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Effectiveness of gaseous CO_2 fertilizer application in China's greenhouses between 1982 and 2010

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ABSTRACT

The biological utilization of CO_2 represents a promising application for carbon capture, utilization, and storage (CCUS) technologies. The *Technical Assessment Report of Carbon Dioxide Utilization in China* recommends gaseous fertilization in greenhouses as an important technological use of CO_2. However, the effectiveness of gaseous CO_2 fertilizers at increasing crop yields unpredictable due to varying climatic and technological conditions in China. Here, we analyzed 188 articles on gaseous CO_2 fertilization technology in China published from 1982 to 2010. We found that gaseous CO_2 fertilizers enhanced the yield of representative fruit vegetable (i.e., cucumber, tomato, chili, zucchini, eggplant, and strawberry) by 33.31% over the past three decades. In addition, crop maturity also advanced (by an average of 6.87 days) and crop resistance to diseases and pests was enhanced. We observed a relatively good linear relationship between crop yield increases and increased CO_2 fertilizer application for cucumber and chili once 240.0–3042.75 kg gaseous CO_2 fertilizer was applied per hectare. For the other four crops, a positive correlation was observed. The mean increase in the yield of the six fruit vegetables supports the *Technical Assessment Report of Carbon Dioxide Utilization in China*, which adopted a 30% increase in yield by gaseous CO_2 fertilizers to calculate the economic benefits of this technique. Finally, we suggest that methods of fertilization and business modes of gaseous CO_2 fertilizer application that fit practical farming conditions in China should be proposed to serve as references for the development of gaseous CO_2 fertilization for CCUS engineering.

1. Introduction

Carbon capture, utilization, and storage (CCUS) engineering is an important strategic technology that has great potential to reduce carbon emissions at a large scale. Captured CO_2 may be used in a variety of ways, with the biological utilization of CO_2 to enhance agricultural output representing a promising option [1]. The *Technical Assessment Report of Carbon Dioxide Utilization in China* listed the use of gaseous CO_2 to fertilize greenhouse crops as an important technological application of CO_2. This report evaluated the importance of gaseous CO_2 based on its potential to reduce emissions, in addition to considering the technological maturity, economic feasibility, and environmental and social impacts of this technique. The report concluded that this technique is likely to have promising developments in the future, with many opportunities already existing; however, the study also stated that gaseous fertilization technologies have not yet matured. The report also encouraged increasing investment in this field, as well as the importance of gradually implementing technological research and development (R&D) and piloting demonstration projects to farmers nationwide [2].

Greenhouses were first used for crop production during the late 1970s in China. Statistics from the Ministry of Agriculture indicate that greenhouse yield levels have increased from 7.2 khm^2 to approximately 3440 khm^2 in China between 1982 and 2010 ([3] and Fig. 1). Furthermore, by 2015, total greenhouse coverage nationwide is expected to increase to more than 4370 khm^2 [4]. With the development of the greenhouse farming culture, the utilization of gaseous fertilization technologies has also rapidly expanded. This method improves crop yield by artificially increasing CO_2 concentration levels in greenhouse farms.

Varying climatic and technological conditions generate different outcomes when using gaseous CO_2 fertilization to improve crop yield in China. Consequently, it is difficult to assess the effectiveness and development potential of gaseous CO_2

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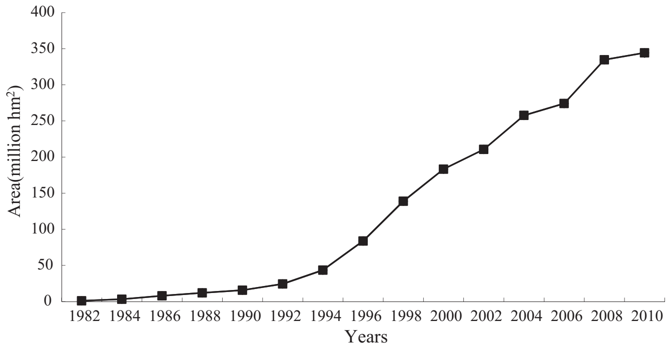

Fig. 1. Area covered by greenhouses in China (in km^2) between 1982 and 2010.

fertilization. Based on the application status of gaseous fertilization technologies in China's greenhouses, the official assessment report adopted a yield increase of 30% as the overall application effectiveness of gaseous CO_2 fertilizers to calculate the economic benefits of this technique. However, yield increases resulting from different gaseous CO_2 fertilizers for various crops should be analyzed based on historical yield data. In addition, the impact of gaseous fertilization on the maturity period of crops and their resistance to diseases and pests requires assessment.

Here, we aimed to investigate the effectiveness of gaseous CO_2 fertilization on the yield increase, maturity period, and resistance to diseases and pests of various crops grown under practical greenhouse farming conditions in China using published data between 1982 and 2010. The effectiveness of gaseous fertilization was also quantitatively described under practical farming conditions. Our results are expected to provide objective indicators for the development of gaseous fertilization technologies and the biological utilization of CCUS technologies.

