CARBON DIOXIDE ENRICHMENT IN THE GREENHOUSE

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Carbon (C) is one of the essential nutrients for plant growth. Carbon is found in plants in greater quantity than any other nutrient. Approximately 40% of the dry matter of a plant is made up of carbon. Carbon is not one of nutrients supplied to the plant through fertilization, but rather the plant obtains carbon through the air. Carbon dioxide gas (CO_2) in the air supplies carbon to the plant. CO_2 diffuses into the plant through stomata and is turned into carbohydrates in the plant. Stomata are small pores on a leaf that allow gas exchange. The process by which CO_2 is turned into carbohydrates, with the addition of water and energy from the sun, is called photosynthesis.

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CO_2 + water + energy from sunlight -> carbohydrate + oxygen

On the average, air contains just over 0.03 % CO_2. Currently that level is about 345 ppm CO_2. Actual levels vary from 200 to 400 ppm, with higher levels found in highly industrial areas where fuels are burned. CO_2 levels have increased over the years, primarily due to deforestation and combustion. In 1880, the CO_2 level of air was approximately 294 ppm. The rate of increase is currently 1-2 ppm per year.

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Benefits of CO_2

The value of CO_2 enrichment in the greenhouse has been recognized for many years. More than 100 years ago the benefits of CO_2 enrichment were reported in Europe. Intermittent reports appeared from this time until after World War II. These studies reported mixed results concerning the use of supplemental CO_2 with respect to plant growth.

CO_2 was originally used in vegetable production to increase yield and was later used in floriculture when larger flower heads, stronger stems and decreased production time were noted following the addition of CO_2 to ambient air in a greenhouse.

Some of the initial research on supplemental CO_2 showed some problems with using higher levels of CO_2. Levels two to three times greater than normal levels of CO_2 caused plant damage. However, later research showed that some of these results were probably due to using impure CO_2.

CO_2 enrichment is generally used in the northern climates during the winter months when greenhouse venting is minimal. Levels of up to 1500 ppm of CO_2 are maintained from September to April to help produce higher quality crops and/or increase yield. Enrichment is done during daylight hours, when plants utilize the additional CO_2 for photosynthesis.

In general, the greatest benefit from CO_2 enrichment is seen in the range of 1000 to 1500 ppm. Over 1500 ppm there seems to be diminishing returns on most crops.

Maximum levels of CO_2 which each crop can tolerate are crop specific. Tomatoes, for example, will continue to have improved growth with levels up to 2200 ppm, cucumbers tolerate

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Table 1. *Some of the specific benefits of using CO_2 enrichment on crops include:*

Roses
- decreased number of blind shoots
- increase in stem length
- increase in stem weight
- greater number of petals
- decreased cropping time in winter

Chrysanthemum
- thicker stems
- greater height
- reduction in cropping time on potted plants

Carnation
- increased weight of flowers
- increased stem strength
- reduced time to flowering
- greater number of cuttings
- longer useful life of stock plants

Geranium
- improved rooting of cuttings
- increased height
- increased branch number

Poinsettia
- increased bract diameter

up to 1500 ppm and for gerbera and chrysanthemum the upper limit is 1200 ppm (Table 1). It is important to know the critical CO_2 concentrations that your crops can tolerate. In tomato, for example, fruit set is lower at 200 ppm than at 1500 ppm and severe leaf necrosis is evident at 3200 ppm, whereas in cucumber, the leaves become necrotic and fruit yields decline when CO_2 concentrations approach 1500 ppm. The critical concentrations for gerbera are lower yet, with leaf chlorosis developing in some cultivars at concentrations as low as 1200 ppm. In chrysanthemum, where an early symptom of "high" CO_2 damage is interveinal chlorosis in older leaves, concentration is 1200 ppm have also been found to be critical. As with gerbera, chrysanthemums show cultivar differences in their response to CO_2.

The greatest improvement in crop growth resulting from supplemental CO_2 occurs during the winter months, when greenhouses are not vented. Levels of CO_2 drop considerably when vents are open more than two inches, and even more when cooling fans are on. Recent research in Europe has shown that when vents are open more than 5 percent of their capacity or when the fans are on, the ambient CO_2 levels are about 330 ppm. When vents are open less than 5 percent, levels up to 1000 ppm are possible.

Since growth increases from CO_2 enrichment, other changes in cultural practices may be necessary. For instance, increased fertilization may be necessary during the winter months because of increased growth.

Sources of CO_2

There are several ways that CO_2 can be added to your greenhouse atmosphere. Choosing the best one for you may depend on the crops you are growing and the size of your operation.

