Greenhouse Carbon Dioxide Supplementation

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Carbon Dioxide (CO_2)

Photosynthesis is the process which involves a chemical reaction between water and carbon dioxide (CO_2) in the presence of light to make food (sugars) for plants, and as a by-product, releases oxygen in the atmosphere. Carbon dioxide currently comprises 0.04 percent (400 parts per million) of the atmospheric volume. It is a colorless and odorless minor gas in the atmosphere, but has an important role for sustaining life. Plants take in CO_2 through small cellular pores called stomata in the leaves during the day. During respiration (oxidation of stored sugars in plants producing energy and CO_2) plants take in oxygen (O_2) and give off CO_2, which complements photosynthesis when plants take in CO_2 and give off O_2. The CO_2 produced during respiration is always less than the amount of CO_2 taken in during photosynthesis. So, plants are always in a CO_2 deficient condition, which limits their potential growth.

CO_2 concentration in relation to plants

Photosynthesis utilizes CO_2 in the production of sugar which degrades during respiration and helps in plant's growth. Although atmospheric and environmental conditions like light, water, nutrition, humidity and temperature may affect the rate of CO_2 utilization, the amount of CO_2 in the atmosphere has a greater influence. Variation in CO_2 concentration depends upon the time of day, season, number of CO_2-producing industries, composting, combustion and number of CO_2-absorbing sources like plants and water bodies nearby. The ambient CO_2 (naturally occurring level of CO_2) concentration of 400 parts per million can occur in a properly vented greenhouse. However, the concentration is much lower than ambient during the day and much higher at night in sealed greenhouses. The carbon dioxide level is higher at night because of plant respiration and microbial activities. The carbon dioxide level may drop to 150 to 200 parts per million during the day in a sealed greenhouse, because CO_2 is utilized by plants for photosynthesis during daytime. Exposure of plants to lower levels of CO_2 even for a short period can reduce rate of photosynthesis and plant growth. Generally, doubling ambient CO_2 level (i.e. 700 to 800 parts per million) can make a significant and visible difference in plant yield. Plants with a C_3 photosynthetic pathway (geranium, petunia, pansy, aster lily and most dicot species) have a 3-carbon compound as the first product in their photosynthetic pathway, thus are called C_3 plants and are more responsive to higher CO_2 concentration than plants having a C_4 pathway (most of the grass species have a 4-carbon compound as the first product in their photosynthetic pathway, thus are called C_4 plants). An increase in ambient CO_2 to 800-1000 ppm can increase yield of C_3 plants up to 40 to 100 percent and C_4 plants by 10 to 25 percent while keeping other inputs at an optimum level. Plants show a positive response up to 700 to need of 1,800 parts per million, but higher levels of CO_2 may cause plant damage (Figure 1).

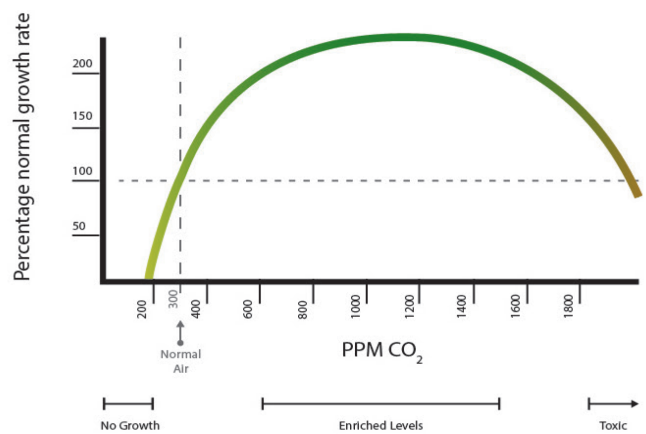

Figure 1. Relation between CO_2 concentration and rate of plant growth. Source: Roger H. Thayer, Eco Enterprises, hydrofarm.com. Redrawn by Vince Giannotti

CO_2 supplementation

In general, CO_2 supplementation is the process of adding more CO_2 in the greenhouse, which increases photosynthesis in a plant. Although benefits of high CO_2 concentration have been recognized since the early 19th century, growth of the greenhouse industry and indoor gardening since the 1970s has dramatically increased the need for supplemental CO_2. The greenhouse industry has advanced with new technologies and automation. With the development of improved lighting systems, environmental controls and balanced nutrients, the amount of CO_2 is the only limiting factor for maximum growth of plants. Thus, keeping the other growing conditions ideal, supplemental CO_2 can provide improved plant growth. This is also called 'CO_2 enrichment' or 'CO_2 fertilization.'

