EXTENSION

# Greenhouse Carbon Dioxide Supplementation

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Megha Poudel
Graduate Student, Ornamentals

Bruce Dunn
Professor, Ornamentals

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## Carbon Dioxide ($CO_2$)

Photosynthesis is the process which involves a chemical reaction between water and carbon dioxide in the presence of light, to make food (sugars) for plants and as a byproduct releases oxygen in the atmosphere. Carbon dioxide currently comprises .04% (400 ppm) 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 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 ppm 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. Carbon dioxide level is higher at night because of plant respiration and microbial activities. Carbon dioxide level may drop to 150-200 ppm 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. 700-800 ppm) can make a significant and visible difference in plant yield. Plants with a C3 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 C3 plants and are more responsive to higher $CO_2$ concentration than plants having a C4 pathway (most of the grass species have a 4-carbon compound as the first product in their photosynthetic pathway, thus are called C4 plants). An increase in ambient $CO_2$ to 800-1,000 ppm can increase yield of C3 plants up to 40%–100% and C4 plants by 10%–25% while keeping other inputs at an optimum level. Plants show a positive response up to 700-1,800 ppm, but higher levels of $CO_2$ may cause plant damage (Fig 1).

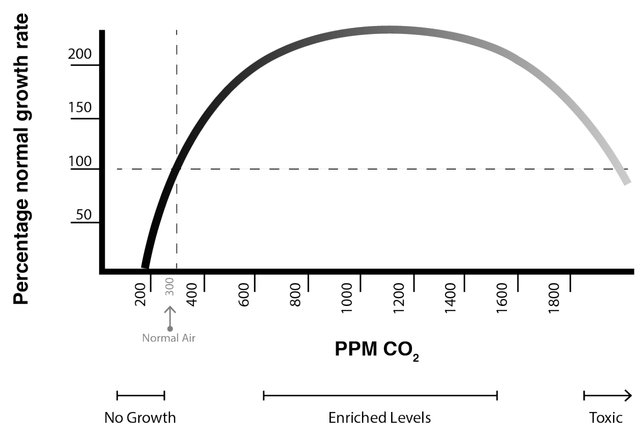


**Figure 1. Relation between $CO_2$ concentration and rate of plant growth.** Source: Roger H. Thayer, Eco Enterprises, hydrofarm.com

## $CO_2$ Supplementation

In general, $CO_2$ supplementation is the process of adding additional $CO_2$ 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 havested 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. So, 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 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 and reaching peak at 2:00-3:00 p.m., followed by a decrease in the rate of photosynthesis. However, leafy greens and vegetables in a hydroponic system can be supplemented with $CO_2$ 24 hours a day with supplemental grow-lighting system. 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 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, and 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, 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 (Fig 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

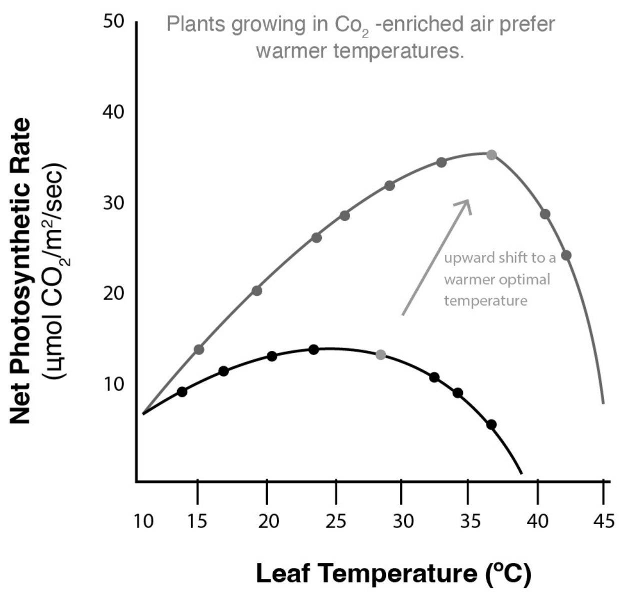


**Figure 2. Relationship between leaf temperature and net photosynthetic rate at ambient and $CO_2$ elevated condition in Populas grandidentata (Jurik et al., 1984).**

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 $CO_2$ 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 ppm; 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 stored in storage tanks in larger operations but small 20-50 lb 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 lb cylinders cost between \$150-\$200 and \$20-\$50 to refill, which will last about two weeks for a 200-sq. ft. room maintaining 1,200-1,500 ppm 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 one pound of fuel can produce 3 pounds of $CO_2$. One pound of $CO_2$ is equivalent to 8.7 cu. ft. of gas at standard

**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. $CO_2$ boost Bucket with pump that helps to control CO2 concentration. Formulation is based on the microbial activity inside the bucket.**

temperature and pressure. At this rate, 5 oz. of ethyl alcohol per day is required to maintain 1300 ppm of $CO_2$ for a 200-sq. ft. 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 sq. ft. of area and costs between $1,000-$2,500 plus an additional $1,000 for gas and electrical installation (Fig. 3). The $CO_2$ burner capacity ranges from 20,000-60,000 Btu/hr and can produce 8.2 pounds of $CO_2$ per hour by burning natural gas.

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 that 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 (Fig. 4), 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 byproduct 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.

## Dry ice

Dry ice is one of the cheapest methods 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 (minus 109 degrees fahrenheit). Slow release of dry ice may help in cooling small hobby greenhouses by a few degrees in the summer. In general, about 1 pound of dry ice is enough to maintain 1,300 ppm of $CO_2$ in a 100-sq. ft. 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 between $1-$3/lb. 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 self-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 ppm, which could limit growth as well could be toxic to plants.


**Figure 5. Extech CO2 Monitor (FLIR Commercial Systems Inc., Nashua, NH) and data logger. It measures CO2, temperature and humidity and has 15,000 data log storage capacity.**

### 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 2 pounds of baking soda with 10-12 liters of 5% acetic acid just produces w1 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 type of system installed, the $CO_2$ level in the greenhouse is controlled manually or through a computer-based system. A $CO_2$ gas sensor (Fig. 5) 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 case of the computer-based system, sensors signal the current $CO_2$ level to the control system and a control system turns on and off the generator 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. Note the Occupational Safety and Health Administration (OSHA) Permissible Exposure Limit (PEL) and American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Value (TLV) for an 8-hour work day is 5,000 ppm $CO_2$ and a ceiling exposure limit (not to be exceeded) of 30,000 ppm for a 10-minute period (https://www.osha.gov/annotated-pels/table-z-1). Have an alert system as you should not enter areas where $CO_2$ levels exceed 20,000 ppm until ventilation has been provided to bring the concentration down to safe levels.
- 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 which 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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