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journal homepage: www.elsevier.com/locate/issn/15375110

Review

Automatic carbon dioxide enrichment strategies in the greenhouse: A review

Yongwei Li [a,b,c,d], Ying Ding [a,b,c,d], Daoliang Li [a,b,c,d,*], Zheng Miao [a,b,c,d]

[a] College of Information and Electrical Engineering, China Agricultural University, Beijing, 100083, China
[b] China-EU Centre for Information and Communication Technologies in Agriculture, China Agricultural University, Beijing 100083, PR China
[c] Key Laboratory of Agricultural Information Acquisition Technology, Ministry of Agriculture, China Agricultural University, Beijing 100083, China
[d] Beijing Engineering and Technology Research Centre for Internet of Things in Agriculture, China Agricultural University, Beijing 100083, China

ARTICLE INFO

Article history:
Received 11 September 2017
Received in revised form
27 March 2018
Accepted 23 April 2018

Keywords:
Carbon dioxide
Greenhouse
Source of carbon dioxide
Data processing
Control method

Greenhouses constitute a proven solution for coping with environmental degradation and for increasing both the quantity and quality of agricultural products. Appropriate carbon dioxide (CO_2) control not only improves crop yield and quality but also reduces the carbon footprint of greenhouses. However, CO_2 enrichment control in greenhouses is a dynamic, interactive and time-delayed process. In practice, optimal CO_2 concentrations in the greenhouse are difficult to maintain because CO_2 is confounded with temperature, humidity, light intensity, etc.; therefore, ambient CO_2 concentrations in greenhouses are often suboptimal or excessive. This paper is a review of the current theoretical and applied studies of CO_2 enrichment in greenhouses and discusses the advantages and limitations of various methods. The major points addressed are as follows: 1) the five sources of CO_2 enrichment in greenhouses; 2) the monitoring and data processing of CO_2 concentrations; and 3) the various methods for controlling automatic CO_2 enrichment. This paper discusses new challenges and perspectives and suggests future studies and methods for a greenhouse CO_2 enrichment system. A new symbiotic greenhouse system requiring sensible CO_2 balance is also presented.

1. Introduction

Economic and social development has increased the requirements for abundant, high-quality agricultural products. Greenhouses are structures that allow growers to control climatic factors, nutrition, biotic factors and other variables that affect crop growth and development; thus, optimal conditions can be imposed during different crop growth stages (Pasgianos, Arvanitis, Polycarpou, Sigrimis, 2003). Moreover, greenhouses allow the production of high-quality products at low cost. Greenhouses have become increasingly important in

* *Corresponding author*. College of Information and Electrical Engineering, China Agricultural University, Beijing, 100083, China.
E-mail addresses: yongweili@foxmail.com (Y. Li), dingying94@163.com (Y. Ding), dliangl@cau.edu.cn (D. Li), zhengmiao_cau@163.com (Z. Miao).
https://doi.org/10.1016/j.biosystemseng.2018.04.018

Nomenclature

ANNs	artificial neural networks
FNN	fuzzy neural network
GAs	genetic algorithms
MIV	mean impact value
MPC	model predictive control
NB-IoT	narrow band internet of things
PCA	principal component analysis
PID	proportional-integral-derivative
PSO	particle swarm optimization
RBF	radical basis function
SVM	support vector machine
WSNs	wireless sensor networks

