value range of factor B.

2) Design of agronomic experimental methods of the growing stage

The values in Table 3 represent the level values of factors A and B in the experiment with the same calculation procedure as listed Table 2. As Table 3 lists, according to the current research results, the fruiting body can grow at 15°C-32°C, and 20°C-28°C. During the test, the temperature level is set at 18°C-30°C. Then, the 90%RH-95%RH humidity range is conducive to earpiece growth. When the air humidity is less than 80%, the fruiting body grows slowly, when air humidity is more than 96%RH, it is easy to flow ear. So, the humidity level is set at 85%RH-95%RH. In addition, it is believed that the appropriate illumination is beneficial to the growth of auricular pieces, and can improve the quality of black fungus. Three factors and three levels of the orthogonal experiment were designed with earpiece diameter as index. Fourteen groups were set for the non-center point test and nine groups were set for the center point test, a total of twenty-three groups. To explore the influence of three factors A: Temperature (°C), B: Humidity (%), C: Illuminance (lx) on ear diameter at three levels, considering the interaction of AB, AC, BC, to carry out correlation analysis on the results, and to obtain precise agronomy and the optimal combination of factors.

Table 3 Factors and levels of the orthogonal experiment in the growing stage

Coded value	A: Temperature/°C	B: Humidity/%	C: Illuminance/lx
−γ level (−1.414)	13.91	81.59	731.82
Low level (−1)	18.00	85.00	800.00
0 level (0)	24.00	90.00	900.00
High level (1)	30.00	95.00	1000.00
γ level (1.414)	34.09	98.41	1068.18
Varying spacing	6.00	5.00	100.00

3 Results and analysis

3.1 Results and analysis of the budding stage

Each test group has six bags which have 100 aeration holes, a total of 600 aeration holes. After the bag was punctured into the aeration hole, all the bags were hung on the support frames of the cultivation workshop for the budding test. For the information processing, First, observe the budding of black fungus by

professional cultivation technicians, then count the number of sprouting and the number of effective punctured aeration holes in the bag. The budding percentage and the number of effective punctured holes in the package are the budding percentages.

3.1.1 Optimal model of the budding stage

The experimental results are listed in Table 4. By using Design Expert software for analysis, the regression model (Equation (1)) described the relationship among budding percentage (Z), temperature (A), and humidity (B).

$$Z = 97.96 + 2.61 \times A - 2.61 \times B + 2.84 \times AB - 15.71 \times A^2 - 6.86 \times B^2 \quad (1)$$

According to the results of the analysis of variance (ANOVA) (Table 5), the model (p<0.01) for predicting the budding percentage and both of the factors had significant effects on budding percentage (p<0.05). With R^2=0.98, Adeq Precision=21.58, and CV=2.85%, it showed that the model fit the data well and can be used to predict the optimal cultivation condition.

Table 4 Result of the budding experiments

Number	A: Temperature	B: Humidity	Z: Budding percentage/%
1	0	0	97
2	−1	−1	88
3	0	0	98
4	1	−1	79
5	−1	1	71
6	0	0	98
7	1	1	81
8	0	0	99
9	−1.414	0	65
10	0	0	97
11	1.414	0	67
12	0	−1.414	75
13	0	1.414	78

Table 5 Results of ANOVA for budding percentage

Source	Squares	DF	Square	F value	p value
Model	2022.62	5	404.52	70.48	<0.0001
A	54.52	1	54.52	9.50	0.0178
B	54.30	1	54.30	9.46	0.0179
AB	32.26	1	32.26	5.62	0.0495
A^2	1717.83	1	1717.83	299.31	<0.0001
B^2	327.30	1	327.30	57.03	0.0001
Residual	40.17	7	5.74		
Lack of fit	35.74	3	11.91	10.74	0.0220
Pure error	4.44	4	1.11		
Cor total	2062.79	12			
R^2	0.98				
Adj R^2	0.97				
Adeq Precision	21.58				
CV	2.85%				

Note: DF: Degree of freedom; CV: Coefficient of Variance.

