American Journal of Biochemistry and Biotechnology

Original Research Paper

Application and Prospect of CO_2 Enrichment Technology in Agriculture

[1,2]Bingbing Wang, [1,2]Xiangjie Lu, [1,2]Wanlin Gao, [1,2]Yun Xia and [1,2,3]Bangjie Yang

[1]College of Information and Electrical Engineering, China Agricultural University, Beijing, 100083, China
[2]Key Laboratory of Agricultural Information Standardization, Ministry of Agriculture and Rural Affairs, Beijing,100083, China
[3]National Engineering Lab for Agri-Product Quality Traceability, Beijing Technology, and Business University, Beijing 100048, China

Article history
Received: 11-10-2021
Revised: 28-12-2021
Accepted: 06-01-2022

Corresponding Author:
Wanlin Gao
College of Information and Electrical Engineering, China Agricultural University,
Beijing, 100083, China
Email: wanlingaocau@163.com

Abstract: With the increasing consumption of fossil fuels for human activities, the emissions of greenhouse gases, such as CO_2, have significantly increased, resulting in an intensified greenhouse effect. As an important element for plant photosynthesis, CO_2 enrichment in an appropriate environment can promote photosynthetic rate, organic matter accumulation, and the growth rate of plants. The CO_2 enrichment technology should be widely used in agriculture. However, only a few studies have emphasized the role of CO_2 enrichment technology and its development in agriculture. In a study, four CO_2 enrichment technologies were introduced based on the different generation principles of CO_2. It can be concluded that the existing CO_2 enrichment methods and technologies benefited from the development of agricultural information technology. Further, the framework of agricultural information technology in CO_2 enrichment is proposed. It will provide an innovative idea for mitigating global climate change and help future research on the environmental adaptability of farmland crops.

Keywords: CO_2 Fertilization Effect (CFE), CO_2 Enrichment, Agricultural Information Technology, Global Climate Change

Introduction

Global climate change has received significant attention owing to the continuous increase in greenhouse gas emissions. Carbon sequestration and emission reduction methods have been widely investigated (Mi *et al.*, 2019). Numerous studies have focused on CO_2 Capture, Utilization, and Storage (CCUS) technology, such as geological sequestration. However, the role of agriculture in carbon sequestration is not completely explored (Janssonet *al.*, 2021). Plant production in agriculture is based on the absorption of CO_2 during photosynthesis. Therefore, the growth and yield of plants can be increased by using abundantly available atmospheric CO_2 resulting from global human activities; this process is known as CO_2 fertilization. The CO_2 Fertilization Effect (CFE) is an important factor in reducing global climate warming and expresses the carbon sink capacity of vegetation.

Recently, the CFE on crop production has been extensively studied and it is widely accepted that higher CO_2 concentration can improve the yield and quality of crops. Several researchers have efficiently used this effect in facility agriculture, such as in greenhouses, where CO_2 concentration is artificially increased to improve yields and quality of crops (Hao *et al.*, 2020). In farmland, research on CFE has mainly focused on two aspects: The estimation of carbon sequestration potential of vegetation at different scales by photosynthesis and the impact of increased CO_2 concentrations on crop yields and nutritional quality(Tang *et al.*, 2019; Dokić *et al.*, 2020; Isah *et al.*, 2020). The application of CO_2 enrichment technology was only employed for experimental purposes and has not been utilized in crop planting.

However, only a few studies have focused on the application of CO_2 enrichment technology. To efficiently utilize the CFE in agricultural production activities, information and intelligent technologies are important. The use of fundamental technologies in the application of agricultural CFE is rare. The Internet of Things (IoT), Artificial Intelligence (AI), and intelligent control technologies have been incorporated to study the CFE. Technologies related to optimal models for controlling CO_2 concentrations in greenhouses, intelligent equipment for CO_2 enrichment, and IoT systems for growth

Science Publications

environment data collection of crops have been continuously developed and updated (Shubham *et al.*, 2017). Numerous researchers are exploring ways and methods in the field of increasing agricultural carbon dioxide application (Rodríguez-Mosqueda *et al.*, 2018).

To solve the limitation of CO_2 enrichment in agriculture, this study aims to demonstrate the role of CO_2 enrichment in agriculture and provide a feasible research direction to investigate the importance of CO_2 enrichment. There are five sections to show our research results, beginning with the introduction of the first section. In the second section, the existing technologies for CO_2 enrichment in agriculture are discussed. In the third section, the status of CO_2 enrichment application is described from three aspects. Finally, a research route and the overall technical framework were proposed for CO_2 fertilization applications in agriculture and the fifth section is the conclusion of this research.

