Development of Artificial Intelligence Climate Chamber and Experimental Study on Crop Phenotype Acquisition

Anhua Ren (✉ 1254114162@qq.com)

Nanjing Agricultural University College of Engineering <https://orcid.org/0000-0003-0087-0084>

Dong Jiang

Nanjing Agricultural University College of Agriculture

Min Kang

Nanjing Agricultural University College of Engineering

Jie Wu

Nanjing Agricultural University College of Agriculture

Fangcheng Xiao

Nanjing Huitong Crop Phenotypic Research Institute Co.,Ltd.

Pei Hou

Nanjing Agricultural University College of Engineering

Xiuqing Fu

Nanjing Agricultural University College of Engineering <https://orcid.org/0000-0002-1124-5586>

Research Article

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Abstract

Background: The deficiencies of traditional artificial climate chambers in phenotypic collection and analysis were improved to achieve the high-throughput acquisition of crop phenotypes during the growth period. This paper has developed an artificial intelligence climate cabin with functions of crop cultivation management and phenotype acquisition during the whole growth period. This research also established an environmental control system, a crop phenotype monitoring system and a crop phenotype acquisition system with environmental parameter adjustment and crop image collection. Phenotypic feature extraction and other functions were carried out in the cultivation experiment, and phenotype acquisition of wheat was performed under different nitrogen fertiliser application rates. Comparison and analyses were performed by the systematic and manual measurement values of crop phenotype characteristics, and the acquisition of wheat table was evaluated based on artificial intelligence climate cabin. The goodness of fit of the model was used to classify data.

Results: During the different growth periods of wheat, the correlation analysis between the systematic and manual measurement values of its leaf area, plant height and canopy temperature showed that the obtained correlation coefficient r was greater than 1, and the fitting determination coefficient R^2 was greater than 0.7156, with errors. The coefficient *root* mean square error was less than 2.42, indicating that the two were positively correlated, and their correlation was excellent.

Conclusion: The results verified the feasibility and applicability of the artificial intelligence climate cabin to study the phenotypic characteristics of crops.

Introduction

The combination of climate change and the new crown epidemic has brought huge challenges to food security in China and the world [1, 2]. The foundation for coping with challenges and ensuring national food security involves the analysis of the regulation mechanism of crop gene and phenotype formation, selection of new varieties with high yield, high quality, are green and stress resistance; realisation of precision cultivation and fine breeding methods and improvement of the utilisation efficiency of crop germplasm resources [3–5]. High-throughput crop-phenotype acquisition is the key to in-depth interpretation of gene functions and breaking through the bottleneck of precision breeding technology. Studies should focus on the laws of crop growth and development, reveal gene regulation pathways and optimise precision management of crop cultivation and acceleration of crop improvement. The phenotype acquisition platform is an important hardware basis for rapid screening of germplasm resources, phenotype identification, and formation mechanism research [6–8], and it is mainly composed of mechanical devices or drones equipped with sensors [9, 10].

The traditional artificial climate room is a key place for crop species cultivation [11–13]. Its functions mostly focus on the control of environmental parameters. In general, this room lacks the function of obtaining high-throughput crop phenotype data. Most works on phenotype collection still needs the help of manual completion, and defects, such as low efficiency and large errors, exist [14, 15]. Given that phenotyping has gradually become a recognised research hotspot in the frontiers of life sciences [16], a crop phenotyping platform that integrates the precise management of crop cultivation, high-precision mechanical transmission and multi-sensor data collection and analysis has become a development trend in high-throughput phenotype acquisition [17, 18].

In summary, based on the traditional artificial climate chamber and combined with the environmental control, phenotype monitoring and phenotype acquisition systems, this article carried out the research and development of an artificial intelligence climate chamber with crop cultivation management and phenotype acquisition functions during the whole growth period of wheat. The precision cultivation test of wheat realised the continuous acquisition of phenotypic characteristics during wheat growth, improved the lack of phenotypic feature extraction and analysis in the traditional artificial climate chamber and verified the feasibility of the artificial climate cabin for crop phenotyping research.