Advantages

- Increase in photosynthesis results in increased growth rates and biomass production.
- Plants have earlier maturity and more crops can be harvested annually. The decrease in time to maturity can help in saving heat and fertilization costs.
- In flower production, supplemental CO_2 increases the number and size of flowers, which increase the sales value because of higher product quality.
- Supplemental CO_2 provides additional heat (depending upon the method of supplementation) through burners, which will reduce heating cost in winter.
- It helps to reduce transpiration and increases water use efficiency, resulting in reduced water use during crop production.

Disadvantages

- Higher production cost with a CO_2 generation system.
- Plants may not show a positive response to supplemental CO_2 because of other limiting factors such as nutrients, water and light. All factors need to be at optimum levels.
- Supplementation is more beneficial in younger plants.
- Incomplete combustion generates harmful gases like sulphur dioxide, ethylene, carbon monoxide and nitrous oxides. These gases are responsible for necrosis, flower malformation and senescence if left unchecked, resulting in a lower quality products.
- Additional costs required for greenhouse modification. Greenhouses need to be properly sealed to maintain a desirable level of CO_2.
- Excess CO_2 level can be toxic to plants as well as humans.
- On warmer days, it is difficult to maintain desirable higher CO_2 levels because of venting to cool the greenhouses.

When to apply

Timing, duration and concentration determines the efficiency of CO_2 supplementation. Carbon dioxide supplementation is not required if all the growing conditions are ideal and the rate of growth is satisfactory to the grower. However, if plants do not meet the required growth, mostly in the fall through early spring, supplemental CO_2 is beneficial. At that time of the year, the vents are closed most of the time, limiting available CO_2. Adding CO_2 one to two hours after sunrise and stopping two to three hours before sunset is the ideal duration of supplementation. Plants are photosynthetically active one to two hours after sunrise reaching peak at 2:00 to 3:00 p.m., followed by a decrease in the rate of photosynthesis. However, leafy greens and vegetables in a hydroponic system can be supplemented with CO_2 and a grow-lighting system 24 hours a day. Seedlings supplemented with CO_2 in flats will be ready to transplant one or two weeks earlier. Supplementing CO_2 at an early age reduces the number of days to maturity and plants can be harvested earlier. Young plants are more responsive to supplemental CO_2 than more mature plants.

Effect of supplemental CO_2 on different growing factors

CO_2-light

The rate of photosynthesis cannot be increased further after certain intensity of light termed as the light saturation point, which is the maximum amount of light a plant can use. However, additional CO_2 increases the light intensity required to obtain the light saturation point, thus increasing the rate of photosynthesis. Mostly in the winter, photosynthesis is limited by low light intensity. An additional lighting system will enhance the efficiency of CO_2 and increase the rate of photosynthesis and plant growth. Thus, supplemental CO_2 integrated with supplemental lighting can decrease the number of days required for crop production.

CO_2-water:

Supplemental CO_2 affects the physiology of plants through stomatal regulation. Elevated CO_2 promotes the partial closure of stomatal cells and reduces stomatal conductance. Stomatal conductance refers to the rate of CO_2 entering and exiting with water vapor from the stomatal cell of a leaf. Because of reduced stomatal conductance, transpiration (loss of water from leaf stomata in the form of water vapor) is minimized and results in an increased water use efficiency (WUE) (ratio of water used in plant metabolism to water lost through transpiration). Lower stomatal conductance, reduced transpiration, increased photosynthesis and an increase in WUE helps plants to perform more efficiently in water-stressed conditions. Supplemental CO_2 reduces water demand and conserves water in water-scarce conditions.

CO_2-temperature

Temperature plays a big role in the rate of plant growth. Most biological processes increase with increasing temperature and this includes the rate of photosynthesis. But the optimum temperature for maximum photosynthesis depends on the availability of CO_2. The higher the amount of available CO_2, the higher the optimum temperature requirement of crops (Figure 2). In a greenhouse supplemented with CO_2, a dramatic increase in the growth of plants can be observed with increasing temperature. Supplemental CO_2 increases the optimum temperature requirement of a crop. This increases production even at higher temperature, which is not possible at the ambient CO_2 level.