Combustion of fuels is a common, and reasonably economical, way to get CO_2 enrichment. Kerosene was among the first commercially used methods of generating CO_2 in the greenhouse, and it is still popular today. Kerosene burns to produce CO_2 and water. It also supplies heat to the greenhouse. There are two types of burners available, one atomizes and one vaporizes the liquid prior to combustion. Atomizing burners are preferred in greenhouses. While precise control in the greenhouse is difficult, atomizing burners can be linked to automatic ventilators so that CO_2 production will cease when the ventilators are open. They can also be put on a time clock to operate at only certain times of the day. One of the possible disadvantages of using kerosene as your CO_2 source is the contamination of the fuel by sulfur compounds. As the kerosene is burnt, sulfur dioxide can be produced and can cause injury to plants. "Clean" grades of kerosene are available which contain less than 0.06% sulphur and these cause few problems. Be sure that your supplier knows that you need low-sulphur kerosene and you should have few problems.

Probably the most popular method of CO_2 enrichment in the United States and Canada is the combustion of propane. This is especially true in small to medium-sized greenhouses. It is readily available in most locations, is easy to store and is generally less expensive than kerosene. Burners are usually hung above plants and the propane is piped in from a tank located outside the greenhouse. Some of the burners act alone, and others incorporate a fan to help distribute the CO_2. A

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fresh air supply is required to achieve 100% combustion of the fuel. Generally air is drawn in from outside the greenhouse.

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Incomplete combustion of propane, either from contaminants in the fuel or from a limited air supply, releases propylene into the atmosphere. Propylene is phytotoxic and will have similar effects as ethylene, i.e. flower bud abortion, reduction in stem elongation and leaf size. To help avoid problems, after the burners are installed, check all joints to avoid leaks. Also, check the burner periodically to be sure the flame shows a uniform blue color. Traces of yellow in the flame suggest that there is incomplete combustion and toxic gases are probably being released.

In some areas natural gas is readily available and inexpensive and is becoming the fuel of choice for CO_2 production. The burners are similar to those used for propane combustion. Generally the levels of contaminants in natural gas is too low to cause problems in the greenhouse. You should be aware, however, that natural gas contains potentially harmful ethane, propylene and ethylene in differing concentrations. However, natural gas, in general, burns cleanly and provides more heat per unit volume than kerosene or propane.

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Pure CO_2, supplied in bulk, is a safe and economical option for some greenhouses. For large greenhouses CO_2 is supplied in bulk tanks in liquid form. The tanks are stored in large, refrigerated, pressurized containers near the greenhouse. The tanks are insulated and are maintained at -18°C (0°F). While there are manufacturers that sell the tanks for prices ranging from $20,000 to $50,000, most greenhouses rent tanks from gas supply companies, and with this rental also receive service on the storage equipment. There are many requirements for installation of these tanks, including a reinforced concrete pad and generally 220V wiring for the compressor. Also, remember that while the CO_2 is generally used only about 6 to 7 months of the year, rental of tanks will usually be applied for the full year. CO_2 is drawn from a vaporized reserve tank and distributed to the greenhouse on demand. A main pipe will bring the CO_2 to the greenhouse where it is generally distributed through flexible tubing throughout the range. This system lends itself to precise control of CO_2 inputs and most growers that use this system are happy with the results. The major drawback to using pure CO_2 is the expense.

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One of the most basic, and difficult to control, tecnhiques for CO_2 enrichment is adding organic materials to your media and allowing CO_2 to be generated from the breakdown of the material. This is a common practice in some greenhouse vegetable operations. This practice will help maintain the CO_2 levels near the plants, but one of the primary drawbacks to this technique is that just as the plants start growing and utilize the CO_2, the levels decrease due to less decomposition of the organic material. It is also difficult to control how much CO_2 is being released. Since it is difficult to control decomposition, the rate of CO_2 release is, for the most part, uncontrollable.

Composting materials on site can also generate CO_2. The most practical way of doing this is to have a composting site and the ability to direct the CO_2 into the greenhouse through polyethylene ducts. This composting is a somewhat involved process and requires both carbon and nitrogen based materials in a 2:1 ratio. In addition, aerobic conditions need to be maintained to help avoid dangerous toxic gases from being produced. Lastly, a readily available source of inexpensive organic materials must be available to make this form of enrichment cost effective.