Materials And Methods

Experimental setup

The experiment was carried out in the artificial intelligence climate cabin of the Baima Base of Nanjing Agricultural University (119.187196°N, 31.62006°W). The test subjects were selected from the Qingnong 2 and Liangxing 77 wheat varieties of the State Key Laboratory of Crop Genetics and Germplasm Innovation. Salt-free coconut bricks were selected as the cultivation substrate for soilless cultivation. The wheat seeds were sown on the root support site of the round root box at a depth of 3 cm, and three repeat groups were set up (Figure 1). A total of $2 \times 3 \times 3$ round root boxes were planted. The nitrogen, phosphorus and potassium fertilisers used in the experiment were urea (containing N46%), superphosphate (containing P_2O_5 18%) and potassium sulphate (containing K_2O 50%), respectively. The amount of nitrogen fertiliser was set as a variable, and the three-leaf stage of wheat was fertilised and irrigated at the tillering stage, jointing stage and growing period. Table 3 shows the environment and cultivation parameters in the crop cultivation and phenotype acquisition area.

Development of artificial intelligence climate cabin

Composition of artificial intelligence climate cabin

Figure 1 shows the developed artificial intelligence climate cabin. Figures 1(a)–1(e) display the environmental control system used to regulate the environmental parameters in the crop cultivation area of the cabin. Figures 1(f) and 1(g) present the crop cultivation devices, namely, the flat root boxes and round root boxes, respectively, that were used for wheat cultivation experiments. Figure 1(h) shows a crop phenotype monitoring system composed of a high-precision mechanical transmission device and the multiple sensors mounted on it. We obtained the phenotypic characteristics of the crop during the growth process. Figure 1(i) shows the software interface of the crop phenotype acquisition system, which was used to analyse and process the image information of the crop and extract phenotypic characteristic parameters. The environmental parameters in the cabin were set by the control system. The crop phenotype monitoring system was used to obtain images and information of crops on the cultivation device, and the crop phenotypic characteristics were obtained based on the phenotype acquisition system.

Environmental Control System

Figure 2 shows the interface of the developed environmental control system. The control of environmental parameters, including the cabin temperature, humidity, light, CO_2 concentration, air pressure, etc., can be realised

through a touch screen, and the circulation ventilation inside and outside the cabin were attained. Table 1 exhibits the control range.

Table 1
Main environmental factor regulation parameter table

Environmental parameters	Adjustment range
temperature	0 °C–50 °C
illumination	0–3000 Lux
Air pressure	atm
humidity	10–80% RH
CO ₂ concentration	1000–1500 PPM

Crop Phenotype Monitoring System

The crop phenotype monitoring system was composed of high-precision mechanical transmission devices and multiple sensors. As shown in Figure 3, the servo motor was controlled by the upper computer (Figure 3a) to drive the high-precision mechanical transmission device equipped with multiple sensors (Figure 3b). The movement in the XYZ direction in the cabin was realised to plan the scanning path of each collection site in the crop cultivation area and control the RGB, depth and thermal imaging and other multi-sensors to obtain the crop leaf area, plant height, canopy temperature and other phenotypic images. Table 2 shows the related information and parameters.

Table 2
Parameters of imaging camera in the crop-phenotype acquisition system

Sensor type	Type	Type of data	Get parameters	Advantage
RGB camera	LT384H/640H	2D imaging	Canopy parameters Leaf area size Green Index	Excellent image quality, fast real-time transmission and support for multiple exposure modes
Depth camera	FM850-GI-E1	Three-dimensional imaging	Plant height Canopy structure	Active binocular, strong anti-interference ability and support trigger mode
Thermal Imager	LT640H	2D imaging	Canopy temperature Lowest temperature Maximum temperature Average temperature	High temperature measurement accuracy, support for secondary development and high frame rate

Crop Phenotype Acquisition System

The developed crop phenotype acquisition system was mainly used for crop image collection, phenotypic feature acquisition and data management. Figure 4(a) shows the flow chart of the system function realisation. The server was used to store data and information collection; the user can perform image collection and data processing operations on the software client; the multiple data obtained by the imaging sensor can be wirelessly transmitted to the storage server, and they were used for post-processing and image processing. Figure 4(b) shows the software interface of the system, where the login interface was used for user registration and login; the setting interface displayed the working status of the sensor and setting of the timing camera; the sensor interface displayed the operating status information, real-time collected crop images and extraction data. The phenotypic data of the crops can be obtained: leaf area size, leaf area index, green index, wheat individual plant height and minimum, maximum and average temperatures of the canopy of individual wheat.