agriculture, and many researchers are dedicated to greenhouse climate control. Greenhouse variables that are generally controlled include CO_2 concentration, temperature, humidity, etc. CO_2 is an important variable, and the positive effects of CO_2 on plant growth were discovered 200 years ago (Panwar, Kaushik, Kothari, 2011). In addition, CO_2 enrichment is ubiquitous in modern greenhouses. CO_2 enrichment improves the rate of photosynthetic assimilation (Thongbai, Kozai, Ohyama, 2010; Xu, Zhu, Li, & Ye, 2014) and as a consequence improves energy and water use efficiency (Deryng et al., 2016; Frantz, 2011; Sánchez-Guerrero, Lorenzo, Medrano, Baille, Castilla, 2009), nutrient uptake rates (Li, Zhou, Duan, Du, Wang, 2007), and product nutritional value, as well as many other production factors (Mohamed, Jellings, Fuller, 2013; Weiss, Mizrahi, & Raveh, 2010; Zhang, Liu, Zhang, Zhang, & Wang, 2014). Plants take up CO_2 when illuminated and evolve CO_2 in the dark, so fluctuations of CO_2 concentrations in greenhouses are governed by the photoperiod (Liu, Hoogenboom, Ingram, 2000). In general, the optimum CO_2 concentration for plant growth is approximately 1000 ppm (Chen, 2010; Jin et al., 2009); however, the CO_2 concentration in the air is approximately 350 ppm and is probably lower than 150 ppm in greenhouses during the daytime, which is far from sufficient for optimal crop growth. Additionally, excess CO_2 concentrations can reduce plant growth, cause leaf injury, and increase the loss of CO_2 via leakage (Panwar et al., 2011). Weather also has a significant influence on CO_2 enrichment (Kuroyanagi, Yasuba, Higashide, Iwasaki, Takaichi, 2014). In sunny chilly weather, the supply of CO_2 at a relatively high concentration is appropriate. However, CO_2 enrichment could be economically prohibitive because of the lower photosynthetically active radiation on cloudy days or because of the loss due to ventilation for cooling in hot weather. Most locations, even in winter time, do need ventilation and challenge is that CO_2 supply is justified when enough solar radiation is reaching the GH, when ventilation is also required. Therefore, CO_2 supply may only be justified in a few instances, or only few morning hours in summer, and mostly in well-equipped greenhouses with shades internal and external. So the optimal CO_2 concentration for greenhouse production depends on many factors, such as local economic conditions, external weather, and ventilation rates. In some symbiotic greenhouses, such as aquaponic systems, the CO_2 concentration affects the environmental and economic efficiency of the entire system (Yogev, Barnes, Gross, 2016). From global energy-saving and emission-reduction perspectives, it is important to control CO_2 enrichment within greenhouses appropriately.

Economic benefit is one of the most important metrics for evaluating greenhouse business aspects (Rodriguez, Berenguel, Arahal, 2003; van Straten, van Henten, van Willigenburg, van Ooteghem, 2010). An important cost of CO_2 enrichment is the source of CO_2; thus, choosing an appropriate CO_2 source is essential. The existing literature about greenhouse enrichment has primarily focused on five sources of CO_2 for enrichment: compost, exhaust gas from fossil fuels, exhaust gas from renewable energy, natural or forced ventilation and pure liquefied CO_2. The choice of the appropriate method for generating CO_2 and supply control in practice will boost efficiency and profits.

Accurate CO_2 concentration data are critical for controller design and actuator control. In conventional greenhouses, actuators are operated by growers, depending on experience (Rodríguez, Berenguel, Guzmán, Ramírez-Arias, 2015). Although an experienced grower can manage a greenhouse well, the profits are not always optimal. The development of sensor technology has allowed the objective monitoring of greenhouse parameters. However, accurate measurements of CO_2 concentrations are difficult because CO_2 is not homogenous in the greenhouse. Wireless sensor networks have been widely applied in modern greenhouses for monitoring greenhouse climate parameters, and more accurate measurement results have been achieved.

The greenhouse process contains both fast and slow dynamics. The greenhouse reacts rapidly to changes in the environmental conditions. But crop development responds slowly to the changes of greenhouse environmental conditions (i.e. CO_2 concentrations and temperature) and the photosynthesis responds relatively quickly to changes in ambient conditions. In addition, CO_2 level has a long time constant when increasing and much longer when supply is shut off (waiting for photosynthesis to deplete the extra CO_2 in the air). In the morning, the question is whether it is worth starting the supply process and more importantly when to cut-off the supply at an early stage to avoid exhausting CO_2 by ventilation, which could make the process economically and environmentally negative. Therefore, accurate weather prediction is important to control CO_2 concentrations within greenhouses precisely. Many control strategies for automatic CO_2 enrichment are based on growers' empirical rules (Rodríguez et al., 2015). The use of computers in greenhouses allows growers to control environment variables and to modify the control parameters automatically. However, several important problems related to the control of CO_2 enrichment exist. First, set-point tracking is affected by control loops and actuators of other parameters (Titus & Wendlberger, 2016). Second, it is difficult to determine scientifically the optimum set-point value because of interactions with other associated parameters, which can affect crop growth (Pasgianos et al., 2003). Third, the control performance is difficult to evaluate because of the uncertainty inherent in biological systems. Additionally, modern greenhouses allow a particularly high degree of freedom and order. These factors