3.1.2 Effect of single factor of the budding stage

When setting each factor (A and B) in the regression equation (Equation (1)) to 0, respectively, regression models for single factor effect can be obtained (Equations (2) and (3)).

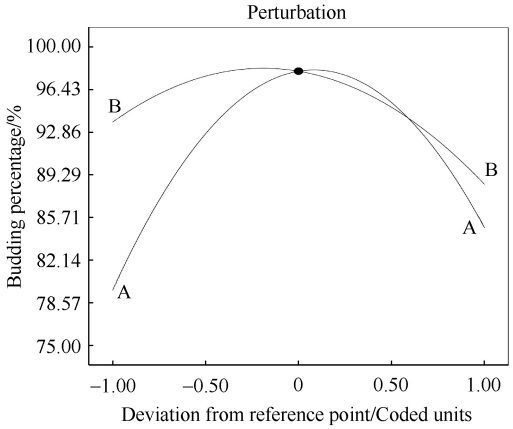
Temperature (A):

$$Z = 97.96 + 2.61 \times A - 15.71 \times A^2 \quad (2)$$

Humidity (B):

$$Z = 97.96 - 2.61 \times B - 6.86 \times B^2 \quad (3)$$

As Figure 6 shows, when the temperature was set at level 0 (24°C), the budding percentage rose first and then descended later with the change in humidity. The budding percentage had about a 3% increase when humidity increased from −1 level to 0 level, which indicates that air humidity had a minor effect on hyphen growth since the mycelium took a longer time compared with based time to grow in the fungus bag. However, when humidity was more than 91.53%RH, water may condense on the inside of the bag and cause the water to satiate on the surface and kill the mycelium. When the humidity was set at 0 level (97%RH), the budding percentage increased first, and then decreased afterwards with the increase in temperature. When the temperature was less than 27.34°C, the growth of the mycelium decreased, as the temperature rose higher than 27.34°C, some of the culture material packages tended to rot, which led to a decrease in budding percentage. In general, the budding stage is 10 days, and the budding speed is about 8.4%/d, which is normal.



Note: A: Temperature; B: Humidity.

Figure 6 Effect of single factor on budding percentage

3.1.3 Effect of Interactions of the budding stage

This convex surface of the two factors' effects is shown in Figure 7. Although it showed that the budding percentage was increased first and decreased afterward with the increase of the temperature and humidity, the degrees of interaction effect on these two factors were not the same. When the humidity was at a low level (87%RH-91%RH), the temperature's impact on the budding percentage had a less curvy line. When humidity is at a high level (95%RH-98%RH), the effect of temperature on budding percentage is more intense. In the process of temperature increasing to 27°C, the budding percentage increased rapidly, afterwards, the budding percentage declined slightly. When the temperature and humidity were close to 0 level (Temperature=27°C, Humidity=92.5%R), the budding percentage reached the maximum of 98.27%.

3.1.4 Best combination of factors of the budding stage

In Design Expert software, the optimal combination of temperature and humidity was obtained at a temperature of 27.34°C and humidity of 91.53%RH, the best budding percentage was predicted at 98.27% by using the optimization model.

3.2 Results and analysis of the growing stage

Three completed budding fungus bags were selected as a group on each cultivation support frame, and then put in the cultivation workshop for the growing test. The results of the orthogonal experiment are listed in Table 6.

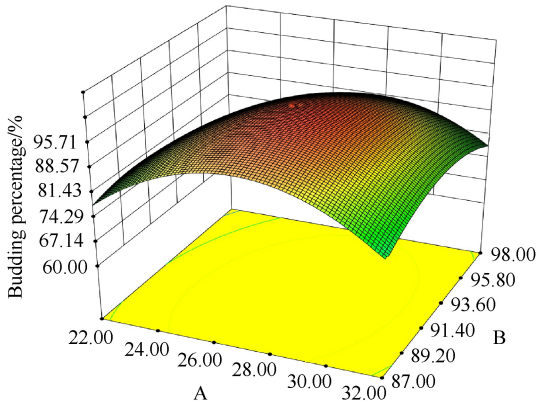


Figure 7 Effect of interaction between temperature and humidity on budding percentage