Table 3
Test condition parameters of wheat cultivation in the artificial intelligence climate cabin

Fertilization /Water volume	Nitrogen fertiliser(N1)	Nitrogen fertiliser(N2)	Nitrogen fertiliser(N3)	Potash fertiliser	Phosphate Fertiliser	Irrigation volume	
	80 kg/hm ²	160 kg/hm ²	240 kg/hm ²	120 kg/hm ²	120 kg/hm ²	450 m ³ /hm ²	
Environmental conditions	Period	CO₂	Humidity	Illumination	Air pressure	Temperature	
	Growth Period	500 PPM	70% RH	Day100% Night30%	500BAR	Day (25 °C)	Night (18 °C)
Acquisition time	Trefoil stage	27 November 2020			9:00–9:30		
		28 November 2020			13:00–13:30		
		29 November 2020			16:00–16:30		
	Pre-tillering	17 December 2020			9:00–9:30		
		18 December 2020			13:00–13:30		
		19 December 2020			16:00–16:30		
	Late tillering	19 January 2021			9:00–9:30		
		20 January 2021			13:00–13:30		
		21 January 2021			16:00–16:30		
	Jointing period	17 March 2021			9:00–9:30		
		18 March 2021			13:00–13:30		
		19 March 2021			16:00–16:30		

Data collection

As shown in Table 3, the systematic measurement values of wheat canopy phenotype were obtained through the crop phenotype acquisition system at the three-leaf, early tillering, late tillering and jointing stages using a graph paper [19, 20] and a ruler. A handheld infrared thermal imager was used to obtain manual measurements of the leaf area, plant height and canopy temperature of wheat.

Data processing

With the help of SPSS software for data sorting and analysis, the correlation coefficient r [21] and determination coefficient R^2 [22] were used to evaluate the degree of correlation between the image feature values and wheat agronomic parameters, and the root mean square error [23] was used for crop-based analysis. The error evaluation between the phenotypic parameters of the canopy part extracted by the phenotype monitoring system and the artificially measured canopy was estimated to estimate the accuracy of the crop phenotype monitoring system in the study of the phenotypic characteristics of wheat.

Results And Discussion

Correlation analysis

Correlation analysis of wheat leaf area

As shown in Figure 5 and Table 4, in the four growth periods of wheat, the systematic measurement value of the wheat leaf area was positively correlated with the manual measurement value, and the fitting determination coefficient R^2 was greater than 0.70. The error coefficients were all less than 2.4. The crop phenotype acquisition system had the smallest measurement error of wheat leaf area during the three-leaf period, and the smallest error coefficient can reach 1.112. The results showed a significant correlation between the leaf area system measurement value obtained by the crop phenotype monitoring system and the manual measurement value. A good fit was also observed. The phenotypic parameters of the wheat canopy leaf area can be studied through the crop phenotype monitoring system.

Table 4
Comparison of fitting analysis between the systematic and manual measurement values of phenotypic characteristic parameters in wheat growth period

Characteristic Parameters	Growth Period	Fitting equation	r	R^2	RSME
Leaf area	Trefoil stage	$y=1.125x+3.043$	0.846	0.7165	1.112
	Pre-tillering	$y=1.344x+2.681$	0.922	0.8509	1.811
	Late tillering	$y=1.238x-3.146$	0.890	0.7924	2.365
	Jointing period	$y=1.098x-0.238$	0.950	0.9021	2.046
Plant height	Trefoil stage	$y=0.5002x+3.833$	0.848	0.8397	0.349
	Pre-tillering	$y=0.823x+2.443$	0.723	0.8464	1.971
	Late tillering	$y=1.228x-1.799$	0.781	0.8452	2.139
	Jointing period	$y=0.8273x+2.013$	0.875	0.8492	2.429
Canopy temperature	Trefoil stage	$y=0.571x+13.93$	0.928	0.8613	0.261
	Pre-tillering	$y=0.8234x+6.416$	0.921	0.8479	1.285
	Late tillering	$y=0.9306x+0.604$	0.948	0.8991	0.930
	Jointing period	$y=0.7405x+5.564$	0.931	0.8669	0.436

Correlation analysis of wheat plant height

As shown in Figure 5 and Table 4, in the four growth periods of wheat, the systematic measurement value of wheat plant height was positively correlated with the manual measurement value, and the fitting determination coefficient R^2 was greater than 0.83. The error coefficients were all less than 2.5. The crop phenotype acquisition system showed the smallest error in the height measurement of wheat during the three-leaf period, and the smallest error coefficient can reach 0.349. The results showed the significant correlation between the plant height system measurement value obtained by the crop phenotype monitoring system and the manual

measurement value, and a good fit was observed. The growth model of wheat plant height can be predicted by the crop phenotype monitoring system.