CO_2-nutrient

A major effect of CO_2 supplementation is the rapid growth of plants because of enhanced root and shoot growth. The enhanced root system allows greater uptake of nutrients from the soil. It is recommended to increase fertilizer rate with increasing CO_2 level. The normal fertilizer rate can be exhausted quickly and plants may show several nutrient deficiency symptoms. Although strict recommendations of nutrients for different crops at different levels of CO_2 are not presently available, in general nutrient requirements increase with increasing levels of CO_2. On the other hand, some micro nutrients are depleted quicker than macro nutrients. Some studies have reported low levels of zinc and iron in crops produced at higher CO_2 levels. Further decrease in transpiration and conductance with CO_2

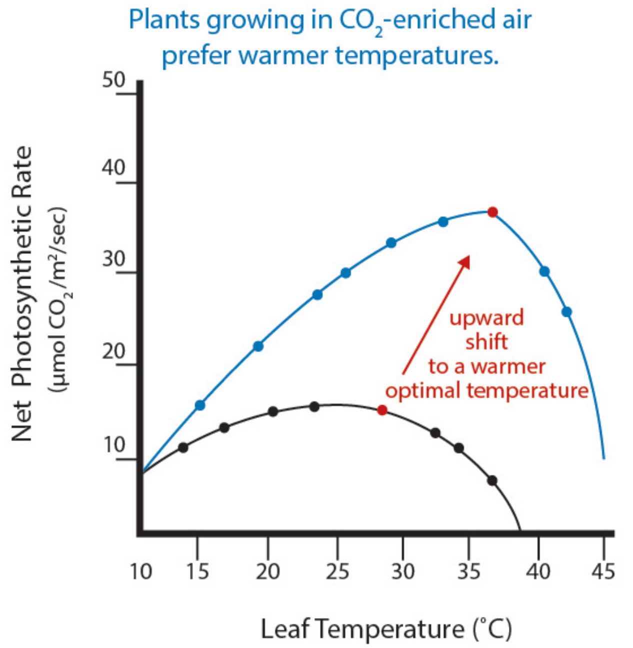

Figure 2. Relationship between leaf temperature and net photosynthetic rate at ambient and CO_2 elevated condition in *Populas grandidentata* (Jurik et al., 1984). Redrawn by Vince Giannotti

supplementation may affect calcium and boron uptake, which should be compensated through addition of nutrients.

Sources of carbon dioxide

Carbon dioxide is a free gas present in the atmosphere. Carbon dioxide should be supplemented in a pure form. A mixture of carbon monoxide, ozone, nitrogen oxides, ethylene and sulfur impurities in some CO_2 sources may damage the plant. Carbon monoxide should not exceed 50 parts per million; otherwise CO_2 supplementation will be harmful rather than beneficial. There are different methods of CO_2 supplementation and the principle of CO_2 production is different depending on the method selected. Some of the methods are discussed below.

Natural CO_2

Since CO_2 is a free and heavy gas, it stays at a lower level in the greenhouse. Carbon dioxide produced by plants at night is depleted within a few hours after sunrise, thus proper ventilation integrated with horizontal airflow fans just above the plant can help in distributing available CO_2 at least to the ambient level. It is the cheapest method for maintaining an ambient level of CO_2. But in winter, the extreme climatic conditions do not favor this method and additional CO_2 sources are required. Another natural way of increasing CO_2 in the greenhouse is through human respiration. Humans also exhale CO_2 during respiration like plants. People working in the greenhouse for pruning, irrigation and other operations can increase CO_2 levels.

Compressed CO_2 tanks

Using compressed CO_2 is a popular method of CO_2 enrichment. The CO_2 is in a compressed liquid form and vaporizes through use of CO_2 vaporizer and is distributed through a distribution system. Holes are added to poly vinyl chloride (PVC) pipes and spread throughout the greenhouse for even distribution in larger operations. However, CO_2 is released directly from a tank in small greenhouses. Generally, it is an expensive method in which liquefied CO_2 is brought by a large truck and put storage tanks in larger operations but small 20- to 50-pound tanks are available for small-scale growers. Along with the tank, a pressure regulator, flow meter, solenoid valve, CO_2 sensors and timers are required for operation. These supplies are available from welding supply stores. Because of increased precision with compressed CO_2, most operators use advanced digital regulators. For small scale growers, 20-pound cylinders cost between \$150 and \$200 and \$20 to \$50 to refill, which will last about two weeks for a 200-square-foot-sized room maintaining 1,200 to 1,500 parts per million of CO_2 concentration. Other accessory costs are higher and makes the method quite expensive.