2. Application of gaseous CO_2 fertilizers in China

Gaseous CO_2 fertilizers used in greenhouses in China include those produced by chemical reactions and combustion, in addition to liquid fertilizers compressed in cylinders. Chemical reactions include sulfuric acid + ammonium bicarbonate, limestone + hydrochloric acid, and calcium carbonate + ammonium sulfate grain + ammonium bicarbonate [5]. Combustion refers to CO_2 being released through the burning of hydrocarbon compounds, such as biogas, natural gas, liquefied petroleum gas, charcoal, anthracite, and kerosene [6]. Compressed liquid CO_2 cylinders are produced as by-products of fertilizer and alcohol factories [7].

Vegetable growth requires specific CO_2 concentrations. The appropriate CO_2 concentration for vegetables is normally 800–1500 ppm, with the compensation and saturation points being 50–100 ppm and 600–2000 ppm, respectively. Between the compensation and saturation points, photosynthesis and the water use efficiency of vegetables improve with increasing CO_2 concentration [8]. However, higher CO_2 concentration is not always better for crop photosynthesis and growth. The concentration of artificially added CO_2 should be 600–1000 ppm and 1000–1500 ppm for leafy and fruity vegetables, respectively, under proper temperature, light, and humidity conditions.

The appropriate concentration of gaseous CO_2 fertilizers that may be used in greenhouses varies according to the species and variety of crop, in addition to the growth periods. Climatic conditions are also important. For instance, CO_2 concentration should be adjusted according to the season, weather, light conditions, temperature, and humidity [9]. According to the standard operating procedures for gaseous CO_2 fertilization, it is best to add CO_2 to a greenhouse when CO_2 concentrations (which vary over time) are at their lowest, which is when crops enter the absorbing state [10]. Fall, winter, and spring are the usual seasons for adding CO_2fertilizers. On sunny days, CO_2 may be added to enclosed greenhouses 0.5–1 h after sunrise or when the temperature exceeds 15 °C. On cloudy or rainy days, or when temperatures are lower than 15 °C, less or no CO_2 should be added because crops have weaker photosynthetic ability [11].

Leafy vegetables may be fertilized over their entire growth period, although the ideal time occurs during the initial growth stage. Vegetables grown in greenhouses maybe fertilized about one week after being planted [12,13]. For fruiting vegetables, CO_2may be added during the attachment and growth period of the pistil late flowers, the flowering period, and the initial fruiting stage. The absorption rate of CO_2 significantly increases during these periods, which enhances fruit size [14,15].

3. Effectiveness of gaseous CO_2 fertilizers under practical farming conditions in China

In the last three decades, 188 articles published by Chinese researchers (based on a search of the *China Academic Journal Network Publishing Database*, CAJD[1]) have reported that the application of gaseous CO_2fertilizers has various benefits. Examples include: (1) increased crop yield/value, (2) fruit crops containing greater quantities of vitamins and total sugar content, (3) improvements in crop quality and appearance, (4) enhanced crop resistance to diseases/pests, (4) advancement in crop maturity period, and (4) extension of the harvesting period. Our analysis showed that, out of the 188 identified articles, 166 articles focused on six representative fruit vegetables, such as cucumber, tomato, chili, zucchini, eggplant, and strawberry. For these crops, yield increase, enhanced resistance to diseases/pests, and advanced maturity period were reported in 93.37%, 41.57%, and 48.80% of the articles, respectively (Table 1). Only 22 articles on leaf vegetables and flowers were identified, with the sample size being insufficient to carry out statistical analysis.

3.1. Relationship between the quantity of gaseous CO_2 fertilizer applied and crop yield increase

Under ideal conditions, yield increases with greater quantities of gaseous CO_2 fertilizer application. Analysis of 25 datasets relating to CO_2 amount and yield increase indicated that the yield of all five representative crops improved after applying gaseous CO_2 fertilizer. For cucumber and chili, a relatively good linear relationship was observed between yield increase and the amount of CO_2 applied (Fig. 2).

3.2. Increase in yield rates

For cucumber, zucchini, tomato, eggplant, chili, and strawberry greenhouse crops, the rate of yield increase was 35.11%, 47.82%, 32.54%, 27.24%, 30.12%, and 27.05%, respectively. The average rate of increase was 33.31% (Fig. 3). The rate of increase, arranged in descending order, was as follows: zucchini > cucumber > tomato > chili > eggplant > strawberry.

3.3. Crop maturity period

The average advancement in the maturity period for cucumber, zucchini, tomato, eggplant, chili, and strawberry greenhouse crops was 6.68, 7.29, 7.17, 7.10, 6.29, and 6.69 days, respectively. The average advancement was 6.87 days (Fig. 4). The effectiveness of gaseous CO_2 fertilizers on the crop maturation period, listed in

[1] Supporting online material: http://www.ieda.org.cn/sites/ieda/.