Table 6 Results of experiment of growing stage

Number	A: Temperature	B: Humidity	C: Illuminance	Z: Diameter/mm
1	−1.681	0	0	6
2	0	0	0	47
3	−1	1	1	23
4	0	0	0	43
5	−1	1	−1	20
6	0	0	0	48
7	−1	−1	−1	23
8	0	0	1.681	45
9	1	1	−1	28
10	0	0	0	50
11	0	0	0	47
12	0	0	−1.681	38
13	−1	-1	1	30
14	0	0	0	50
15	1	1	−1	23
16	0	0	0	50
17	0	−1.681	0	6
18	0	1.681	0	10
19	0	0	0	39
20	1	−1	1	8
21	0	0	0	47
22	1	−1	−1	6
23	1.681	0	0	5

3.2.1 Optimal model of the growing stage

The experimental results are listed in Table 6. Experiment No.19 was an outlier because the other seven experiments are all around 50. The model can look better, so illumination might be a significant factor. The regression model (Equation (4)) described the relationship between the ear diameters of the black fungus and the three factors (temperature, humidity, and illumination) in a suitable environment.

$$Z = 46.7 - 2.39 \times A + 2.47 \times B + 2.11 \times C + 5.88 \times AB - 0.37 \times AC - 0.12 \times BC - 13.86 \times A^2 - 12.98 \times B^2 - 1.14 \times C^2 \quad (4)$$

According to the results of ANOVA (Table 7), the model significance test was effective (p<0.01) which sufficiently interpreted the experimental data and made preliminary analysis and prediction for precise agronomic characters in the stage of growing of black fungus. The temperature and humidity had significant effects (p<0.05) on the ear size, but the illumination had little effect on the ear size (p=0.0757).

Table 7 Results of ANOVA of growing stage

Source	Squares	DF	Square	F value	p value
Model	6206.36	9	689.60	42.39	<0.0001
A	78.21	1	78.21	4.81	0.0471
B	83.29	1	83.29	5.12	0.0414
C	60.62	1	60.62	3.73	0.0757
AB	276.13	1	276.13	16.97	0.0012
AC	1.13	1	1.13	0.07	0.7967
BC	0.13	1	0.13	0.01	0.9315
A^2	3054.37	1	3054.37	187.77	<0.0001
B^2	2677.35	1	2677.35	164.59	<0.0001
C^2	20.53	1	20.53	1.26	0.2816
Residual	211.47	13	16.72		
Lack of fit	103.91	5	20.78	1.55	0.2778
Pure error	107.56	8	13.44		
Cor total	6417.83	22			
R^2	0.9827				
Adj R^2	0.9442				
Adeq precision	16.38				
CV	13.14%				

3.2.2 Effect of single factor of the growing stage

Set two factors in regression equation to 0 level respectively, single factor regression model (Equations (5)-(7)) were obtained by considering the effect of temperature (A), humidity (B), and illumination (C) on black fungus diameter.

Temperature (A):

$$Z = 46.7 - 2.39 \times A - 13.86 \times A^2 \quad (5)$$

Humidity (B):

$$Z = 46.7 + 2.47 \times B - 12.98 \times B^2 \quad (6)$$

Illumination (C):

$$Z = 46.7 + 2.11 \times C - 1.14 \times C^2 \quad (7)$$

As can be seen from Figure 8, temperature, and humidity are set to 0 level, and illumination has no significant confluence on the diameter of black fungus, but when the illumination reaches 1000 lx, the color of black fungus gets darker, which makes black fungus look better. When the temperature and illumination are at 0 level, the change curve of the diameter of black fungus first increases and then decreases. In the former humidity level ((−1)-0), there was the fiercest impact on the diameter of black fungus. The Diameter of black fungus was sharply increased by 12 mm. At the level of 0.07, the optimum humidity was 90.36%RH. The influence of humidity at the latter level (0-1) on the diameter of the black fungus was significant, and the diameter was decreased by 8 mm. At the 0 level of humidity and illumination, the diameter of black fungus was increased by 10 mm at the level of the former temperature level (−1-0). After the temperature level (0-1), the diameter of black fungus was impacted significantly, and the diameter of black fungus dropped by 15 mm. Above all, the descending order of influence on the diameter of the black fungus was obtained: Temperature (later level), Humidity (former level), Temperature (former level), Humidity (later level), and Illumination.