CO_2 generator

Combustion of hydrocarbon fuels generally produces CO_2, water and heat. Greenhouse operators can use small CO_2 generators operated with propane or natural gas. Burning 1 pound of fuel can produce 3 pounds of CO_2. One pound of CO_2 is equivalent to 8.7 cubic feet of gas at standard temperature and pressure. At this rate, 5 ounces of ethyl alcohol per day is required to maintain 1300 parts per million of CO_2 for a 200-square-foot-sized room. The amount of CO_2 produced depends on the type and purity of fuel. But combustion without adequate oxygen may produce impurities which are harmful to plants. So, smaller areas should be opened for fresh air even in sealed greenhouse conditions. These generators are kept just above the plants and each unit covers about 4,800 square feet of area and costs between \$1,000 and \$2,500, plus an additional \$1,000 for gas and electrical installation (Figure 3). The CO_2 burner capacity ranges from 20,000 to

Figure 3. Carbon dioxide generator manufactured by Johnson Gas Appliance Company (Iowa). The generator operates with either propane or natural gas and has pressure gauge to control the size of burner.

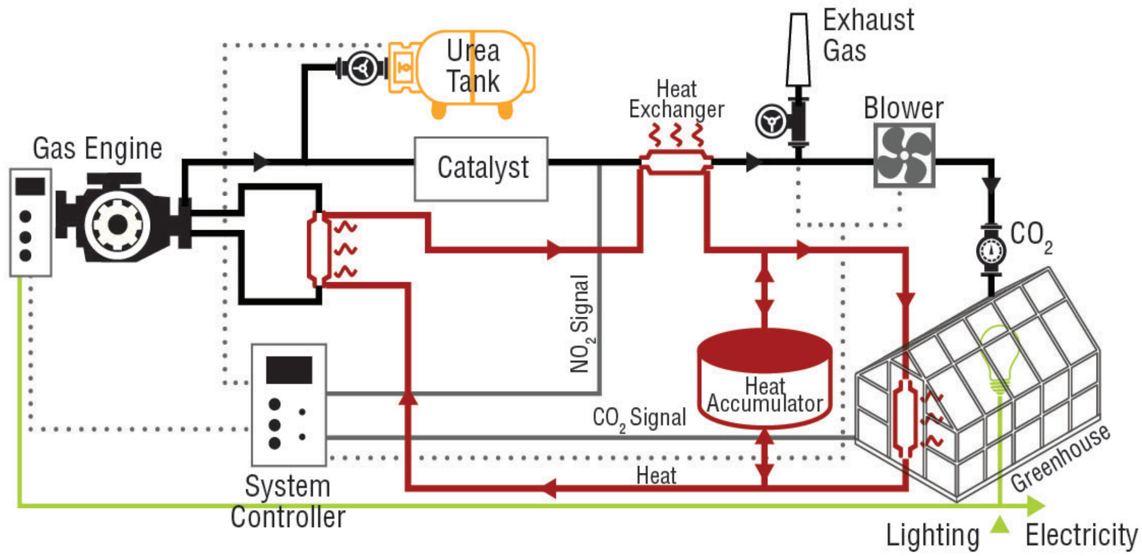

Figure 4. Schematic diagram of flue gas generator in greenhouse. (Source: Vadogroup) (http://www.vadogroup.com/index.php/en/power-engineering1/solutions/for-greenhouses.html). Redrawn by Vince Giannotti.

60,000 Btu per hour and can produce 8.2 pounds of CO_2 per hour by burning natural gas. Based on natural gas price of Oklahoma (i.e. $7.07 per 1,000 cubic feet of natural gas) in 2016, the cost of operation will be about $4.80 per day or $0.38 per square foot per year, if operated 12 hours a day.

Instead of using small generators in multiple greenhouse bays, larger greenhouse operations use gas engines to produce flue gas (exhaust gas of engine), which passes through a series of filters to give pure CO_2. The main advantage of this system is, it produces both heat and electricity along with CO_2. Heat is stored in a tank in the form of hot water and will be used in heating the greenhouses at night. Such big generators are capable of minimizing heating and electricity cost. However, such a complex system costs up to $80,000 to cover 10 acres worth of greenhouse.

Decomposition and Fermentation

Organic matter decomposed by microbial action produces CO_2. Organic waste can decompose in plastic containers and the CO_2 produced can be used by plants. However, this method may require more space and substrate to produce adequate CO_2. It helps in the utilization of waste and later can be used as a compost. Although it is an inexpensive method, it is hard to control the concentration of CO_2 and gives off bad odors. To eliminate these disadvantages, many commercial products have been introduced in the market. The CO_2 boost bucket (Figure 5), Pro CO_2 and Exhale mushroom bag are some commercial products which claim to produce the desired level of CO_2 without odors. They could be beneficial for small-scale growers and indoor gardens.