Overview of CO_2 Enrichment in Agriculture

CO_2 Enrichment Technology

As a primary substrate of photosynthesis, CO_2 plays an important role in the secondary reactions of photosynthesis (light-independentstage). The products derived from light reactions form Carbon-Carbon (C-C) covalent bonds in carbohydrates from CO_2 through the Calvin cycle. Higher CO_2 concentrations have significant potential to promote the photosynthetic rate and primary productivity of crops, which is known as CFE; this can decrease the environmental risks from the ambient air (Wang *et al.*, 2020). Since the last century, the CFE has obtained significant attention. To meet the research needs of the CFE on crops at different agricultural scales, CO_2 enrichment technology has been developed.

Currently, no formal definition exists for CO_2 enrichment technology. As its name implies, it is a technique to increase CO_2 concentrations in the crop growth environment, which integrates environmental perception, intelligent decision-making, and effect evaluation. It can be helpful to realize the application of the CFE in agriculture and promote crop yield and quality.

Main Principles of CO_2 Enrichment Technology

The objectives of CO_2 enrichment are to produce CO_2 gas using different methods and increase the concentration of the crop growth environment under specific conditions. In this study, commonly used CO_2 enrichment methods in agriculture were classified based on the different generation principles of CO_2. Further, the advantages and disadvantages of various methods were summarized to guide in selecting an appropriate CO_2 enrichment technology.

The characteristics of different CO_2 enrichment methods with their benefits and drawbacks are listed in Table 1.

Typical CO_2 Enrichment System

Global climate change has long-term effects on agricultural ecosystems and remained a fundamental issue worldwide. Several researchers have studied crop adaptability under elevated CO_2 concentrations and global climate change(Dusenge *et al.*, 2019). To determine the response of CFE to elevated CO_2 concentrations and the greenhouse effect, some typical CO_2 enrichment systems have been widely used in agriculture. These enrichment systems are suitable for different agricultural environments and updated with the development of technology.

For a facility agricultural environment, the CO_2 concentration is usually lower than that of the atmosphere, which leads to a serious shortage of CO_2. To address this issue, IoT is employed to control the supply of CO_2 within a reasonable range. In this application, the CO_2 enrichment equipment is connected to various sensors by embedding a control module in the networks. Figure 1 shows a schematic illustration of the CO_2 enrichment system.

In addition, the Open-Top Chamber (OTC) and Free-Air CO_2 Enrichment (FACE) systems can be used to increase the CO_2 concentration in farmland environments for simulating the real conditions of a crop-growing environment under future climate change in farmland. These systems can be used to study the effects of higher CO_2 concentrations on the yield and quality of crops; this will assist the studies investigating the measures for crops to deal with climate change and the greenhouse effect.

OTCs are comprised of a plastic enclosure with inclined walls and an open top, which is used to grow crops. It is a gas chamber having a volume of approximately 10-20 m^3 (Karbin *et al.*, 2015). Generally, OTCs do not control environmental factors, such as temperature, humidity, and light. These require a high-power blower to blow high-concentration CO_2 into the box and after flowing through the crop colony, CO_2 is discharged into the atmosphere from the open top. A typical OTC is shown in Fig. 2, which was developed by George and Walter in 1992 (Mauri, 2010). It is composed of a lower plenum system, main chamber, frustum, and other appendages. With the development of technology and changing requirements of experiments, this system has been updated in terms of shape, size, materials, structures, and functions. Recently, a few changes were proposed to modify this system based on experimental results of crops.

FACE is an open CO_2 control system that eliminates the constraints of small laboratory space, therefore it can carry out simulation experiments in the ecological environment of farmland. FACE consists of a series of vertical vent pipes placed circularly around the plot, which release CO_2 toward the center of the ring (Tang *et al.*, 2010). Generally, the scale of this system is large and the environmental conditions, such as light, temperature, humidity, and wind, in the system, are similar to those of farmland. The CO_2 concentration, wind direction, and wind speed in FACE can be adjusted through CO_2 storage, ventilation, control, data acquisition, and processing systems. Some prominent FACE experiment system cases are Fig. 3 and 4.

According to the characteristics of these systems, several factors limit their development such as the cost, source of CO_2, and availability, which lead to low promotion values of these systems. Therefore, it is necessary to develop a CO_2 enrichment technology that should be convenient, intelligent, and widely accepted using agricultural information technology.

