



Greenhouse Carbon Dioxide Supplementation

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Carbon Dioxide (CO₂)

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 CO₂ through small cellular pores called stomata in the leaves during the day. During respiration (oxidation of stored sugars in plants producing energy and CO₂) plants take in oxygen (O₂) and give off CO₂, which complements photosynthesis when plants take in CO₂ and give off O₂. The CO₂ produced during respiration is always less than the amount of CO₂ taken in during photosynthesis. So, plants are always in a CO₂ deficient condition, which limits their potential growth.

CO₂ Concentration in Relation to Plants

Photosynthesis utilizes CO₂ 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 CO₂ utilization, the amount of CO₂ in the atmosphere has a greater influence. Variation in CO₂ concentration depends upon the time of day, season, number of CO₂-producing industries, composting, combustion and number of CO₂-absorbing sources like plants and water bodies nearby. The ambient CO₂ (naturally occurring level of CO₂) 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 CO₂ is utilized by plants for photosynthesis during daytime. Exposure of plants to lower levels of CO₂ even for a short period can reduce rate of photosynthesis and plant growth. Generally, doubling ambient CO₂ 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 CO₂

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 CO₂ 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 CO₂ may cause plant damage (Fig 1).

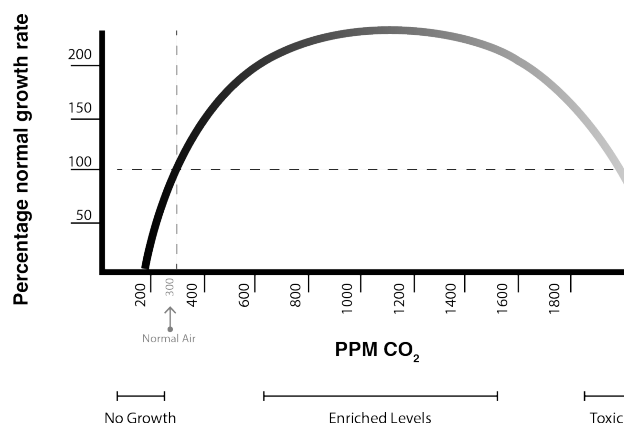


Figure 1. Relation between CO₂ concentration and rate of plant growth. Source: Roger H. Thayer, Eco Enterprises, hydrofarm.com

CO₂ Supplementation

In general, CO₂ supplementation is the process of adding additional CO₂ in the greenhouse, which increases photosynthesis in a plant. Although benefits of high CO₂ 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 CO₂. 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 CO₂ is the only limiting factor for maximum growth of plants. Thus, keeping the other growing conditions ideal, supplemental CO₂ can provide improved plant growth. This is also called CO₂ enrichment' or 'CO₂ 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 CO₂ increases the number and size of flowers, which increase the sales value because of higher product quality.
- Supplemental CO₂ 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 CO₂ generation system.
- Plants may not show a positive response to supplemental CO₂ 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 CO₂.
- Excess CO₂ level can be toxic to plants as well as humans.
- On warmer days it is difficult to maintain desirable higher CO₂ levels because of venting to cool the greenhouses.

When to apply

Timing, duration and concentration determines the efficiency of CO₂ 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 CO₂ is beneficial. At that time of the year, the vents are closed most of the time, limiting available CO₂. Adding CO₂ 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 CO₂ 24 hours a day with supplemental grow-lighting system. Seedlings supplemented with CO₂ in flats will be ready to transplant one or two weeks earlier. Supplementing CO₂ at an early age reduces number of days to maturity and plants can be harvested earlier. Young plants are more responsive to supplemental CO₂ than more mature plants.

Effect of supplemental CO₂ on different growing factors

CO₂-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 CO₂ 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 CO₂ and increase the rate of photosynthesis and plant growth. Thus, supplemental CO₂ integrated with supplemental lighting can decrease the number of days required for crop production.

CO₂-water:

Supplemental CO₂ affects the physiology of plants through stomatal regulation. Elevated CO₂ promotes the partial closure of stomatal cells and reduces stomatal conductance. Stomatal conductance refers to the rate of CO₂ 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 CO₂ reduces water demand and conserves water in water-scarce conditions.

CO₂-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 CO₂. The higher the amount of available CO₂, the higher the optimum temperature requirement of crops (Fig 2). In a greenhouse supplemented with CO₂, a dramatic increase in the growth of plants can be observed with increasing temperature. Supplemental CO₂ increases the optimum temperature requirement of a crop. This increases production even at higher temperature, which is not possible at the ambient CO₂ level.