Carbon dioxide is also a by-product of fermentation. Some growers use sugar solution and yeast to supplement CO_2. A pound of sugar produces half a pound of ethanol and half a pound of CO_2. A suitable size plastic container, sugar, yeast and a sealant (to seal the container tightly) are necessary to start the production of CO_2. This method provides CO_2 faster than decomposition but has the disadvantages of foul odors, difficulty in maintaining desired concentrations and occupying a larger space. The major advantage of this method is the ethanol production. Ethanol is an organic fuel and can produce more CO_2 when burned.

Figure 5. CO_2 boost Bucket with pump that helps to control CO_2 concentration. Formulation is based on the microbial activity inside the bucket.

Dry ice

Dry ice is one of the cheapest method adopted by growers in smaller greenhouses. In advanced greenhouses, special cylinders with a gas flowmeter are used to control CO_2 regulation through sublimation of dry ice. Dry ice is a solid state of CO_2 obtained by keeping CO_2 at an extremely low temperature (-109 F). Slow release of dry ice may help in cooling small hobby greenhouses by a few degrees in the summer. In general, about one pound of dry ice is enough to maintain 1,300 parts per million of CO_2 in a 100-square-foot area throughout the day. In a normal greenhouse, dry ice is sliced into small pieces and replaced every two hours to maintain a desired level of CO_2 or kept inside an insulator with small holes through which CO_2 escapes. It is cheap, readily available and roughly costs $1 to $3 per pound and can last for a whole day. Since it has an extremely low temperature, it should be handled with care. The major disadvantages are low shelf-life and difficulty in storing at normal conditions. Rapid sublimation of dry ice may lead to increase level of CO_2 higher than 2,000 parts per million, which could limit growth as well could be toxic to plants.

Chemical Method

The chemical reaction of baking soda with acid (mostly acetic acid) can produce CO_2, but a large quantity of materials is required to produce adequate CO_2. Reaction of about two pounds of baking soda with 10 to 12 liters of 5 percent acetic acid just produces one pound of CO_2. Thus, this is considered an expensive method of CO_2 production. The acetic acid is dripped on baking soda and CO_2 is generated. Slow release of acetic acid by drip increases the life of the reaction. The reaction takes a long time to generate enough CO_2 and it is difficult to control the CO_2 concentration.

Control and Distribution of CO_2

Depending on the size of the greenhouse and types of system installed, the CO_2 level in the greenhouse is controlled

Figure 6. Extech CO_2 Monitor (FLIR Commercial Systems Inc., Nashua, NH) and data logger. It measures CO_2, temperature and humidity and has 15,000 data log storage capacity.

manually or through a computer based system. A CO_2 gas sensor (Figure 6) gives the level of CO_2 concentration in the greenhouse atmosphere and a generator is manually turned on and off based on the readings of the sensor. The sensor measures temperature and humidity along with CO_2 and helps in developing a crop management strategy. However, in the computer-based system, sensors signal the current CO_2 level to the control system and the control system turns the generator on and off based on the set points created by the grower.

CO_2 diffuses slowly, so proper air circulation is essential to distribute CO_2 evenly. Generally, a small greenhouse with a single CO_2 generator uses fan jets or horizontal air flow fan for distribution. However, a large connected greenhouse with a flue gas generator generally uses plastic tubes underneath the bench (right below the crop level) and are perforated at different intervals to diffuse CO_2. The main advantage of such tubing is to supply adequate CO_2 to the boundary layer of a leaf even in dense canopy conditions.

Things to remember

- Never allow CO_2 to exceed plant requirements. Have an alert system when CO_2 level reaches 2,000 parts per million, because a high level of CO_2 (5,000 parts per million and above) can kill people.
- Always monitor the CO_2 levels through sensors and adjust to required level.
- Use a pure form of CO_2, and provide enough oxygen for combustion to eliminate toxic gases.
- Always keep the CO_2 source above the plant (except in the flue gas system) and evenly distribute the air inside the greenhouse.
- Choose the method of supplementation that suits your operation. Develop a strategy based on a cost/benefit analysis. Choose a high value crop and follow manufacturer's manual for operation.
- Maintain ideal growing condition like proper lighting, moisture, temperature, nutrition and humidity to make CO_2 supplementation effective.
- Plants may need additional nutrition because of faster growth rates.

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