3.2.3 Effect of interactions of the growing stage

1) Effect of interactions of AB in the growing stage

Figure 9 shows that when humidity was at a low level (85%RH-89%RH), the image of temperature's impact on diameter had a smooth surface. The effect was more intense when humidity was at a high level (93%RH-95%RH), particularly in the process of temperature rising to 24°C, diameter increased sharply.

When the temperature was at a low or high level, the influence of humidity on diameter was not severe. However, at 0 level of temperature, humidity had a strong effect on diameter and diameter increased sharply at the high level of humidity.

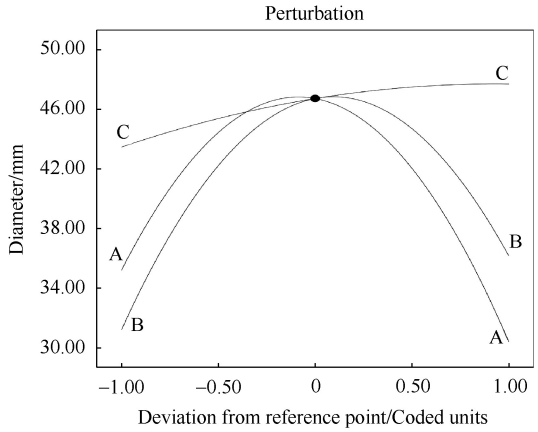


Figure 8 Effect of single factor on growing stage

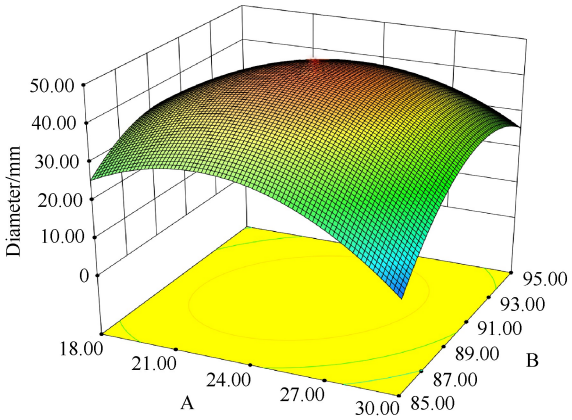
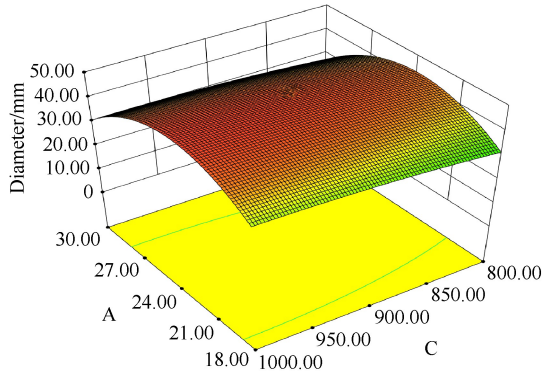


Figure 9 Effect of interaction between temperature and humidity on black fungus diameter

2) Effect of interactions of AC in the growing stage

From Figure 10, when the temperature is at high (27°C-30°C) or low level (18°C-21°C), the image surface of illumination impact on diameter was smooth. When the temperature is at the 0 level (24°C), influenced by illumination, the diameter changes a little.



Note: C: Illumination.

Figure 10 Effect of interaction between temperature and illumination on black fungus diameter

3) Effect of interactions of BC in the growing stage

From Figure 11, there was no significant change in diameter at any stage of humidity and illumination, thus interaction between the two factors was not obvious.