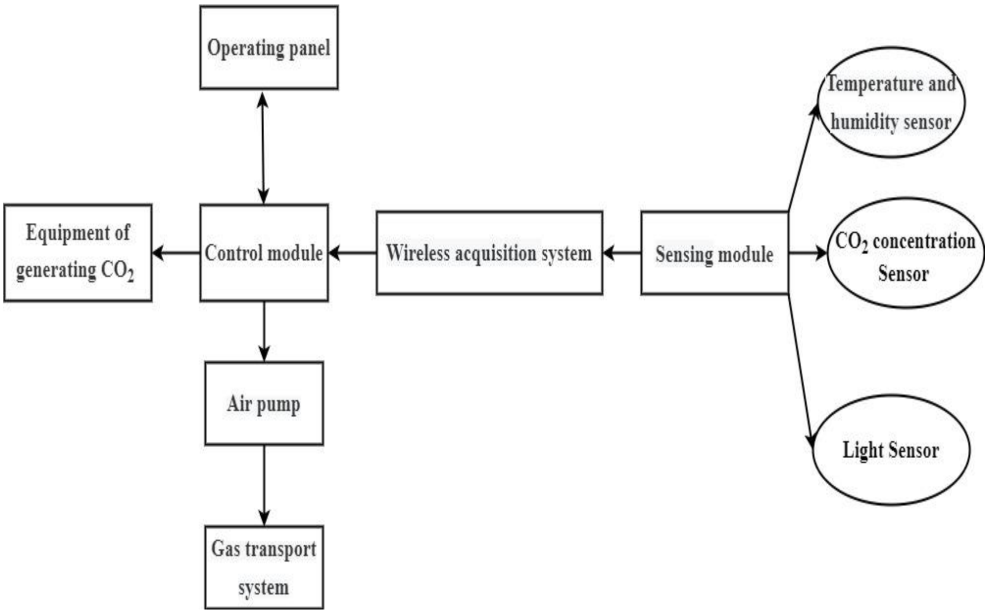

Fig. 1: Schematic illustration of CO_2 enrichment system in a greenhouse

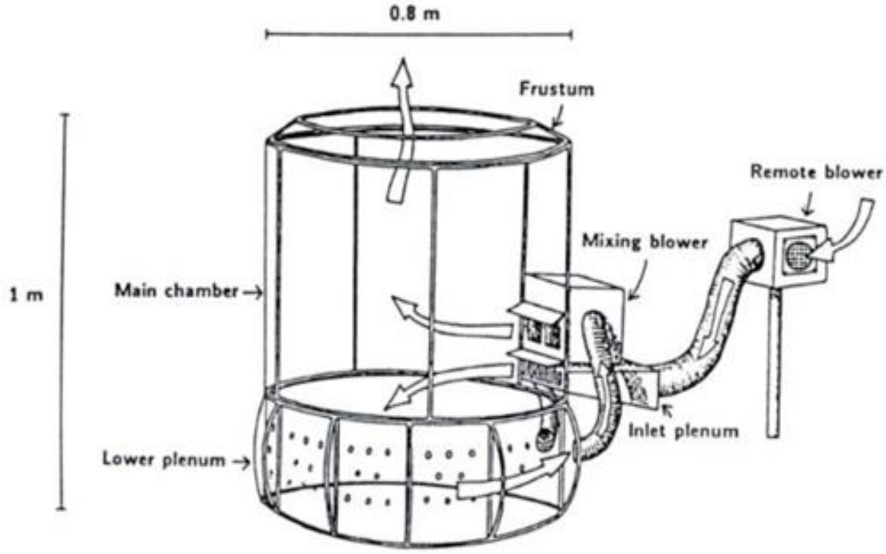

Fig. 2: Open top field chamber design (Mauri, 2010)

Fig. 3: Soy FACE (Feng *et al*., 2017)

Fig. 4: Vegetable FACE experiment produced by FACE (Jager *et al*., 2003)