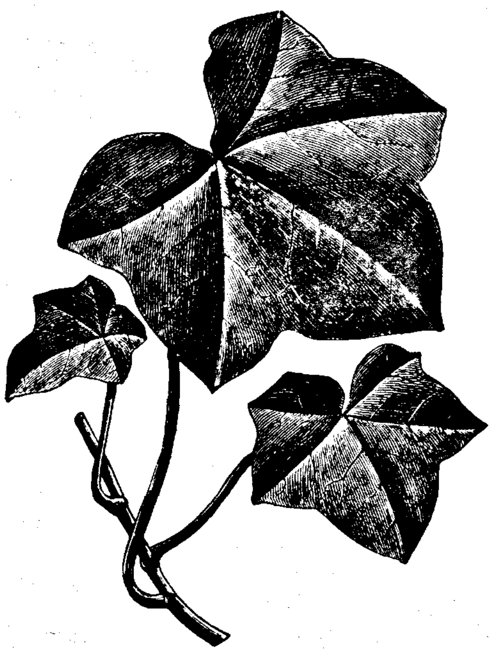
If you are in a location where there is industrial or agricultural processing, you may have a readily available source of CO_2. A by-product of processes such as brewing or distillation, coal mining and hog farming is CO_2. However, the logistics of getting the CO_2 from the source to your location may be limiting. Recently manufacturing companies have started to operate greenhouses to utilize their "waste" by-products. One of the most common, and often underutilized, sources of CO_2 from industry is air from mine shafts. Abandoned mine shafts are often a rich source of "free" CO_2 in many parts of the country. As with anything, "free" is a relative term. Air derived from industrial or farming operations needs to be scrubbed to remove potentially hazardous contaminants.

Related to the use of air and gases from industrial concerns, is the use of flue gases from your own greenhouse if you are burning natural gas. There are similar set-up concerns that you have with this technique compared to obtaining gas from other industries. If there is improper burning of the gas, toxic contaminants can be present and can be piped into your greenhouse.

You will need to set up a piping system to bring the CO_2 back into the greenhouse, but with some basic engineering it can be done. One other draw back to using your own flue gases is that when your boiler is shut down, so is your CO_2 source. This can be a problem in the spring when you start getting warm days.

Distribution of CO_2

Simply supplying CO_2 to the greenhouse is not enough. The CO_2 needs to be distributed throughout the house and it also needs to be monitored. While the distribution of CO_2 can be difficult due to the effect that light, wind speed and ventilation can have on enrichment, by using computers, monitoring and adjusting levels of CO_2 can be quite simple. In many operations CO_2 production is controlled by a computer system coupled with an infrared gas analyzer and is engaged when CO_2 levels in the greenhouse drop below a set point.



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CO_2 is heavier than air. Without some air turbulence, CO_2 will sink to low areas in your greenhouse. Generally this is not a problem in a greenhouse. Air movement from heating and horizontal air flow fans generally provides enough air movement. One difficulty can be even distribution throughout the greenhouse. Generally levels are higher near the burner, when using open combustion devices. For this reason, burners with fans incorporated will help reduce the distribution problem by moving the CO_2 from the source. Placement of the burners will also help. In a quonset type house, place the burners as high as possible above the crop, without danger of heating the poly over 70°C. In a greenhouse with eaves, place the burner slightly below the level of the eaves.

If you are bringing CO_2 in from an external source using fans can often mix a single point source of CO_2 with the air. Another way to disperse CO_2 is to direct the CO_2 through finely-perforated tubing that is placed close to the crop canopy. Even with this technique, uneven distribution can be found due to differences in air speed and movement of the CO_2 through the tubing.

When supplying pure CO_2 from a pressurized source, the pressure must be reduced to approximately 10 psi before entering the greenhouse distribution system. When the system is set up, companies will generally recommend the type of regulator that should be used. If there is only one supply line from the source to the greenhouse, only one regulator will be needed.

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While CO_2 may be a common gas in the air, you will want to control its flow and distribution in the greenhouse so that it is not "wasted". Control of the volume of CO_2 will be specific to your operation and will require monitoring. Most supply systems will give you approximate volumes that will be provided, but they are only that, approximate. Spot measurements should be done periodically throughout the greenhouse under a variety of conditions to monitor enrichment to plan increased or decreased enrichment depending on climatic conditions. Simple measuring devices are available that take in a small amount of greenhouse air and will give a colormetric change to indicate CO_2 level. These test kits will generally allow you to read levels between 300 and 1000 ppm with about ± 40 ppm accuracy.

For larger operations, or those that have computer controls, CO_2 levels can be programmed in as one of the readings taken. Solenoids can be set up to give "feedback" readings to compare current CO_2 levels to set points that are programmed into the computer. While this type of monitoring is expensive, growers often find that they save in CO_2 use. Several methods of sampling are available to give readings to the solenoids, the need for accuracy and your budget can help you determine which may be best for you.