CO₂-nutrient

A major effect of CO₂ 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 CO₂ level. The normal fertilizer rate can be exhausted quickly and plants may show several nutrient deficiency symptoms. Although strict recommendations of

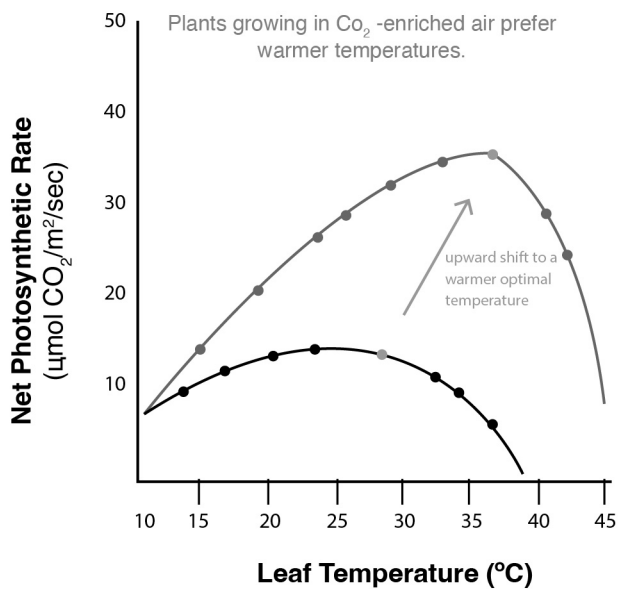


Figure 2. Relationship between leaf temperature and net photosynthetic rate at ambient and CO₂ elevated condition in *Populus grandidentata* (Jurik et al., 1984).

nutrients for different crops at different levels of CO₂ are not presently available, in general nutrient requirements increase with increasing levels of CO₂. 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 CO₂ levels. Further decrease in transpiration and conductance with CO₂ 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 CO₂ sources may damage the plant. Carbon monoxide should not exceed 50 ppm; otherwise CO₂ supplementation will be harmful rather than beneficial. There are different methods of CO₂ supplementation and the principle of CO₂ production is different depending on the method selected. Some of the methods are discussed below.

Natural CO₂

Since CO₂ 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 CO₂ at least to the ambient level. It is the cheapest method for maintaining an ambient level of CO₂. But in winter, the extreme climatic conditions do not favor this method and additional CO₂ sources are required. Another natural way of increasing CO₂ in the greenhouse is through human respiration. Humans also

exhale CO₂ during respiration like plants. People working in the greenhouse for pruning, irrigation and other operations can increase CO₂ levels.

Compressed CO₂ tanks

Using compressed CO₂ is a popular method of CO₂ enrichment. The CO₂ is in a compressed liquid form and vaporizes through use of CO₂ 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, CO₂ is released directly from a tank in small greenhouses. Generally, it is an expensive method in which liquefied CO₂ 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, CO₂ sensors and timers are required for operation. These supplies are available from welding supply stores. Because of increased precision with compressed CO₂, 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 CO₂ concentration. Other accessory costs are high and makes the method quite expensive.

CO₂ generator

Combustion of hydrocarbon fuels generally produces CO₂, water and heat. Greenhouse operators can use small CO₂ generators operated with propane or natural gas. Burning one pound of fuel can produce 3 pounds of CO₂. One pound of CO₂ 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. CO₂ 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 CO₂ for a 200-sq. ft. room. The amount of CO₂ 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 CO₂ burner capacity ranges from 20,000-60,000 Btu/hr and can produce 8.2 pounds of CO₂ 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 CO₂. The main advantage of this system is that it produces both heat and electricity along with CO₂. 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 CO₂. Organic waste can decompose in plastic containers and the CO₂ produced can be used by plants. However, this method may require more space and substrate to produce adequate CO₂. 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 CO₂ and gives off bad odors. To eliminate these disadvantages, many commercial products have been introduced in the market. The CO₂ boost bucket (Fig. 4), Pro CO₂ and Exhale mushroom bag are some commercial products which claim to produce the desired level of CO₂ 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 CO₂. A pound of sugar produces half a pound of ethanol and half a pound of CO₂. A suitable size plastic container, sugar, yeast and a sealant (to seal the container tightly) are necessary to start the production of CO₂. This method provides CO₂ 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 CO₂ 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 CO₂ regulation through sublimation of dry ice. Dry ice is a solid state of CO₂ obtained by keeping CO₂ 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 CO₂ 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 CO₂ or kept inside an insulator with small holes through which CO₂ 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 CO₂ 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 CO₂, but a large quantity of materials is required to produce adequate CO₂. Reaction of about 2 pounds of baking soda with 10-12 liters of 5% acetic acid just produces w1 pound of CO₂. Thus, this is considered an expensive method of CO₂ production. The acetic acid is dripped on baking soda and CO₂ is generated. Slow release of acetic acid by drip increases the life of the reaction. The reaction takes a long time to generate enough CO₂ and it is difficult to control the CO₂ concentration.

Control and Distribution of CO₂

Depending on the size of the greenhouse and type of system installed, the CO₂ level in the greenhouse is controlled manually or through a computer-based system. A CO₂ gas sensor (Fig. 5) gives the level of CO₂ 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 CO₂ and helps in developing a crop management strategy. However, in the case of the computer-based system, sensors signal the current CO₂ level to the control system and a control system turns on and off the generator based on the set points created by the grower.

CO₂ diffuses slowly, so proper air circulation is essential to distribute CO₂ evenly. Generally, a small greenhouse with a single CO₂ 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 CO₂. The main advantage of such tubing is to supply adequate CO₂ to the boundary layer of a leaf even in dense canopy conditions.

Things to remember

- Never allow CO₂ 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 CO₂ 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 CO₂ levels exceed 20,000 ppm until ventilation has been provided to bring the concentration down to safe levels.

- Always monitor the CO₂ levels through sensors and adjust to required level.
- Use a pure form of CO₂ and provide enough oxygen for combustion to eliminate toxic gases.
- Always keep the CO₂ 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 CO₂ supplementation effective.
- Plants may need additional nutrition because of faster growth rates.

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