Correlation analysis of wheat canopy temperature

As shown in Figure 5 and Table 4, during the wheat growth period, the systematic measurement value of wheat canopy temperature was positively correlated with the manual measurement value. The fitting determination coefficient R^2 was greater than 0.84, and the error coefficient was less than 1.3. The crop phenotype acquisition system exhibited the smallest measurement error of the wheat canopy temperature during the three-leaf period, and the smallest error coefficient can reach 0.261. The results showed a significant correlation between the canopy temperature system-measured values obtained by the crop phenotype monitoring system and manual measurement values. A good fit was also observed. The crop phenotype monitoring system can be used to further study the water stress of wheat [24].

Conclusion

In order to achieve high-throughput collection of phenotypes during the growth period of crops, to improve the deficiencies of phenotypic collection and analysis in traditional artificial climate chambers, to promote phenotypic research and to improve crop breeding efficiency to increase food production, this paper developed an artificial intelligence climate with crop cultivation management and phenotype acquisition functions during the growth period of wheat. In the cabin, an environmental control system that can set parameters, such as temperature, humidity and light in the cabin, was developed, and a crop phenotype monitoring system composed of high-precision mechanical transmission devices and multiple sensors was designed. A phenotypic feature extraction and management system was also developed.

By selecting two wheat varieties with different early vigor, the cultivation experiment and phenotype acquisition of wheat under different nitrogen fertilizer application rates were carried out in the artificial intelligence climate cabin. The crop phenotype acquisition system was used to carry out the cultivation experiment and phenotype acquisition research of wheat under different nitrogen fertiliser application rates. Phenotypic images and information of wheat leaf area, plant height, canopy temperature, etc., were obtained during the three-leaf period, early tillering period, late tillering stage and jointing stage. The crop phenotype system measurement values and manual measurement values of characteristics were compared and analysed.

The test results showed that in the four growth periods of wheat, the systematic measurement values of leaf area, plant height and canopy temperature were highly correlated with manual measurement values. The correlation coefficient r was positive, and the determination coefficient R^2 was greater than 0.7156. The error coefficient RSME was less than 2.42. The crop phenotype acquisition system showed the smallest measurement error for the phenotypic characteristics of wheat during the three-leaf period. The measurement error of the layer temperature can be as small as 0.261. A significant positive correlation was noted between the systematic and manual measurement values of wheat phenotypic characteristics, showing an excellent degree of fit, and the error was within an acceptable range.

Therefore, the wheat cultivation experiment and phenotype acquisition research based on the artificial intelligence climate cabin had high accuracy, which verified the feasibility and applicability of the artificial

intelligence climate cabin for crop phenomics research, which will be used as a crop table. This cabin can be a powerful tool in the field of typology and crop breeding.

Declarations

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Authors' contributions

Dong Jiang and Min Kang: conceptualisation; Anhua Ren and Xiuqing Fu: methodology; Anhua Ren and Pei Hou: experimentation; Anhua Ren: original draft preparation; Jie Wu, Fangcheng Xiao and Xiuqing Fu: review and editing of the paper. All authors read and approved the final manuscript.

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Competing interests

The authors declare no conflicts of interest.

Author details

¹ College of Engineering, Nanjing Agricultural University, Nanjing 210031, China; ² Plant Phenomics Research Center, Nanjing Agricultural University, Nanjing 210095, China; ³ Jiangsu Key Laboratory of Intelligence

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Figures

Figure 1

Schematic of the overall structure of the artificial intelligence climate cabin

Figure 2

Environmental control system architecture

(a)

Figure 3

Hardware device of crop phenotype monitoring system

Figure 4

Figure 5

Linear fitting between systematic and manual measurements of phenotypic characteristic parameters in wheat growth period