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Impurities Resulting from CO_2 Generation

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Propylene is a major component of propane and does not cause a problem if the gas is completely combusted. If there is incomplete combustion, or vaporized propane leaks from joint fittings there can be serious crop damage. Plant damage will initiate near the location of the leak, or near the burner if there is a combustion problem. Effects will be similar to damage caused by ethylene, since the two chemicals are closely related (although much higher concentration of propylene are needed for damage than with ethylene). Symptoms of injury include:

* overall reduction of growth,
* curling and twisting of leaves,
* delay in flowering and
* the abscission and/or malformation of flowers.

Propylene can be detected by a distinctive "fishy" smell. If this is noticed, act immediately to avoid damage to your crop. The best way to avoid propylene damage to your plants is to pay special attention to the installation of propane burners and fuel supply lines and also, to be sure that the flame is burning blue so that you are getting complete combustion of the propane.

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Ethylene

While ethylene is a chemical that is produced by the plant, and is, therefore, important to plant growth, higher levels of ethylene can cause great damage to a plant. Higher levels are a relative term, because plants exposed to concentrations of 0.1 to 0.5 ppm ethylene will often show symptoms similar to those of propylene damage. Severe effects will be seen when ethylene concentrations are $\geq$ 1 ppm.

Ethylene is produced during the combustion of propane and natural gas. One problem is that even complete combustion of these gases can not guarantee that ethylene will not be present. Generally, even if ethylene is present, it is dispersed in the air and diluted to a level that will not damage plants. However, if the amount of fresh air for combustion is limited, or if air containing ethylene is reburned, the levels can become toxic. Be sure that the fresh air intake is working properly and that the fans distributing the CO_2 are moving air away from the burner and disbursing it through the greenhouse.

Tomatoes are one of the most sensitive crops to ethylene damage. For this reason, they ar often used as 'indicator' plants. Even very low levels of ethylene will casue 'epinasty', or downward curling of leaves. Exposure to a concentration of 0.5 ppm for as short as four days can cause abscission of two-fifths of the flowers on the first and second inflorescences. Continuous exposure to ethylene will lead to foliar twisting and distortion. In roses, exposure to 0.5 ppm ethylene for as few as three days will cause terminal bud abortion. Longer exposure periods will lead to more severe symptoms and plants may not recover. With chrysanthemums, ethylene concentrations of 1 to 4 ppm during short-days prevented flowering and caused distortion of the leaves and stems.

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Sulphur-dioxide

Potentially phytotoxic levels of SO_2 can be released when kerosene containing levels of 0.06% (by volume) of sulphur compounds, or greater, are burned. Plant damage caused by SO_2 is slight, provided that other contaminants are not in the air and the concentration does not exceed 0.5 ppm over a 4-hour period. With greater levels of sulfur-dioxide than this, leaves will typically show interveinal necrosis on both leaf surfaces. The level of necrosis increases in severity with increased concentration and/ or exposure duration. When using atomizing kerosene burners and low-sulphur kerosene very low atmospheric levels of SO_2 are generally found.

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Nitrogen oxides

Nitrogen gas is a major component of the earth's atmosphere. It generally is unreactive and has little or no direct impact on the growth of plants. At extremely high temperatures, however, it combines with atmospheric oxygen to form nitrogen oxide (NO). NO may then react spontaneously with oxygen to form nitrogen dioxide (NO_2). Since both gases are present at the same time, and it is never certain what the relative proportions of NO to NO_2 will be, they are generally referred to as NOx or nitrogen oxides.

Concentrations of NOx in unpolluted air are generally below 0.01 ppm. In areas of minor pollution the concentrations can increase to 0.05 to 0.1 ppm. On a city street readings of 0.5 ppm have been found. Readings of 0.5 ppm can also be found in greenhouses using open-flame propane or kerosene burners for CO_2 production. This is twice the concentration required to cause phytotoxic responses in sensitive plants such as tomatoes.

Symptoms of NOx injury range from leaf chlorosis and necrosis in extreme cases to reductions in leaf area and plant growth. Since the latter is much more common, high levels of NOx can be difficult to detect, especially in early stages of plant development. Later in development, foliage quality may deteriorate and stem length of cut flowers may be decreased and flowering of some plants may be delayed. Some crops, such as chrysanthemum, kalanchoe and Boston fern appear to be insensitive to NOx concentrations of up to 0.85 ppm.

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CO_2

Problems with leaf injury and growth reduction in a greenhouse are not always due to gaseous pollutants. High concentrations of CO_2 itself can cause problems. Some symptoms of "high" CO_2 injury include:

* leaf rolling,
* chlorosis and
* necrosis, particularly in the older leaves of plants such as tomato, cucumber, chrysanthemum and gerbera.

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