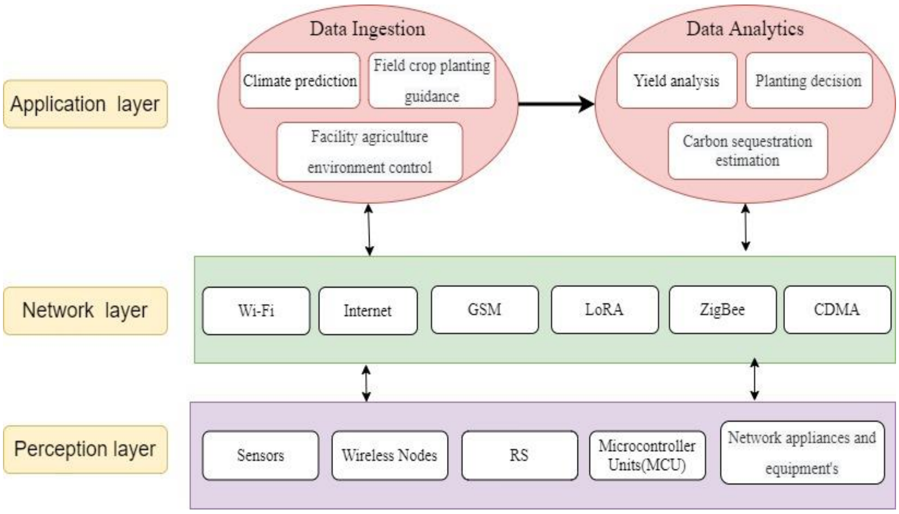

Fig. 5: Technical architecture of research on the application of CO_2 enrichment

Table 1: Comparison of main principles of CO_2 enrichment technology

Name	Principles	Advantages	Disadvantages	Case studies
Chemical reaction method	CO_2 is produced by the reaction of carbonate and acid chemicals, such as the the reaction of NH_4HCO_3 with H_2SO_4 in a special container enrichment (Wei, 2000).	a. Rapid reaction b. Easy operation c. Good controllability	a. Produces toxic gases b. Higher cost	Wei Min used this method of a solar greenhouse to study the effects and a mechanism of CO_2
Combustion method	Hydrocarbon fuels, such as hard coke, natural gas and briquette, produce CO_2 through combustion that can also generate heat for greenhouse in winter.	a. Provides heating in greenhouse b. Low cost	a. Produces toxic gases b. Low gas production	Takeya *et al*. (2017) created equipment to consume CO_2 produced from a heating boiler in greenhouse (Takeya *et al*., (2017)
Solid granular CO_2 fertilizer	This fertilizer is buried in the soil, where CO_2 is released slowly after a certain period.	a. Good physical properties b. Stable chemical properties c. Long fertilizing effect period	a. Low gas production b. Soil pollution	Wei (2000) studied the effect of CO_2 fertilizer on vegetables planted in a greenhouse
Liquid CO_2 release a method in a cylinder	The liquid CO_2 is stored in an can be released by decrease the pressure of the cylinder cylinder. To control the release of CO_2, the cylinders can be connected to intelligent control devices. The emitted CO_2 has the highest purity among the aforementioned methods	a. Safe and convenient b. High purity studied its effect under an elevated	a. Expensive b. Difficult to replace this method for soybean and	Provided CO_2 through CO_2 (Jin *et al*., 2017)

Table 2: Comparison of carbon sink calculation models in farmland ecosystem

Name	Data source	Characteristic
DNDC	different environmental factors; crop growth factors; soil water movement in farmland; greenhouse gas emissions	the most widely used organic carbon model; the time step is day
CENTURY	mean monthly maximum and minimum temperatures; monthly total precipitation; C, N, P, and S contents in plants; soil texture change;	including inert carbon pool, chronic carbon pool and activated carbon pool; Simulation time scales can be measured in years or even thousands of years
Rothc	different environmental factors; meteorological data; soil texture change;	the structure is simple and the required parameters are easy to obtain
Agro-C	meteorological data; crop and soil monitoring data; Field management data	Crop-C and Soil-C submodels are included; static model
SMPT-SB	Plant ecophysiological parameters; Light, temperature, and other environmental data	model based on stomatal behavior;

Current Status of CO_2 Enrichment in Agriculture

Agro-Ecosystem Carbon Sequestration Potential Under Higher CO_2 Concentrations

Higher CO_2 concentrations promote plant photosynthesis and enhance crop productivity owing to the CFE. Estimating the amount of carbon sequestration in crops under higher CO_2 concentrations helps evaluate the role of crops in mitigating greenhouse gases. Investigating long-term CO_2 concentration measurements is the main method employed in the relevant research. The FACE and OTCs experiments can provide a CO_2 enrichment environment and the covariation of CO_2 with other environmental drivers of crop productivity through field experiments. At present, the research for the carbon sequestration potential of agroecosystems under greenhouse conditions is based on soil organic carbon and crop carbon storage estimations. Carbon sequestration can be estimated using three methods: Statistical methods of measured data, regression model method of environmental factors (such as temperature and rainfall), and remote sensing data (Li *et al.*, 2019). The mainly representative models for estimating the carbon sequestration potential of vegetation in farmland ecosystems are Table 2.

In terms of crop carbon storage estimation, Feng *et al*. (2017) conducted a long-term field management experiment on corn to quantify the potential for CO_2 fixation in the above-ground biomass. A study of regional disparities in the CFE uses experimentally determined and grid-level data on climate, crop areas, and yields to estimate the implication of increased CO_2 concentration. Used corresponding models and GIS spatial analysis methods to assess the carbon stock, density, and sequestration potential of crops in the Upper Yangtze River Basin based on the statistical data of crop yield in 1995, 2000, 2004, and monthly average meteorological data.

Research on soil carbon storage in farmland mainly focused on the behavior of organic carbon in the soil. Recently, several new aspects related to the properties, functions, and changes of soil organic carbon in global change have been investigated. Long-term field experiments and observations are increasingly becoming the main approaches to studying the soil carbon cycle and global change in farmland. The FACE, soil, and air warming experiments have attracted significant attention. Dietzen *et al*. (2019) used the FACE experiment to increase atmospheric CO_2 concentrations in the CO_2 treatment plots to 510 ppm from dawn until dusk and switched off overnight and during periods of complete snow cover. The results showed that the accumulation of soil carbon under increased CO_2 concentration was unaffected by warming and drought.