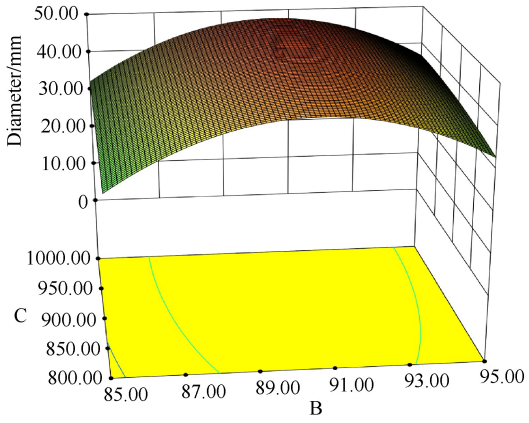


Figure 11 Effect of interaction between humidity and illumination on black fungus diameter

3.2.4 Brief summary

By using the optimization model of software Design Expert, taking acquisition of the maximum diameter as the final aim, the optimal combination of temperature, humidity, and illumination is obtained, the temperature is 23.49°C, humidity is 90.36%RH, illuminance is 993.6 lx, black fungus diameter is 47.88 mm.

4 Agronomy verification

4.1 Agronomy verification of budding stage

The accuracy of the best combination of environmental parameters was verified. Two groups of different combinations of environmental parameters were set up in the upper and lower levels with a temperature range of ±2°C and humidity range of ±5%RH. The budding test was carried out in the designed workshop environment. After the end of the budding stage, the budding percentage was taken as the verification index[18,19]. Under the five parameter combinations, the budding percentage and ear bud growth condition of each package are quite different. Through the calculation of black fungus, the number of buds and the number of effective holes in the package are obtained, and the ratio of the number of buds and the number of effective holes in the package is the budding percentage. Through the observation and comparison of the growth of ear buds in each group, the verification result of the best parameter combination in the budding stage is obtained. The budding percentage results are listed in Table 8.

Table 8 constitutes each experiment number (see column 1 of Table 8) by taking the level values of the relevant factors (see columns 2 and 3 of Table 8) around the optimal values. In row 2 in Table 8, the temperature is 27.3°C and the relative humidity is 91.5%. The values of these factors are the optimal levels obtained by the optimal model. The factor level values of other experiment numbers were selected around this optimal factor value. These factor level values (including the optimal factor level) are set manually, and then the control system designed by us will maintain these factor values unchanged during the experiment so that whether the optimal factor level values obtained by the optimal model are correct can be verified through real experiments.

It can be seen from Table 8 that the second group, as the best combination of environmental parameters, has the highest budding percentage and the best growth effect compared with other test groups, with a budding percentage of 97.8%. Some ear buds have started to grow rapidly and form earpieces; the first group has a budding percentage of 94.4%, which is because the respiration of

ear buds is inhibited after the increase in humidity, and the growth of ear buds is slow, but the uniformity of ear buds in this group is high; the third group and the fourth group, the budding percentage and ear bud growth were average; in the fifth group, because of the high temperature and humidity, the internal culture materials had rotted, the budding percentage was average, and the ear bud growth was the worst.

4.2 Agronomy verification of growing stage

Hang the culture bag in good budding conditions in the workshop, and verify the accuracy of the obtained optimal combination of environmental parameters in ear emergence stage. Set two groups of different combinations of environmental parameters at each factor level, upper and lower than the small area. The temperature range is ±2°C, the humidity range is ±5%RH, the illuminance range is ±50 lx, and the diameter of the earpiece is taken as the verification index. There are differences in the growth of the fruiting bodies of black fungus in five combinations of parameters. The diameter of the earpiece is calculated by the method used in the design of agronomic experiments in the ear stage, and the verification result of the best combination of parameters in the ear stage is obtained. The test results are listed in Table 9.

In experiment No.2, the temperature was set at 23.4°C, the relative humidity was 90.3%, and the light intensity was 993.6, which was also the best level value given by the optimal model. The level values of each factor were manually set (see columns 2-4 of Table 9) in each experiment number (see column 1 of Table 9), and our control system will ensure that these level values remain unchanged during the experiment. At the end of the experiment, it is measured to obtain the values in column 5 of Table 9. The value 49 of ear diameter in Table 9 is the experimental result in the practical experiment after controlling the optimal level value of factor in experiment No.2, and the predicted result of the optimal model is 47.88. It can be seen that the two are relatively close, and the results of each experiment number show that the experimental results of the optimal level value of the factor provided by the model are also optimal. So this further indicates that our control system is stable and reliable.