The CFE can increase the GPP of crops by directly accelerating photosynthesis, which improves the carbon sequestration of crops and soil. The carbon sequestration potential of agroecosystems has been widely studied by several researchers worldwide with the concept of low-carbon agriculture and zero "carbon footprint." The development of CO_2 enrichment technology can promote the absorption of CO_2 by agroecosystems and reduce carbon emissions.

Effects of CO_2 Enrichment on Crops

It is well-known that CO_2 is the substrate for photosynthesis and its concentration affects plant growth. Several studies have demonstrated the beneficial effects of CO_2 on photosynthetic rate, plant growth, and crop yield. Moreover, increased CO_2 concentrations can improve the nutritional quality of crops. Recently, various CO_2 enrichment systems and devices have been employed to increase CO_2 concentrations under appropriate environments. These studies focused on the CO_2 enrichment in agriculture and methods to improve crop adaptability to future climate change.

In facility agriculture, crop growth can be enhanced by controlling environmental factors, such as gas, light, and temperature. Several studies have reported that the concentration of CO_2 is one of the primary factors affecting the quality of greenhouse plants when the value is lower. It has been reported that the optimal concentration of CO_2 for plant growth ranges between 800-1000 ppm. Therefore, it is important to increase the CO_2 concentration in the greenhouse, which is less than 250 ppm during the daytime due to hermetic conditions. Recently, numerous studies have focused on the effects of CO_2 enrichment on crop yield and the quality of the main health-promoting compounds and organoleptic characteristics. Observed that tomatoes planted in greenhouses had enhanced contents of health-promoting compounds and organoleptic characteristics due to CO_2 enrichment (Zhang *et al.*, 2014). Plant growth can be promoted by regulating the CO_2 concentration at the facility to an optimal value. Jin *et al.* (2017) have shown that the yields of celery (*Apiumgraveolens L.*), leaf lettuce (*Lactucavirosa L.*), stem lettuce (*Lactucasaiva L.*), oily sow thistle (*Sonchusoleraceus L.*) and Chinese cabbage (*Brassica Chinensis L.*) were improved under crop-residues and animal-manure composting application environment, which produced higher amount of CO_2. The nutritional quality of vegetables was also improved by CO_2enrichment experiments. However, Khan *et al*. (2013) found that different varieties of tomatoes have different responses in nutritional composition to high CO_2 environments. Because the methods of CO_2 enrichment for these studies were conventional and inefficient, few reports considered the impacts of different CO_2 enrichment methods and indicated ways of effective management measures for different crops. Previous studies have also shown that the precision of environmental factors and the control model significantly influence the effects of CO_2 enrichment (Chai *et al.*, 2011).

A free open-field environment has more complex and uncontrollable environmental factors. The FACE and OTC systems are the commonly used research platforms to simulate and verify the impact of increased atmospheric gas concentration on ecosystems. Through long-term field experiments in FACE systems, crops such as rice, wheat, and soybean have shown that CFE enhanced the yields and changed nutritional quality in some areas under higher CO_2 concentrations (Jin *et al.*, 2017). The results of these studies showed the response of crops under increased CO_2 environments only because the research on the adaptation of crops cannot be controlled by these systems. Verified that kinetin significantly improved the CFE of rice named Takanari by foliar spray, owing to the increased sink size resulting from a higher panicle density(Zhang *et al.*, 2021). This provides a new idea for investigating the adaptation of crops to global climate change.

Development of CO_2 Enrichment Technology in Agriculture

The positive effects of CO_2 enrichment on crops were demonstrated, but related technologies and models developed gradually. The technology used in this area still has the disadvantages of high cost, inconvenience, and low utilization. For instance, manual data acquisition is still adopted in experimental studies (Yun *et al.*, 2018). The development of a CO_2 enrichment system is mainly focused on facility agriculture. Through an extensive review of the existing literature, it is observed that the development of the FACE system has entered a bottleneck, while some large-scale FACE systems are stopped worldwide. With the advancement in industrial control technology and simplification of infrastructure construction, the future FACE system should pay attention to integration and mobility and realize the goal of single construction and multiple utilization. Meanwhile, the control of the gas concentration remains the bottleneck of the current FACE system. Various gas release methods should be explored and the meteorological factors in the program control should be combined to achieve stable conditions. This could be a potential solution to avoid uneven gas release to the plant canopy and simulate the gas concentration under future conditions more accurately.

In the present era of information technology, the development of agricultural information databases has attracted significant attention. Environmental factor monitoring and acquisition are the important parts of the CO_2 enrichment system, while the agricultural IoT has played an important role in environmental information monitoring and data collection. Recently, several CO_2 enrichment systems have been assisted by IoT technology as an automatic data acquisition system. Liao proposed an AGCP protocol, which was combined with the IoT framework to monitor environmental information and the regulation of corresponding equipment in greenhouses.