Table 8 Verification results of budding

Experiment	Temperature/°C	Humidity/%	Buds number/s	Effective number of holes	Budding percentage/%	Ear buds growth
1	28.3	94.0	85	90	94.4	++++
2	27.3	91.5	89	91	97.8	+++++
3	26.3	89.0	87	93	93.5	+++
4	25.3	86.5	77	89	86.5	++
5	29.3	96.5	80	94	85.1	+

Note: '+': The more "+", the better the growth of black fungus.

Table 9 Verification results at the growing stage

Experiment number	Temperature/°C	Humidity/%	Illumination/lx	Ear diameter/mm	Color
1	22.4	87.8	968.6	28	Black
2	23.4	90.3	993.6	49	Dark brown
3	24.4	92.8	1018.6	32	Dark brown
4	21.4	85.3	843.6	25	Black
5	25.4	95.3	1043.6	24	Black and yellow

As listed in Table 9, the second group, as the best environmental parameter group, has the best growth effect of its fruiting body, with the largest earpiece diameter of 49 mm, and the fruiting body is dark brown and glossy; the third group has limited growth of the fruiting body after the increase in humidity, the diameter decreases, and the color character does not change; the first group has low temperature and humidity, and the earpiece diameter drops significantly to 28 mm; the fourth group and the fifth group were in the extreme level due to temperature and humidity (the fourth group was the lowest, the fifth group was the highest), and the diameter of earpiece was the smallest at 25 mm and 24 mm respectively, and the earpiece was black yellow. In addition, illumination has little effect on the growth of the earpiece, so the verification of illumination factors needs to be further explored and improved. For hydroponic pakchoi cultivation in plant factories, the optimal red:blue ratio of full-spectrum LEDs has been studied[20]. This research result provides a further possible research direction of the influence of light on the growth of *Auricularia auricula*.

The cultivation area of the four conjoined greenhouses is about 150 m^2, there are 45 fungus bags hung per square meter. It is predicted that each fungus bag will produce 0.75 kg of wet black fungus, and the yield of the wet fungus is about 5000 kg. According to the dry-wet ratio of 0.12:1, the yield of the dry fungus is about 600 kg. The black fungus can produce three crops every year, and the total yield of wet fungus is estimated to be 12 000 kg due to nutrient attenuation

5 Conclusions

At present, the main production mode of black fungus is cultivation in the facility, and the key to cultivation technology is its agronomic and growth environment regulation. In this regard, the design of high-efficiency control methods for the relevant environment and the construction of an intelligent control system was carried out to the precise agronomy in each stage of black fungus growth, and the following conclusions are drawn:

1) Intelligent detection and control technology was used to build an intelligent control system. Programmable Logic Controller (PLC) was the core controller to send out the corresponding temperature, humidity, and light behavior instructions. The system output layer which includes the environmental control equipment was designed to achieve the precise and efficient regulation of the black fungus cultivation workshop environment. Develop and build four closed black fungus cultivation workshops to explore the best factor combination of environment and precise agronomy. The results showed that all the functions of the intelligent control system could meet the needs of the cultivation technology and environment of black fungus.

2) Aiming at the problems of poor accuracy and slow response

of data acquisition and control, we use the way of shortening the distance between the sensor and the fungus bag to sense the environment within its effective range, and use the method of multi-sensor and multipoint acquisition data taking the mean value to obtain precise environmental data; use real-time spray, ventilation, heating, refrigeration and other ways to regulate the environment until the control system reaches the goal to steady state.

3) By applying the smart control system to the precision cultivation of black fungus, the best environment factor combination and precise agronomy of "Black 29" species black fungus were obtained: the best factor combination in the germination stage of the temperature of 27.34°C, humidity of 91.53%RH, and budding percentage of 98.27%; The best combination of factors in ear stage: temperature 23.49°C, humidity 90.36%RH, illuminance 993.6 lx, ear diameter: 47 mm. The results show that all functions of the intelligent control system can meet the needs of the cultivation technology and environment of black fungus.

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