Based on these information technologies, numerous CO_2 concentration control models have been developed, which can suggest the increase in CO_2 according to crop growth. Recently, several researchers have proposed optimization models based on artificial neural networks and machine learning algorithms. The CO_2 optimal control model based on the discrete curvature algorithm improved photosynthetic rate prediction model based on BPNN and PSO-SVM model at all growth stages of tomato for photosynthesis prediction is the related optimization control model appropriate for greenhouse environments. However, the generalization ability of these models needs to be improved for different crops.

Accordingly, the development of information technology can help promote the application of CO_2 enrichment technology in agriculture. The development of intelligent CO_2 enhancement systems employed for open cropland environments should be accelerated to meet the adaptation of cropland crops to higher CO_2 concentrations. Applying advanced agricultural information technology to the field of CO_2 enrichment in agriculture can promote the rapid application of the carbon dioxide fertilization effect and provide technical support for research on the potential of crops to reduce the greenhouse effect and mover building an environmentally friendly ecosystem.

Prospect Research Direction on CO_2 Enrichment Application in Agriculture

By summarizing the aforementioned development status, the application of CO_2 enrichment technology mainly focuses on the estimation of crop carbon sequestration and increasing crop yield and quality in facility agriculture. The results of these two aspects depend on the accuracy of the data acquisition and estimation model. Information technology can play a significant role in assisting the development of CO_2 enrichment. Research on the application of CO_2 enrichment for crops on small area scales or facility agriculture uses advanced information technology. Figure 5 illustrates the technical architecture of the research route.

The technical architecture consists of three layers, where the bottom, middle, and top layers represent perception, network, and application layers, respectively. The perception layer consists of sensors, gateways, routers, switches, and hubs. The main role of the perception layer is to determine how efficiently the sensing devices and other equipment can work together to collect data. The network layer serves as a bridge and comprises network and communication technologies.

The application layer is responsible for the processing and analysis of data.

Data Collection

To obtain accurate and real-time environmental data, agricultural information technology should be used, which provides information management and services for agricultural pre-production, production and post-production links and promote the process of smart agriculture. In particular, agricultural production and environment information monitoring tasks employ IoT technology. During the growth of crops, information on the leaf scale should be obtained using portable equipment and a small integrated micro weather station, which is time-consuming and laborious (Dusenge *et al.*, 2019). These data can be divided into environmental factors, crop growth data, and field management data for modeling and estimation as model parameters.

Model Building

The models should be built in the application of CO_2 enrichment in agriculture, including a control model of CO_2 concentration, crop growth model, and yield prediction model.

CO_2 has a high resource cost and should be applied efficiently. Therefore, the concentration of CO_2 should be within a reasonable range. The rate of photosynthesis has an optimal value when the CO_2 concentration changes; therefore, an intelligent optimization control model can be built to predict the appropriate CO_2 concentration under the best photosynthesis rate for crops. The growth model of crops can quantitatively describe the relationships among facilities, crops, environment, and management technical measures. It is important to control the facility environment and crop management optimization method. Crop growth models based on photosynthetic characteristics under increased CO_2 concentrations can accurately predict crop dry matter accumulation, which will help to estimate the amount of carbon sequestration for crops.

The yield of crops will increase under increased CO_2 owing to the enhanced photosynthetic rate. It is important to establish a yield prediction model using artificial intelligence and computer technologies to evaluate the impact of increased CO_2 application on crops.

Carbon Sequestration Potential Assessment

The purpose of the research on the application of CO_2 enrichment technology is to analyze the effect of crops on increased CO_2. Crops can absorb more CO_2 to increase the amount of carbon sequestration in the CO_2 enrichment environment, resulting in a reduction of CO_2 in the atmosphere. Agriculture is an important source of greenhouse gas emissions, which emits 5.1-6.1 Gt CO_2 eq/year, accounting for 10-12% of the total anthropogenic emissions of greenhouse gases. Plants can convert CO_2 from the atmosphere into organic matter via photosynthesis and transform it into the soil through the interaction between soil microorganisms and roots.

Therefore, CO_2 enrichment during crop growth can increase carbon sequestration. To evaluate the CFE on crops using CO_2 enrichment technology, the potential of carbon sequestration of crops can be estimated as follows:

$$C_{NEP} = C_{NPP} - C_{Rm} \tag{1}$$

$$\begin{cases} C_{NEP} >, crop\, is\, absorption \sin k\ \ for\, CO_2 \\ \\ \quad C_{NEP} >, crop\, is\, emission\, k\ \ for\, CO_2 \end{cases} \tag{2}$$

where, C_{NEP}, $C_{NPP,}$ and C$_R$M are the net ecosystem productivity carbon storage, primary productivity carbon storage, and carbon release from soil microbial heterotrophic respiration, respectively. These factors are obtained using biomass methods or models and depend on the scales of the research object.

To minimize the impact of global warming on agriculture, we should increase the assimilation of vegetation on CO_2 first by improving the photosynthesis of plants and then promoting the transformation of carbon into crops and soil, which is an effective way to increase carbon sink. Second, the increase in organic fertilizer and change in field management measures also contribute to the carbon sequestration of farmland ecosystems, such as no-tillage, changing water and fertilizer conditions, improving fertilization methods, and retaining residue in the field.

The aforementioned three aspects, demonstrate the significance of the application of CO_2 enrichment technology and provide a preliminary understanding of the research route for CO_2 enrichment. This will help promote the development of research on the role of crops in mitigating global climate change.

Conclusion

According to the results above, the utilization of CO_2 by crops can reduce the atmospheric CO_2, which is the major source of the greenhouse effect. Both crops and soil in agro-ecosystems have a strong ability to absorb and transform CO_2, which is important for reducing the increased level of CO_2 in the atmosphere. The CO_2 fertilization enhances crop photosynthesis and transforms atmospheric CO_2 into the ecosystem. The CO_2 enrichment can realize the positive effects of CFE on crops.

Various CO_2 enrichment methods with different characteristics have been practiced in the past years. For the selection of appropriate methods, the application area and cost should be considered. In addition, with the help of information technology, some CO_2 enrichment methods will be widely used in future crop planting. Based on intelligent information technologies, research on the CFE has not only received rapid progress in facility agriculture but also highlighted the importance of crops in mitigating climate change.

In the future, the potential of carbon sequestration in farmland crops will be estimated using information technology. Several CO_2 enrichment methods provide solutions for future research on the environmental adaptability of farmland crops.

Acknowledgment

We would like to express our gratitude to all those who helped me during the writing of this study.

Author’s Contributions

Bingbing Wang: Methodology. Writing-original draft preparation. Visualization.

Xiangjie Lu, Yun Xia and Bangjie Yang: Validation.

Wanlin Gao: Project administration, Funding acquisition.

Ethics

The authors declare their responsibility for any ethical issues that may arise after the publication of this manuscript.

References

Chai, R. S., Niu, Y. F., Zhu, L. Q., Wang, H., & Zhang, Y. S. (2011). Effects of elevated CO_2 concentration on the quality of agricultural products: A review. Ying Yong Sheng Tai Xue bao = The journal of applied ecology, 22(10), 2765-2775. https://europepmc.org/article/med/22263486

Dietzen, C. A., Larsen, K. S., Ambus, P. L., Michelsen, A., & Arndal, M. F. (2019). Accumulation of soil carbon under elevated CO_2 unaffected by warming and drought. Global Change Biol, 25, 2970-2977. doi.org/10.1111/gcb.14699

Dokić, D., Gavran, M., Gregić, M., &Gantner, V. (2020). The impact of the trade balance of agri-food products on the state's ability to withstand the crisis. HighTech and Innovation Journal, 1(3), 107-111. doi.org/1093/cje/bep023

Dusenge, M. E., Duarte, A. G., & Way, D. A. (2019). Plant carbon metabolism and climate change: Elevated CO_2 and temperature impact photosynthesis, photorespiration, and respiration. New Phytologist, 221(1), 32-49. doi.org/10.1111/nph.15283

Feng, Q., Xu, J., Zhang, Y., Li, X., Xu, J., Han, H., ... & Li, Z. (2017). CO_2 fixation in above-ground biomass of summer maize under different tillage and straw management treatments. Scientific reports, 7(1), 1-8. doi.org/10.1038/s41598-017-17247-8

Hao, P. F., Qiu, C. W., Ding, G., Vincze, E., Zhang, G., Zhang, Y., & Wu, F. (2020). Agriculture organic wastes fermentation CO_2 enrichment in a greenhouse and the fermentation residues improve growth, yield, and fruit quality in tomatoes. Journal of Cleaner Production, 275, 123885. doi.org/10.1016/j.jclepro.2020.123885

Isah, S., Gbanguba, A. U., Abdullah, Y., Bubuche, T. S., & Mohammed, T. (2020). Effects of Variety and Nitrogen Levels on the Performance of Pearl Millet: PennisetumGlaucum (L.) R. BR. Journal of Human, Earth, and Future, 1(4), 188-196. doi.org/10.28991/HEF-2020-01-04-04

Jager, H. J., Schmidt, S. W., Kammann, C., Grunhage, L., Muller, C., &Hanewald, K. (2003). The University of Giessen free-air carbon dioxide enrichment study: Description of the experimental site and a new enrichment system. Journal of Applied Botany, 77(5/6), 117-127.

Jansson, C., Faiola, C., Wingler, A., Zhu, X. G., Kravchenko, A., de Graaff, M. A., ... & Beckles, D. M. (2021). Crops for Carbon Farming. Frontiers in Plant Science, 12, 938. doi.org/10.3389/fpls.2021.636709

Jin, J., Li, Y., Liu, X., Wang, G., Tang, C., Yu, Z., ... & Herbert, S. J. (2017). Elevated CO_2 alters the distribution of nodal leaf area and enhances nitrogen uptake contributing to the yield increase of soybean cultivars grown in Mollisols. PLoS One, 12(5), e0176688. doi.org/10.1371/journal.pone.0176688

Karbin, S., Guillet, C., Kammann, C. I., & Niklaus, P. A. (2015). Effects of long-term CO_2 enrichment on soil-atmosphere CH_4 fluxes and the spatial micro-distribution of methanotrophic bacteria. PloS one, 10(7), e0131665. doi.org/10.1371/journal.pone.0131665

Khan, I., Azam, A., & Mahmood, A. (2013) The impact of enhanced atmospheric carbon dioxide on yield, proximate composition, elemental concentration, fatty acid and vitamin C contents of tomato (Lycopersiconesculentum). Environment Assess, 185, 205-214. doi.org/ 10.1007/s10661-012-2544-x

Li, T., Zhang, F., Jiao, Y., Zhang, M., Chang, Y., & Matomela, N. (2019). Study on Carbon Sequestration Capacity of Typical Crops in Northern China. Journal of Plant Biology, 62(3), 195-202. doi.org/10.1007/s12374-018-0401-3

Mauri, A. (2010). Field experiments using CO_2 enrichment: A comparison of two main methods. iForest-Biogeosciences and Forestry, 3(4), 109. doi.org/10.3832/ifor0545-003

Mi, Z., Guan, D., Liu, Z., Liu, J., Viguié, V., Fromer, N., & Wang, Y. (2019). Cities: The core of climate change mitigation. Journal of Cleaner Production, 207, 582-589. doi.org/10.1016/j.jclepro.2018.10.034

Rodríguez-Mosqueda, R., Bramer, E. A., & Brem, G. (2018). CO_2 capture from ambient air using hydrated Na_2CO_3 supported on activated carbon honeycombs with application to CO_2 enrichment in greenhouses. Chemical engineering science, 189, 114-122. doi.org/10.1016/j.ces.2018.05.043

Shubham, L., Phogat, V. K., & Neeraj, K. (2017). Sustainable agriculture for sustaining mankind-a review of international literature. Vegetos, 30 (Special Issue 2), 477-481. https://www.cabdirect.org/cabdirect/welcome/?target=%2fcabdirect%2fabstract%2f20183382187

Takeya, S., Muromachi, S., Maekawa, T., Yamamoto, Y., & Mimachi, H. (2017). Design of Ecological CO_2 Enrichment System for Greenhouse Production using TBAB+CO_2 Semi-Clathrate Hydrate. Energies 2017, 10, 927. doi.org/10.3390/en10070927

Tang, H. Y., Liu, G., Han, Y., Zhu, J. G., & Kobayashi, K. (2010). Ozone concentration enrichment system under a fully free-air condition in an agricultural field (O3-FACE). Soils, 42(5), 833-841. doi.org/10.13758/j.cnki.tr.2010.05.002

Tang, H., Liu, Y., Li, X., Muhammad, A., & Huang, G. (2019). Carbon sequestration of cropland and paddy soils in China: Potential, driving factors, and mechanisms. Greenhouse Gases: Science and Technology, 9(5), 872-885. doi.org/10.1002/ghg.1901

Wang, S., Zhang, Y., Ju, W., Chen, J. M., Ciais, P., Cescatti, A., & Peñuelas, J. (2020). The recent global decline of CO_2 fertilization affects vegetation photosynthesis. Science, 370(6522), 1295-1300. doi.org/10.1126/science.abb7772

Wei, M. (2000) Effects and Mechanism of CO_2 Enrichment on Vegetables as Well as Regulation Techniques of CO_2 Environment in Solar Greenhouse. Ph.D. dissertation; Nanjing Agricultural University: Weigang, Nanjing.

Yun, D. L., Kim, H. J., & Kim, Y. J. (2018). CO_2 enrichment increased leaf initiation and photosynthesis in Doritaenopsis Queen Beer 'Mantefon'orchids. Horticulture, Environment, and Biotechnology, 59(2), 159-165. doi.org/10.1007/s13580-018-0025-z

Zhang, G., Sakai, H., Yoshimoto, M., Wakatsuki, H., Tokida, T., Ikawa, H., ... & Hasegawa, T. (2021). Effect of foliar spray of kinetin on the enhancement of rice yield by elevated CO_2. Journal of Agronomy and Crop Science, 207(3), 535-543. doi.org/10.1111/jac.12457

Zhang, Z., Liu, L., Zhang, M., Zhang, Y., & Wang, Q. (2014). Effect of carbon dioxide enrichment on health-promoting compounds and organoleptic properties of tomato fruits grown in a greenhouse. Food Chemistry, 153, 157-163. doi.org/10.1016/j.foodchem.2013.12.052